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REVIEW ARTICLE

TEMPOROMANDIBULAR JOINT DYSFUNCTION: CURRENT CONCEPTS IN ETIOLOGY, DIAGNOSIS, AND EVIDENCE-BASED MANAGEMENT-A NARRATIVE REVIEW

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Abstract

Background: Temporomandibular joint dysfunction (TMD) is a common disorder affecting the temporomandibular joint, masticatory muscles, and associated structures. It has a multifactorial etiology involving mechanical, neuromuscular, inflammatory, biological, and psychosocial factors. Recent advances in diagnostic criteria, imaging techniques, and therapeutic options have improved the understanding and management of TMD.

Objective: To provide an updated narrative review of the etiology, pathogenesis, clinical manifestations, diagnosis, and evidence-based management of temporomandibular joint dysfunction, with emphasis on conservative, minimally invasive, and surgical treatment approaches.

Materials and Methods: A narrative review was performed using PubMed/MEDLINE, Scopus, Web of Science, and Google Scholar. The review included systematic reviews, meta-analyses, randomized clinical trials, clinical studies, guidelines, and consensus statements published between January 2000 and March 2026, together with landmark publications relevant to TMD diagnosis and treatment.

Results: Current evidence indicates that TMD should be regarded as a multifactorial functional disorder requiring individualized assessment. Diagnosis is primarily based on the Diagnostic Criteria for Temporomandibular Disorders (DC/TMD), supported by magnetic resonance imaging (MRI) and cone-beam computed tomography (CBCT) when clinically indicated. Conservative treatment remains the first-line approach and includes patient education, self-management, physiotherapy, therapeutic exercises, occlusal splints, pharmacological therapy, and behavioral interventions. In patients with persistent symptoms, minimally invasive procedures such as arthrocentesis, arthroscopy, and intra-articular injections of hyaluronic acid or platelet-rich plasma may improve clinical outcomes. Open surgical procedures and total joint reconstruction are reserved for severe structural abnormalities. Emerging technologies, including artificial intelligence, digital mandibular tracking, biomarkers, and regenerative medicine, may support future personalized treatment strategies.

Conclusion: Effective TMD management requires an individualized, multidisciplinary, and evidence-based approach. Early diagnosis and conservative therapy remain the foundation of treatment, whereas minimally invasive and surgical interventions should be reserved for selected patients. Future integration of digital technologies and regenerative approaches may further improve personalized patient care.

Keywords: Temporomandibular joint dysfunction; Temporomandibular joint; Orofacial pain; Diagnosis; Conservative treatment; Arthrocentesis; Multidisciplinary management.

INTRODUCTION

Temporomandibular joint dysfunction (TMJ dysfunction) represents a common functional disorder affecting the temporomandibular joint and associated

masticatory structures. It is characterized by disturbances in joint function, altered mandibular biomechanics, pain symptoms, and impairment of normal stomatognathic function. Because of the complex anatomical and functional relationships within the maxillofacial system,

TMJ dysfunction may present with a broad spectrum of clinical manifestations, including preauricular and facial pain, limitation or deviation of mandibular movements, joint sounds, impaired mastication, headaches, otologic symptoms, and a significant reduction in oral health-related quality of life.¹⁻³

Over the past two decades, the understanding of temporomandibular joint dysfunction has undergone a substantial transformation. Historically, TMJ dysfunction was frequently interpreted primarily as a local mechanical disorder associated with occlusal abnormalities, altered mandibular function, or excessive loading of the joint structures. However, contemporary evidence supports a multifactorial model in which the development and persistence of symptoms result from complex interactions among biological, mechanical, neuromuscular, inflammatory, and psychosocial factors. Biological contributors include structural alterations of the joint components, changes in neuromuscular regulation, altered pain-processing mechanisms, genetic susceptibility, and inflammatory responses. Psychosocial factors, including stress, anxiety, depression, and sleep disturbances, may influence symptom severity, pain perception, and functional impairment. This modern perspective emphasizes that TMJ dysfunction cannot be explained solely by structural abnormalities but rather reflects dynamic interactions between peripheral joint tissues, muscular function, central pain modulation pathways, and individual patient characteristics.^{2,4,6}

Epidemiological studies indicate that temporomandibular joint dysfunction represents one of the most frequently encountered functional and pain-related conditions affecting the craniofacial region. Although reported prevalence rates vary depending on diagnostic criteria, study populations, and assessment methods, clinically relevant symptoms associated with TMJ dysfunction are observed in a considerable proportion of adults. Pain-related manifestations are frequently reported among young and middle-aged individuals, with many studies demonstrating a higher prevalence among women compared with men. This difference has been associated with multiple contributing factors, including hormonal influences, variations in pain sensitivity, genetic susceptibility, and psychosocial determinants. Nevertheless, demographic characteristics alone cannot fully explain the development of TMJ dysfunction, supporting the concept that this condition results from complex interactions between multiple biological and environmental factors.^{5,9}

The clinical significance of TMJ dysfunction extends

beyond localized joint discomfort and impaired mandibular function, as it may considerably affect patients' daily activities, social interactions, and overall quality of life. Limitation of mouth opening, altered mandibular movement patterns, difficulty with mastication, joint noises, facial and cervical pain, tinnitus, and persistent discomfort may interfere with normal function and contribute to psychological burden. Increasing evidence demonstrates associations between persistent TMJ-related pain, sleep disturbances, anxiety, depressive symptoms, and altered pain modulation mechanisms. Therefore, TMJ dysfunction should be considered not merely as a localized joint disorder but as a complex functional condition involving interactions between joint structures, masticatory muscles, pain-processing mechanisms, and psychosocial factors.^{4,10}

Current evidence indicates that the development of TMJ dysfunction cannot be attributed to a single etiological factor. Instead, it results from the interaction of mechanical loading, biological changes, neuromuscular activity, inflammatory processes, and individual adaptive responses. Frequently reported contributing factors include increased masticatory muscle activity, parafunctional behaviors such as bruxism, trauma, inflammatory alterations of joint tissues, degenerative changes, genetic susceptibility, and prolonged psychological stress. These factors may influence disease development through mechanisms involving altered muscle function, increased mechanical stress on joint components, activation of inflammatory pathways, and changes in peripheral and central pain processing. Consequently, clinical manifestations and disease progression vary considerably among individuals depending on biological susceptibility, environmental influences, functional adaptation capacity, and individual responses to pain.^{6,24,26}

Recent advances in research on temporomandibular joint dysfunction have substantially influenced contemporary diagnostic strategies. Current diagnostic concepts emphasize that comprehensive clinical assessment remains the foundation of evaluation, whereas imaging and instrumental investigations should be selected according to specific clinical indications rather than applied routinely in all patients. The Diagnostic Criteria for Temporomandibular Disorders (DC/TMD) provide a standardized framework for the assessment of temporomandibular conditions through structured clinical examination, evaluation of mandibular function, and assessment of relevant clinical and psychosocial factors. The application of standardized diagnostic approaches has improved diagnostic reliability and facilitated more individualized treatment planning for patients with TMJ dysfunction.^{1,11,12}

Advanced imaging techniques provide complementary

information in patients with suspected structural abnormalities or intra-articular pathology associated with temporomandibular joint dysfunction. Magnetic resonance imaging (MRI) remains the preferred imaging modality for evaluation of the soft tissue components of the temporomandibular joint, including articular disc position and morphology, joint effusion, inflammatory changes, and early degenerative alterations. MRI findings should always be interpreted together with clinical symptoms, as structural abnormalities may also be present in individuals without clinical manifestations. Cone-beam computed tomography (CBCT) and computed tomography (CT) are primarily used for evaluation of osseous structures, including condylar morphology, cortical changes, erosive alterations, osteophyte formation, anatomical deformities, and advanced degenerative joint changes.

The integration of clinical examination with appropriately selected imaging modalities improves diagnostic accuracy and reduces the risk of unnecessary interventions based solely on radiographic findings.^{13,14}

The therapeutic approach to temporomandibular joint dysfunction has progressively shifted from irreversible mechanical interventions toward patient-centered, minimally invasive, and evidence-based management strategies. Current recommendations support a stepwise treatment model in which reversible and conservative approaches are prioritized before invasive procedures. The primary objectives of treatment include reduction of pain, restoration of mandibular function, improvement of oral health-related quality of life, and prevention of chronic symptom progression rather than correction of anatomical abnormalities alone. This contemporary treatment philosophy reflects the recognition that structural changes identified by imaging do not always correlate directly with clinical symptoms and that treatment decisions should be based on comprehensive evaluation of each patient's functional status, pain characteristics, contributing factors, and individual expectations.¹⁵⁻¹⁷

Conservative management remains the cornerstone of treatment for temporomandibular joint dysfunction and includes patient education, self-management strategies, behavioral modification, physiotherapy, therapeutic exercises, occlusal splints, pharmacological interventions, and psychological support when clinically indicated. These approaches aim to reduce pain, improve functional adaptation, and address contributing factors rather than focusing

exclusively on anatomical correction. In patients who demonstrate insufficient improvement despite appropriate conservative therapy, minimally invasive procedures may be considered.

Arthrocentesis, arthroscopy, and intra-articular injections with agents such as hyaluronic acid and platelet-rich plasma (PRP) have been investigated as therapeutic options, particularly in selected patients with persistent intra-articular symptoms, inflammatory changes, or degenerative joint alterations. Surgical interventions, including open joint procedures and temporomandibular joint prosthetic reconstruction, remain reserved for patients with severe structural abnormalities, advanced degenerative disease, ankylosis, or failure of less invasive treatment approaches.^{18,25,26,27,28,34}

Despite substantial progress in understanding temporomandibular joint dysfunction, several aspects of its pathophysiology, diagnostic classification, and therapeutic decision-making remain under active investigation. The considerable variability of clinical manifestations, differences in diagnostic approaches, heterogeneity of treatment protocols, and complex interactions between biological and psychosocial determinants continue to represent challenges for individualized patient management. Contemporary research emphasizes the importance of standardized diagnostic approaches, evidence-based therapeutic algorithms, and multidisciplinary strategies integrating dental, medical, physiotherapeutic, and behavioral perspectives.²⁹⁻³³

Although numerous clinical studies, systematic reviews, and consensus statements have expanded current knowledge regarding temporomandibular joint dysfunction, differences in study methodologies, diagnostic criteria, patient characteristics, and outcome assessment methods continue to limit direct comparison between published findings. Therefore, an updated synthesis of contemporary concepts related to the etiology, pathogenesis, diagnosis, and evidence-based management of temporomandibular joint dysfunction remains clinically relevant. The principal contemporary treatment modalities for temporomandibular joint dysfunction and their clinical characteristics are summarized in Table 1.

Table 1. Contemporary Classification of Treatment Modalities for Temporomandibular Joint Dysfunction

Treatment modality	Main indications	Advantages	Limitations	Level of evidence
Patient education and self-management	Patients with temporomandibular joint dysfunction	Non-invasive, low cost, promotes patient participation and self-care	Requires patient adherence and motivation	High
Physiotherapy and therapeutic exercise	Functional limitation, muscular dysfunction, impaired mandibular mobility	Improves mandibular function and reduces pain	Treatment protocols and duration vary among studies	High
Occlusal splints	Bruxism, muscular pain, selected functional disorders	Reversible and conservative therapeutic option	Effectiveness depends on appropriate patient selection and indication	Moderate–High
Pharmacological therapy	Acute pain, inflammatory symptoms, muscular discomfort	Provides symptom relief and improves patient comfort	Potential adverse effects and limited role for long-term management	Moderate
Electrostimulation therapies	Chronic muscular pain and rehabilitation	Non-invasive adjunctive therapy	Limited standardization and heterogeneous evidence	Moderate
Biological therapies (PRP, hyaluronic acid)	Degenerative TMJ changes and persistent intra-articular symptoms	Potential biological and regenerative effects	Lack of standardized protocols and variable evidence quality	Moderate
Arthrocentesis	Internal derangement, persistent joint pain, limited response to conservative therapy	Minimally invasive and effective symptom improvement in selected cases	Requires appropriate patient selection	High
Arthroscopy	Persistent intra-articular pathology	Provides both diagnostic and therapeutic benefits	Technically demanding and operator-dependent	High
Open surgery and TMJ reconstruction	Severe structural pathology, ankylosis, advanced degenerative joint disease	Definitive treatment for complex structural disorders	Greater surgical morbidity and longer recovery period	High

Abbreviations: TMJ, temporomandibular joint; PRP, platelet-rich plasma.

This narrative review aims to provide a comprehensive overview of contemporary concepts regarding temporomandibular joint dysfunction, including current understanding of its etiology, pathogenesis, diagnostic approaches, and evidence-based management strategies, with particular emphasis on recent scientific developments and evolving clinical perspectives.

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2.1. Review Design

This study was designed as a narrative review aimed at providing a comprehensive and critical synthesis of current evidence regarding temporomandibular joint dysfunction (TMJ dysfunction), with particular emphasis on contemporary concepts of etiology, pathogenesis, diagnostic approaches, and evidence-based therapeutic strategies. The review methodology was developed according to the principles of narrative reviews, allowing integration and interpretation of findings from different types of scientific publications, including systematic reviews, meta-analyses, randomized clinical trials, observational studies, clinical guidelines, and expert consensus documents.

The narrative approach was selected because TMJ dysfunction represents a complex clinical condition characterized by interactions among biological, mechanical, neuromuscular, inflammatory, and psychosocial factors. This methodology enables a broad evaluation of current concepts, emerging diagnostic approaches, and evolving treatment strategies while considering differences in study designs, clinical populations, and reported outcomes.

2.2. Literature Search Strategy

A narrative literature synthesis was performed using the electronic databases PubMed/MEDLINE, Scopus, Web of Science Core Collection, and Google Scholar. The literature search included publications primarily published between January 2020 and March 2026. In addition, earlier landmark publications were considered when they represented fundamental contributions to the development of diagnostic classifications, clinical criteria, pathophysiological concepts, and treatment principles related to TMJ dysfunction.

The search strategy was developed using Medical Subject Headings (MeSH) terms and relevant keywords combined with Boolean operators. The search strategy was adapted according to the requirements of each database.

The following search terms and combinations were applied: ("temporomandibular joint dysfunction", "etiology", "pathogenesis", "diagnosis", "clinical criteria", "MRI", "CBCT", "management", "conservative treatment", "physiotherapy", "occlusal splints", "pharmacological therapy", "botulinum toxin", "electrostimulation", "TENS", "arthrocentesis", "arthroscopy", "platelet-rich plasma", "hyaluronic acid", "surgical treatment").

Additional manual searches of reference lists from relevant publications were performed to identify important studies that were not retrieved through electronic database searches.

2.3. Eligibility Criteria

Publications were considered eligible when they provided clinically relevant information regarding the etiology, pathophysiology, diagnosis, clinical manifestations, imaging assessment, or management of temporomandibular joint dysfunction.

The review included:

- systematic reviews and meta-analyses;
- randomized clinical trials;
- prospective and retrospective clinical studies;
- observational studies;
- international clinical guidelines;
- consensus statements and expert recommendations.

Articles were selected based on their relevance to contemporary concepts of TMJ dysfunction etiology, diagnosis, and management. Due to the narrative design of the review, no formal screening process, systematic review workflow, or quantitative synthesis was performed.

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2.4. Inclusion Criteria

Studies were included if they met the following criteria:

1. Focused on temporomandibular joint dysfunction or related disorders affecting temporomandibular joint function.
2. Addressed at least one of the following aspects: etiology, pathogenesis, diagnostic evaluation, clinical manifestations, imaging assessment, or therapeutic management.
3. Were published in peer-reviewed scientific journals.
4. Provided sufficient methodological information and clinically meaningful outcomes.
5. Were available as full-text publications in English.

2.5. Exclusion Criteria

The following publications were excluded:

- duplicate records;
- conference abstracts without full scientific reports;
- non-peer-reviewed materials;
- opinion articles without supporting scientific evidence;
- experimental studies without direct clinical relevance;
- publications unrelated to the etiology, diagnosis, imaging assessment, or management of TMJ dysfunction.⁶

2.6. Data Extraction and Narrative Synthesis

Relevant information was extracted from selected publications, including study design, patient characteristics, diagnostic criteria, imaging modalities, therapeutic interventions, follow-up periods, and reported clinical outcomes. The extracted evidence was organized according to the main clinical domains of TMJ dysfunction:

1. Etiology and pathogenesis;
2. Modern diagnostic approaches;
3. Conservative and non-surgical management;
4. Minimally invasive interventions;
5. Biological therapies;
6. Surgical treatment strategies;
7. Emerging technologies and future perspectives.

Because of substantial heterogeneity among available studies regarding patient populations, diagnostic criteria, treatment protocols, and outcome measures, a qualitative narrative synthesis was performed. The findings were critically interpreted according to clinical relevance, consistency of available evidence, methodological characteristics, and applicability to contemporary clinical practice.

2.7. Quality Considerations

As this study was designed as a narrative review, a formal risk-of-bias assessment according to systematic review methodology and quantitative meta-analysis were not performed. However, methodological characteristics of included studies, study design, level of evidence, sample characteristics, and potential limitations were considered during interpretation and synthesis of the available evidence. The strength and clinical relevance of findings were evaluated according to the consistency of reported outcomes, methodological quality of available studies, and applicability to current TMJ dysfunction management approaches.

2.8. Ethical Considerations

Ethical approval was not required for this narrative review because the study involved analysis of previously published scientific literature and did not include direct participation of human subjects, patient recruitment, or collection of individual patient data.

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3. RESULTS

3.1. Overview of Included Evidence and General Findings

The synthesis of the available literature demonstrated that temporomandibular joint dysfunction (TMJ dysfunction) represents a complex multifactorial condition involving interactions among articular structures, masticatory muscles, neuromuscular regulation, inflammatory mechanisms, and psychosocial factors. Current evidence indicates that TMJ dysfunction is no longer considered an isolated mechanical disorder but rather a multidimensional functional condition influenced by biological, biomechanical, psychological, and environmental determinants. This conceptual transition has shifted contemporary management toward a patient-centered biopsychosocial approach integrating structural, functional, and pain-related mechanisms.^{1,4,14,18}

The literature analyzed in this review included systematic reviews, meta-analyses, randomized clinical trials, observational studies, and clinical recommendations addressing different aspects of TMJ dysfunction. Although substantial heterogeneity was observed regarding diagnostic criteria, patient populations, therapeutic protocols, and outcome assessment methods, several consistent findings were identified across studies. These included the importance of standardized diagnostic approaches, early conservative management, multidisciplinary care, and individualized treatment planning based on clinical characteristics rather than isolated imaging findings.^{1,12,21,22}

Clinical manifestations demonstrated considerable variability among patients. The most frequently reported symptoms included temporomandibular and masticatory muscle pain, limitation or deviation of mandibular movements, joint sounds, impaired mastication, headaches, and associated otologic symptoms. Current evidence suggests that symptom severity is influenced not only by structural changes but also by individual pain sensitivity, psychological status, functional adaptation, and central pain-processing mechanisms.^{4,5,10,23}

The reviewed evidence demonstrated a progressive transition toward minimally invasive and reversible treatment strategies. Conservative approaches, including patient education, self-management, physiotherapy, behavioral modification, pharmacological support, and occlusal appliance therapy, remain the foundation of initial management. More invasive procedures are generally reserved for selected patients with persistent symptoms, failure of conservative therapy, or significant structural joint pathology.^{15,16,18,25,26,27}

3.2. Etiology and Pathophysiological Mechanisms of Temporomandibular Joint Dysfunction

The reviewed evidence confirmed that TMJ dysfunction develops through the interaction of multiple etiological factors rather than a single pathological mechanism. Current concepts emphasize the dynamic relationship between mechanical loading, neuromuscular activity, inflammatory processes, tissue adaptation, genetic susceptibility, and psychosocial influences.^{4,5,24} Frequently reported contributing factors include masticatory muscle overload, parafunctional activity, trauma, inflammatory joint alterations, degenerative changes, genetic predisposition, and psychological stress. However, contemporary evidence indicates that these factors should be interpreted as interacting modifiers rather than independent causes, explaining the considerable variability in clinical presentation and disease progression among patients.^{4,24,26}

3.2.1. Masticatory Muscle Dysfunction and Bruxism

Altered masticatory muscle function represents an important component in the development and maintenance of TMJ-related symptoms. Increased muscle activity, prolonged contraction, fatigue, and impaired neuromuscular coordination may contribute to myofascial pain, restricted mandibular movements, and functional limitation.^{23,24}

The role of bruxism has been substantially reconsidered in recent years. Earlier theories suggested that bruxism represented a primary etiological factor; however, current evidence indicates a more complex relationship. Bruxism is now regarded as a potential modifying factor that may increase muscular loading, aggravate existing dysfunction, and contribute to symptom persistence in susceptible individuals rather than acting as an isolated cause of TMJ dysfunction.

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3.2.2. Occlusal Factors

The relationship between occlusion and TMJ dysfunction has undergone significant revision. Earlier concepts

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considered occlusal abnormalities as the dominant cause of joint dysfunction; however, contemporary evidence does not support occlusion as an independent primary etiological factor.^{20,21}

Current studies indicate that occlusal characteristics may influence functional adaptation and load distribution within the stomatognathic system but represent only one component within a broader multifactorial model. This change in understanding has reduced the use of irreversible occlusal interventions without clear clinical indications.^{20,21,27}

3.2.3. Psychosocial and Central Pain Mechanisms

Recent studies emphasize the important contribution of psychosocial factors to the development and persistence of TMJ-related pain. Stress, anxiety, depression, sleep disturbances, and emotional disorders may influence pain modulation pathways and contribute to chronic symptom development.^{4,8,10} The involvement of central sensitization mechanisms has become increasingly recognized, particularly in patients with persistent pain symptoms. Altered central processing of nociceptive signals may explain why clinical symptoms do not always correspond directly with the extent of structural abnormalities identified by imaging.^{4,5,23}

Overall, current evidence supports a biopsychosocial model in which TMJ dysfunction results from interactions between peripheral joint structures, neuromuscular function, inflammatory processes, and individual pain-processing characteristics, as illustrated in Figure 1.^{4,5,14}

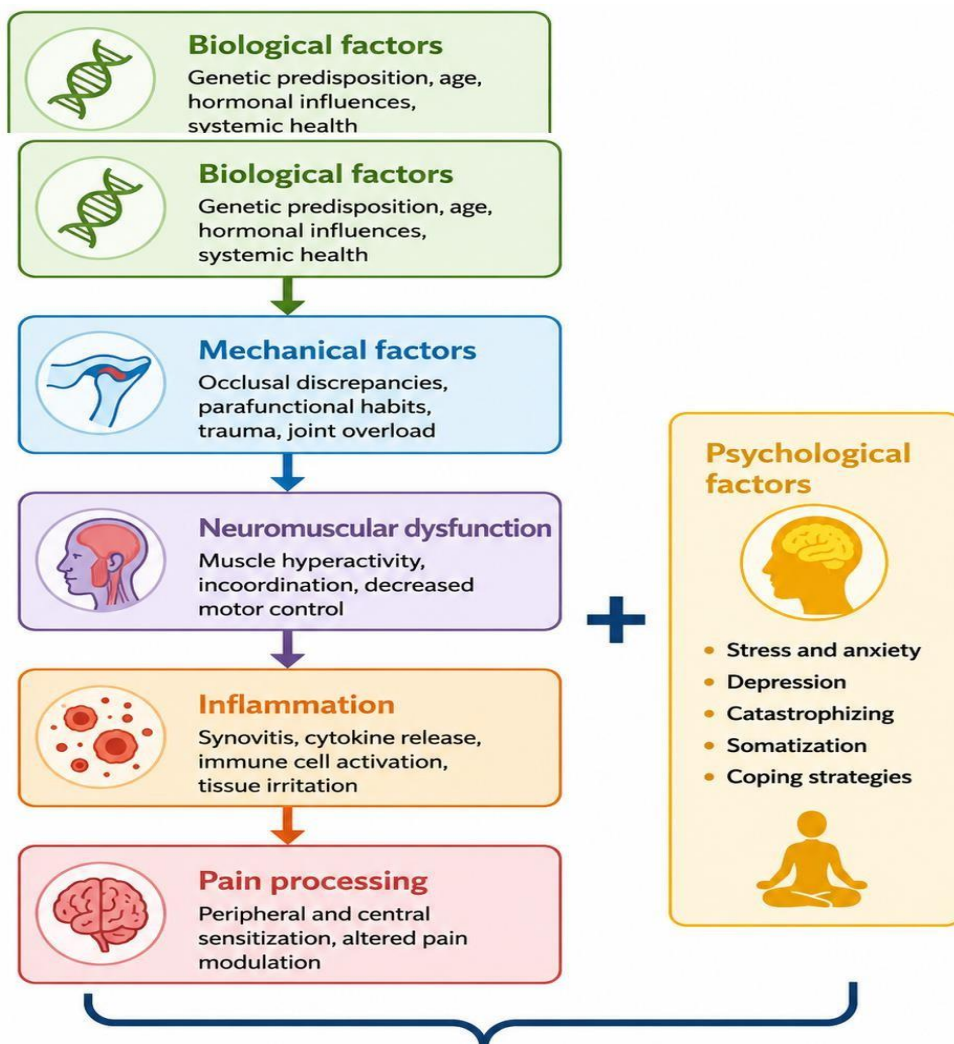


Figure 1. Contemporary Biopsychosocial Model of Temporomandibular Joint Dysfunction

This conceptual framework explains why successful management of temporomandibular disorders requires a multidisciplinary approach that addresses both peripheral joint pathology and central pain modulation.

3.3. Contemporary Diagnostic Approaches in Temporomandibular Joint Dysfunction

The analysis of current evidence demonstrated that accurate diagnosis remains the cornerstone of effective TMJ dysfunction management. Contemporary diagnostic strategies emphasize standardized clinical assessment combined with selective use of imaging modalities according to individual clinical indications.^{1,12,22}

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3.3.1. Diagnostic Criteria for Temporomandibular Disorders (DC/TMD)

The Diagnostic Criteria for Temporomandibular Disorders (DC/TMD) represent the most widely accepted standardized diagnostic framework for evaluation of temporomandibular conditions. This system provides structured assessment of pain-related disorders and intra-articular abnormalities through patient history, clinical examination, mandibular movement evaluation, and assessment of relevant anatomical structures.^{1,12}

Studies applying DC/TMD demonstrate improved diagnostic reliability compared with previous classification approaches and provide greater consistency in both clinical practice and research investigations.^{12,22}

3.3.2. Magnetic Resonance Imaging and Soft Tissue Assessment

Magnetic resonance imaging (MRI) remains the preferred imaging modality for evaluation of soft tissue components of the temporomandibular joint. The reviewed literature confirms its value in detecting:

- disc displacement;
- joint effusion;
- inflammatory changes;
- early degenerative alterations;
- retrodiscal tissue abnormalities.

However, MRI findings should always be interpreted together with clinical symptoms and functional examination because structural alterations may also be present in asymptomatic individuals.^{13,14}

3.3.3. CBCT and Assessment of Osseous Changes

Cone-beam computed tomography (CBCT) and computed tomography (CT) remain important methods for evaluation of hard tissue alterations associated with TMJ dysfunction. These modalities are particularly useful for identifying:

- condylar remodeling;
- erosive changes;
- osteophyte formation;
- anatomical deformities;
- advanced degenerative alterations.

Current recommendations support imaging selection according to clinical necessity rather than routine application in all patients.^{13,18}

3.3.4. Emerging Digital Diagnostic Technologies

Recent publications demonstrate increasing interest in digital approaches, including mandibular motion tracking, computerized functional analysis, electromyographic assessment, and artificial intelligence-assisted imaging interpretation.

These technologies may provide additional objective information regarding mandibular function and disease

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characterization. However, current evidence remains insufficient to replace validated clinical examination methods and established diagnostic criteria.^{29–33}

The current evidence supporting different diagnostic modalities varies considerably. Established clinical assessment methods and conventional imaging techniques demonstrate stronger validation compared with emerging digital and biological diagnostic approaches. The current evidence level of major diagnostic modalities used in the evaluation of TMJ dysfunction is summarized in **Table 2**.

Table 2. Current Evidence Level of Diagnostic Modalities in Temporomandibular Joint Dysfunction

Diagnostic modality	Main clinical application	Evidence level
DC/TMD clinical criteria	Standardized clinical assessment of temporomandibular joint dysfunction	Strong
MRI	Evaluation of disc position, soft tissue structures, and intra-articular changes	Moderate–Strong
CBCT	Assessment of osseous changes and degenerative joint alterations	Moderate
Ultrasonography	Dynamic assessment and preliminary evaluation of joint structures	Emerging–Moderate
Digital mandibular tracking	Functional movement analysis and quantitative assessment of mandibular dynamics	Emerging
Artificial intelligence models	Automated image analysis, diagnostic prediction, and clinical decision support	Emerging
Biomarkers (saliva/synovial fluid)	Biological characterization and disease monitoring	Experimental

3.4. Conservative and Non-Surgical Management Strategies

The reviewed literature confirms that conservative treatment remains the cornerstone of contemporary management of temporomandibular joint dysfunction. Current international recommendations emphasize reversible, minimally invasive, and patient-centered approaches as the preferred initial therapeutic strategy. The modern treatment concept follows a stepwise model in which conservative interventions are prioritized before consideration of minimally invasive or surgical procedures.^{3,15,16,21}

The evidence-based stepwise management pathway recommended for patients with temporomandibular joint dysfunction is summarized in Figure 2.

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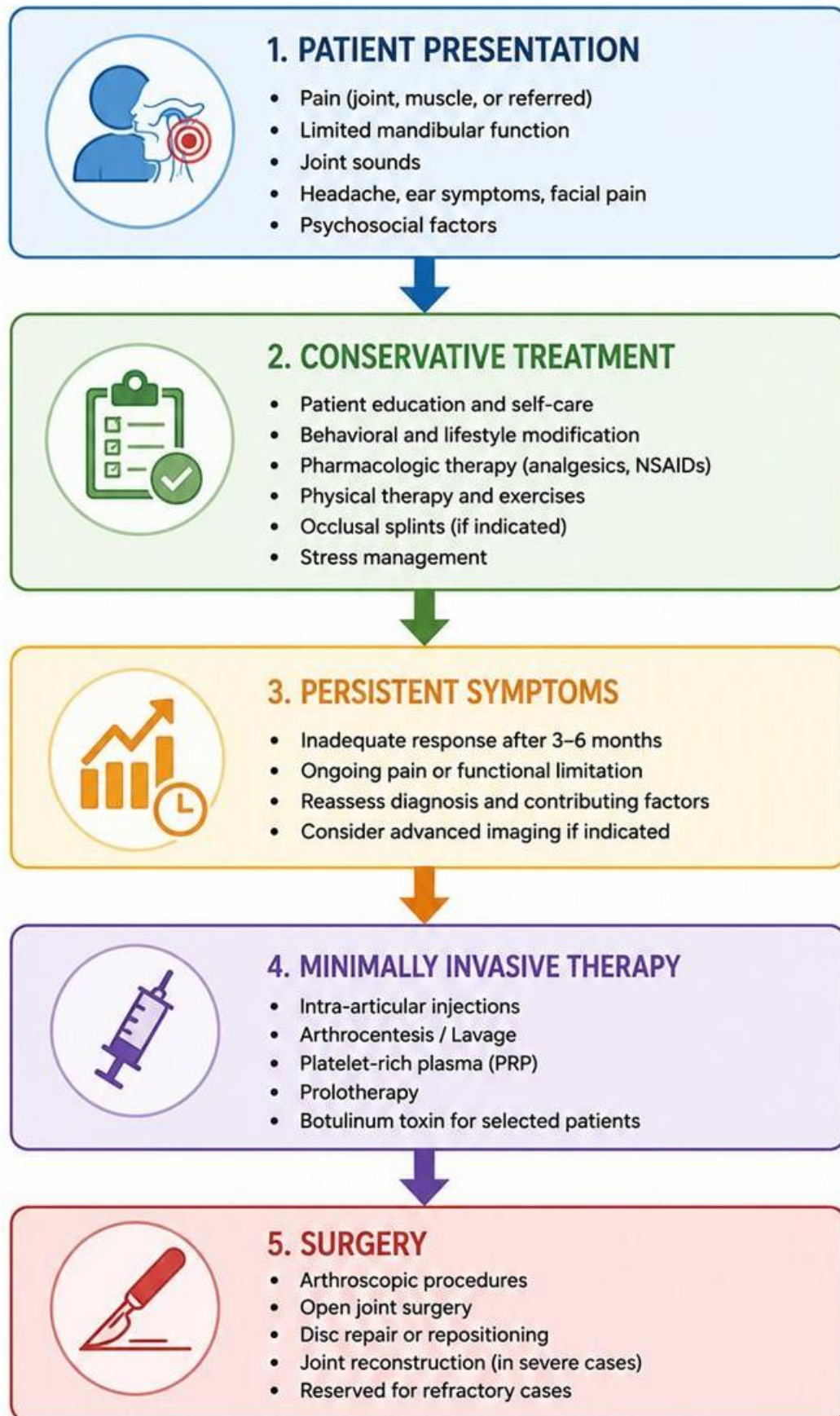


Figure 2. Evidence-Based Management Algorithm for Temporomandibular Joint Dysfunction

This stepwise algorithm reflects current international recommendations that prioritize conservative and reversible interventions before progressing to minimally invasive procedures or surgical treatment in appropriately selected patients.

3.4.1. Patient Education and Self-Management

Patient education represents one of the most consistently supported components of conservative management. Contemporary approaches focus on improving patient understanding of the mechanisms contributing to temporomandibular joint dysfunction, reducing excessive mechanical loading, controlling parafunctional behaviors, modifying dietary habits, and maintaining appropriate mandibular function.

Recent systematic reviews indicate that self-management strategies, including patient education, behavioral modification, home-based exercises, and lifestyle adaptation, may contribute to reduction of pain intensity and improvement of functional outcomes. Active patient participation and adherence to recommended strategies appear to play an important role in long-term symptom control and may enhance the effectiveness of combined therapeutic approaches.^{3,15,16}

3.4.2. Physiotherapy and Functional Rehabilitation

Physiotherapy represents one of the most extensively investigated conservative approaches for temporomandibular joint dysfunction. The reviewed evidence demonstrates beneficial effects of therapeutic exercises, manual therapy, muscle stretching techniques, relaxation protocols, and mandibular movement coordination training.

These interventions may improve mandibular mobility, decrease excessive muscular tension, enhance neuromuscular coordination, and promote functional adaptation of the stomatognathic system.^{15,28,30}

Current evidence supports multimodal rehabilitation programs combining exercise therapy, manual techniques, patient education, and behavioral strategies rather than isolated therapeutic interventions. Recent systematic reviews and clinical studies suggest that combined conservative approaches may provide clinically meaningful improvements in pain reduction and mandibular function, although treatment response depends on individual patient characteristics and the underlying clinical phenotype.^{15,16,28}

3.4.3. Electrostimulation and Novel Physical Therapy Approaches

Recent publications demonstrate increasing interest in electrostimulation techniques as complementary approaches for the management of temporomandibular joint dysfunction. These methods are primarily aimed at modulating pain perception, reducing abnormal masticatory muscle activity, and improving neuromuscular coordination.^{18,19}

Among currently investigated modalities, transcutaneous electrical nerve stimulation (TENS), neuromuscular electrical stimulation, and other low-intensity electrotherapeutic approaches have been evaluated in patients with muscular pain, increased muscle tension, and functional limitation of mandibular movements.^{18,19}

The proposed mechanisms include modulation of peripheral nociceptive input, activation of inhibitory pain pathways, reduction of excessive muscle activity, improvement of local circulation, and restoration of neuromuscular balance. These effects may be particularly relevant in patients with predominant muscular manifestations associated with temporomandibular joint dysfunction.^{18,23}

However, current evidence does not support electrostimulation as an independent first-line treatment. Its greatest clinical value appears to be as an adjunctive component of multimodal rehabilitation programs that include therapeutic exercises, behavioral modification, manual therapy, and other conservative interventions.^{3,18,19}

3.4.4. Patch-Based Transcutaneous Electrostimulation in Temporomandibular Joint Dysfunction

Recent clinical investigations have introduced portable patch-based transcutaneous electrostimulation systems as a potential advancement in conservative management. Unlike conventional electrotherapy devices requiring repeated clinical visits, patch-based systems allow prolonged stimulation through adhesive electrodes placed on the skin

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surface, potentially improving treatment accessibility and patient compliance.^{18,19}

Available clinical evidence suggests that patch-based electrostimulation may contribute to reduction of pain intensity, improvement of mandibular function, and decreased muscular hyperactivity in selected patients with temporomandibular joint dysfunction.^{19,34}

A clinical investigation by Khachatryan A, Hakobyan G, et al. evaluated the effect of transcutaneous electrostimulation in patients with temporomandibular joint dysfunction associated with occlusal disturbances. The authors reported improvements in pain-related symptoms and functional parameters following electrostimulation therapy, suggesting its potential role as an adjunctive conservative treatment modality.¹⁹

Nevertheless, available evidence remains limited by relatively small sample sizes, differences in stimulation protocols, and insufficient long-term follow-up. Therefore, although patch-based electrostimulation represents a promising minimally invasive approach, further randomized controlled studies are required to determine optimal stimulation parameters, treatment duration, and long-term clinical effectiveness.^{18,19,34}

3.4.5. Pharmacological Management

Pharmacological therapy remains an important supportive component in the management of temporomandibular joint dysfunction, particularly for controlling pain, inflammatory manifestations, and muscular discomfort. Current evidence indicates that medication should not be considered as an isolated treatment approach but rather as part of a comprehensive therapeutic strategy combined with patient education, rehabilitation, and behavioral interventions.^{3,18,21}

The choice of pharmacological agents should be individualized according to the clinical characteristics of each patient, including the intensity and duration of pain, presence of inflammatory signs, muscular involvement, and associated chronic pain mechanisms.^{18,21}

3.4.5.1. Non-Steroidal Anti-Inflammatory Drugs and Analgesic Therapy

Non-steroidal anti-inflammatory drugs (NSAIDs) remain among the most commonly used pharmacological agents in patients with temporomandibular joint dysfunction, particularly during episodes of acute pain, inflammatory joint manifestations, and symptom exacerbation.

Clinical studies indicate that NSAIDs may provide short-term reduction of pain intensity and inflammatory symptoms through inhibition of cyclooxygenase-mediated inflammatory pathways and reduction of prostaglandin synthesis. However, their therapeutic effect is primarily symptomatic, and they do not directly modify the underlying mechanisms responsible for temporomandibular joint dysfunction.^{18,21}

Analgesic medications may be considered according to individual pain characteristics and clinical severity. They may provide temporary relief in patients with functional discomfort or acute exacerbations, but their prolonged use should be approached cautiously because of potential adverse effects and limited evidence regarding sustained long-term benefits.^{18,21}

Current recommendations emphasize that pharmacological therapy should be integrated with conservative interventions, including physiotherapy, functional rehabilitation, behavioral modification, and self-management strategies, rather than used as a stand-alone treatment modality.^{3,16}

3.4.5.2. Muscle Relaxants and Central Pain Modulation

Muscle relaxants may be considered in selected patients with temporomandibular joint dysfunction associated with increased masticatory muscle activity, muscle spasm, or significant muscular discomfort. Their potential benefits include temporary reduction of muscle hyperactivity, improvement of muscular relaxation, and decreased pain associated with excessive muscle contraction.^{18,21} However, clinical response may vary considerably among patients, and the use of muscle relaxants requires careful consideration of possible adverse effects, including sedation and functional impairment. Therefore, their application

should be limited to appropriate clinical situations and generally used as a short-term supportive therapy.¹⁸

In patients with chronic pain characteristics, including features of altered pain processing or central sensitization, conventional analgesic approaches may provide insufficient symptom control. Current research has emphasized the importance of therapies targeting central pain modulation mechanisms, particularly in patients whose symptoms persist despite adequate management of peripheral factors.^{4,5,10}

Recognition of central pain mechanisms has contributed to a broader understanding of temporomandibular joint dysfunction as a condition involving interactions between peripheral tissues, neuromuscular regulation, and central nervous system processing. Consequently, management of chronic pain presentations may require multidisciplinary approaches incorporating rehabilitation, behavioral strategies, psychological support, and individualized pharmacological interventions.^{4,8,10}

Overall, current evidence supports the use of pharmacological therapy as an adjunctive component within a multimodal treatment strategy. Optimal outcomes are generally achieved when medication is combined with conservative rehabilitation approaches aimed at improving function, reducing pain sensitivity, and addressing contributing factors.^{3,16,18}

3.5. Occlusal Splints and Orthopedic Management

Occlusal splints remain among the most extensively studied conservative treatment modalities for temporomandibular joint dysfunction. The reviewed evidence indicates that appropriately designed occlusal appliances may reduce excessive loading of the temporomandibular joint and masticatory muscles, improve functional stability, and contribute to symptom reduction in selected patients.^{20,21,27}

The proposed therapeutic mechanisms include redistribution of occlusal forces, reduction of parafunctional muscle activity, improvement of neuromuscular adaptation, and temporary stabilization of mandibular function. However, contemporary evidence emphasizes that occlusal splints should not be considered corrective devices for all forms of temporomandibular joint dysfunction. Their clinical effectiveness depends primarily on accurate diagnosis, appropriate patient selection, and integration into a comprehensive treatment strategy.^{3,20,21}

The role of irreversible occlusal interventions has substantially decreased in modern clinical practice. Current evidence does not support routine occlusal adjustment or extensive prosthodontic alteration solely for the management of temporomandibular joint dysfunction, as the disorder cannot be explained exclusively by occlusal abnormalities.^{20,21}

Orthopedic dental interventions may still be indicated in selected patients with significant tooth wear, occlusal instability, or functional rehabilitation requirements. In such cases, treatment objectives should focus on restoration of the overall masticatory system rather than isolated correction of occlusal relationships.^{20,21}

3.6. Botulinum Toxin Therapy

Botulinum toxin application has become an increasingly investigated therapeutic option, particularly in patients with muscular manifestations of temporomandibular joint dysfunction characterized by increased masticatory muscle activity, bruxism-related symptoms, and chronic myofascial pain.^{24,37}

The therapeutic effect is primarily associated with temporary inhibition of acetylcholine release at the neuromuscular junction, resulting in decreased muscle contraction intensity and reduction of excessive muscular activity.³⁷

Several clinical studies have reported improvement in pain scores and reduction of muscle activity following botulinum toxin injections, particularly in patients with involvement of the masseter and temporalis muscles.^{37,38}

Nevertheless, the current evidence remains heterogeneous. Differences in injection techniques, dosage protocols, outcome assessment methods, and patient selection criteria limit direct comparison among published studies.

Therefore, botulinum toxin should currently be considered a selective therapeutic option rather than a routine first-line treatment modality.^{37,38}

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Further high-quality randomized clinical trials are required to determine optimal indications, standardized injection protocols, long-term effectiveness, and safety profiles.^{37,38}

3.7. Biological Intra-Articular Therapies

Recent literature demonstrates increasing interest in biological approaches for temporomandibular joint dysfunction, particularly intra-articular administration of hyaluronic acid and platelet-rich plasma (PRP). These therapies aim to influence inflammatory processes, improve joint environment, and potentially enhance tissue repair mechanisms.^{41,45}

3.7.1. Hyaluronic Acid Injections

Hyaluronic acid therapy is based on restoration of synovial fluid characteristics, improvement of joint lubrication, reduction of friction, and modulation of inflammatory activity within the intra-articular environment.⁴¹ Clinical studies have demonstrated beneficial effects on pain reduction and improvement of mandibular function, particularly in patients with degenerative joint changes and inflammatory manifestations.^{41,42}

However, differences in molecular characteristics, injection protocols, treatment schedules, and patient selection criteria contribute to variability among reported outcomes. Further studies are required to establish standardized clinical protocols and define long-term effectiveness.^{41,42}

3.7.2. Platelet-Rich Plasma Therapy

Platelet-rich plasma therapy has attracted considerable attention due to its potential regenerative properties associated with growth factors and biologically active mediators contained within platelet concentrates.^{44,45}

The proposed mechanisms include modulation of inflammatory responses, stimulation of tissue repair pathways, improvement of joint homeostasis, and potential enhancement of regenerative processes within damaged tissues.^{44,45} Although several clinical studies have reported favorable short-term outcomes regarding pain reduction and functional improvement, substantial variability remains regarding PRP preparation methods, platelet concentration, activation protocols, injection techniques, and evaluation criteria.^{26,45} Current evidence supports PRP as a promising adjunctive biological approach; however, its definitive clinical role requires confirmation through larger controlled clinical studies with standardized protocols and longer follow-up periods.^{26,45}

3.8. Minimally Invasive and Surgical Management

The reviewed evidence confirms that minimally invasive procedures are generally reserved for patients who demonstrate insufficient improvement following appropriate conservative management or those presenting with significant intra-articular pathology. The current therapeutic philosophy emphasizes preservation of joint function and avoidance of unnecessary invasive procedures whenever possible.^{25,34,47}

3.8.1. Arthrocentesis

Arthrocentesis represents one of the most frequently applied minimally invasive procedures for selected cases of temporomandibular joint dysfunction associated with internal derangement and persistent intra-articular symptoms. The procedure involves lavage of the upper joint compartment, removal of inflammatory mediators, reduction of intra-articular adhesions, and improvement of joint mobility.^{25,34} Clinical studies demonstrate favorable outcomes in appropriately selected patients, including reduction of pain intensity, improvement of maximum mouth opening, and enhancement of mandibular function.^{25,34,48}

Although arthrocentesis is considered a relatively safe minimally invasive intervention, treatment success depends on appropriate patient selection, accurate diagnosis, and the stage of intra-articular pathology.^{34,47}

3.8.2. Arthroscopy

Temporomandibular joint arthroscopy provides both diagnostic and therapeutic advantages by allowing direct visualization of intra-articular structures and minimally invasive management of selected pathological conditions.^{49,50}

The reviewed literature indicates that arthroscopy may be beneficial in patients with persistent intra-articular symptoms, disc displacement, adhesions, and limited response to conservative treatment.^{49,50}

Compared with open surgical procedures, arthroscopy is associated with reduced surgical trauma and shorter recovery periods; however, its application requires specialized equipment, technical expertise, and appropriate clinical indications.⁴⁹

3.8.3. Open Surgical Procedures and Joint Reconstruction

Open surgical intervention remains reserved for advanced structural abnormalities, severe degenerative changes, ankylosis, trauma-related deformities, and cases in which conservative and minimally invasive approaches fail to provide adequate improvement.^{27,51}

Modern reconstructive strategies increasingly incorporate virtual surgical planning, digital technologies, and patient-specific temporomandibular joint prosthetic systems. These approaches allow individualized reconstruction and may improve anatomical restoration and functional outcomes in selected patients with severe joint pathology.^{27,28,39} A comparative overview of the principal therapeutic approaches, including their main clinical indications, advantages, and current limitations, is presented in Table 3.

Table 3. Advantages and Limitations of Contemporary Therapeutic Approaches for Temporomandibular Joint Dysfunction

Therapeutic approach	Main indications	Principal advantages	Current limitations
Patient education and self-management	Initial management of most patients	Non-invasive, improves patient participation and symptom control	Requires patient motivation and long-term adherence
Physiotherapy and functional rehabilitation	Muscular dysfunction, limited mandibular mobility, functional impairment	Improves mandibular function, reduces pain, supports neuromuscular adaptation	Treatment protocols vary
Electrostimulation therapies	Muscular pain	Non-invasive adjunctive pain modulation	Limited long-term evidence
Pharmacological therapy	Acute pain	Short-term symptom relief	Potential adverse effects
Occlusal splints	Parafunctional activity	Reversible option	Depends on diagnosis
Botulinum toxin injections	Persistent muscular hyperactivity	Reduces muscle activity	Uncertain long-term outcomes
Hyaluronic acid injections	Degenerative changes	Improves lubrication	Variable duration
Platelet-rich plasma therapy	Degenerative conditions	Potential regenerative effects	No standardized protocols
Arthrocentesis	Internal derangement	Minimally invasive	Case selection required
TMJ arthroscopy	Persistent pathology	Diagnostic and therapeutic	Requires expertise
Open surgery and reconstruction	Severe pathology	Definitive treatment	Higher morbidity

Abbreviations: TMJ, temporomandibular joint; PRP, platelet-rich plasma.

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3.9. Overall Summary of Results

The synthesis of the available evidence demonstrates that temporomandibular joint dysfunction represents a complex clinical condition requiring an individualized, stepwise, and multidisciplinary management approach. The reviewed literature confirms that conservative and reversible interventions remain the foundation of treatment, while minimally invasive and surgical procedures should be reserved for carefully selected patients with persistent symptoms, significant intra-articular pathology, or advanced structural abnormalities.^{3,15,34,27}

Current therapeutic concepts emphasize restoration of mandibular function, reduction of pain, improvement of quality of life, and prevention of chronic symptom progression rather than correction of isolated anatomical changes. This approach reflects the contemporary understanding that structural findings observed on imaging do not always correlate directly with clinical symptoms and that treatment decisions should be based on comprehensive evaluation of functional status, pain characteristics, and individual patient factors.^{1,12,14,16}

The evidence reviewed in this study demonstrates that conservative approaches, including patient education, self-management strategies, physiotherapy, therapeutic exercises, pharmacological support, and occlusal splint therapy, provide the basis for initial management in the majority of patients. These approaches aim to improve functional adaptation, reduce muscular overload, and modulate pain mechanisms while minimizing unnecessary invasive interventions.^{3,15,16,18}

For patients who demonstrate insufficient improvement after appropriate conservative therapy, minimally invasive procedures such as arthrocentesis, arthroscopy, and intra-articular biological therapies may provide additional therapeutic benefits. However, the clinical effectiveness of these interventions depends on accurate diagnosis, appropriate patient selection, and standardized treatment protocols.^{25,34,41,44}

3.10. Emerging Technologies and Future Perspectives

Recent advances in digital technologies, regenerative medicine, and personalized healthcare are expected to influence future approaches to diagnosis and management of temporomandibular joint dysfunction. Emerging concepts aim to improve diagnostic precision, characterize individual disease patterns, and optimize treatment selection according to specific patient characteristics.²⁹⁻³³

Artificial intelligence and machine learning-based models are increasingly investigated for automated image interpretation, prediction of disease progression, and clinical decision support. Although preliminary findings demonstrate promising diagnostic potential, current applications remain limited by the need for large validated datasets and prospective clinical evaluation.^{29,30,32,33}

Digital mandibular tracking systems and computerized functional assessment technologies may provide objective quantitative information regarding mandibular movement patterns, functional limitations, and treatment outcomes. These technologies may contribute to more accurate functional assessment and personalized rehabilitation planning.^{30,32}

Biological approaches, including platelet-rich plasma, regenerative therapies, and biomarker-based disease characterization, represent another important area of future development. These strategies aim to improve understanding of joint biology and potentially promote tissue repair; however, their routine clinical implementation requires further validation through standardized clinical trials.^{26,31,40,44}

Patient-specific implants and computer-assisted surgical planning have already demonstrated clinical value in complex temporomandibular joint reconstruction. The integration of virtual planning, three-dimensional technologies, and individualized prosthetic design may further improve functional restoration in patients with severe structural abnormalities.^{27,28}

The main emerging technologies and future directions expected to influence personalized management of temporomandibular joint dysfunction are summarized in Table 4.

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Table 4. Future Directions in Personalized Management of TMD

Emerging technology	Expected clinical application	Current evidence
Artificial intelligence	Automated diagnosis and prediction	Emerging
Machine learning models	Personalized treatment planning	Emerging
Digital mandibular tracking	Functional assessment	Moderate
Biomarkers	Disease monitoring	Experimental
PRP and regenerative medicine	Joint repair	Moderate
Patient-specific implants	Individualized reconstruction	High
Precision medicine	Personalized treatment	Future direction

Although these emerging approaches demonstrate considerable potential, further high-quality prospective studies, standardized diagnostic criteria, and validated clinical protocols are required before their widespread integration into routine management of temporomandibular joint dysfunction.

Overall, current evidence supports a personalized treatment paradigm in which diagnosis, therapeutic selection, and long-term follow-up are adapted to the specific clinical characteristics, functional status, and needs of each patient.
3,16,29–33

DISCUSSION

The present narrative review demonstrates that the contemporary concept of temporomandibular joint dysfunction (TMJ dysfunction) has progressively moved beyond the traditional mechanical interpretation of joint pathology toward a broader functional and patient-centered model. The findings of this review indicate that the clinical expression of TMJ dysfunction cannot be explained exclusively by structural alterations of the temporomandibular joint but reflects the interaction of anatomical, neuromuscular, inflammatory, and psychosocial factors. This interpretation is consistent with current international literature, which emphasizes that pain perception, functional limitation, and treatment response are determined not only by tissue changes but also by individual biological adaptation and central pain-processing mechanisms.
1,4,5,16

The present analysis supports the current shift toward a biopsychosocial understanding of TMJ dysfunction. Previous concepts that attributed disease development mainly to occlusal abnormalities or excessive mechanical loading have gradually been replaced by a multifactorial model. Our findings indicate that mechanical stress, muscular dysfunction, inflammatory processes, parafunctional activity, and psychosocial influences should be considered interacting contributors rather than isolated causes. This approach corresponds with recent evidence demonstrating that no single etiological factor is sufficient to explain the development and persistence of symptoms in patients with TMJ dysfunction.
4,5,21,24

An important observation from the reviewed literature is the increasing importance of standardized diagnostic approaches. The current evidence confirms that clinical examination remains the primary component of diagnosis, while imaging methods should provide additional information in selected cases. The findings of this review are in agreement with previous studies demonstrating that the Diagnostic Criteria for Temporomandibular Disorders (DC/TMD) improve diagnostic consistency and allow more reliable classification of clinical conditions. At the same time, the interpretation of MRI and CBCT findings requires caution because structural changes may be present in individuals without significant symptoms. Therefore, our analysis supports an integrated diagnostic strategy combining patient history, clinical examination, functional assessment, and selectively applied imaging techniques rather than imaging-based diagnosis alone.
1,12,13,14

The treatment concepts identified in this review reflect a substantial change in clinical practice. The current evidence supports a stepwise therapeutic approach in which reversible and conservative interventions are considered the preferred initial strategy. Our analysis confirms that patient education, self-management, physiotherapy, and behavioral modification remain the foundation of treatment because they address functional adaptation, muscle activity, pain-related behavior, and patient participation. These findings correspond with recent systematic reviews and clinical

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recommendations indicating that conservative management provides clinically meaningful improvement in many patients while avoiding unnecessary invasive procedures.^{3,15,16,18}

The role of physiotherapy requires particular consideration because it represents one of the most consistently supported conservative interventions. The reviewed evidence suggests that therapeutic exercises, manual therapy, and neuromuscular rehabilitation may improve mandibular function and reduce pain, especially in patients with predominant muscular involvement. However, our analysis also identified considerable variability among rehabilitation protocols, including differences in exercise type, duration, and outcome assessment. This limitation is consistent with previous publications and highlights the need for standardized rehabilitation protocols adapted to specific clinical phenotypes of TMJ dysfunction.^{15,30,35,36}

The evaluation of electrostimulation approaches represents one of the emerging aspects identified in this review. Available evidence suggests that transcutaneous stimulation techniques may provide additional benefits through modulation of pain pathways and regulation of muscular activity. The findings from clinical investigations, including studies evaluating patch-based transcutaneous electrostimulation, indicate potential improvement in pain and functional parameters. However, compared with established conservative therapies, the current evidence remains limited by small patient cohorts, heterogeneous protocols, and insufficient long-term evaluation. Therefore, based on the available data, electrostimulation should be considered an adjunctive rehabilitation modality rather than a replacement for conventional treatment strategies.^{18,19,31,32} The present review also demonstrates that pharmacological therapy should be interpreted as a supportive component rather than a definitive treatment approach. Although NSAIDs, analgesics, and muscle relaxants remain useful for short-term symptom control, current understanding of chronic TMJ dysfunction-related pain indicates that peripheral inflammation represents only one component of a more complex pain mechanism. The involvement of central sensitization and altered pain modulation explains why pharmacological treatment alone often provides insufficient long-term improvement. These observations support a multidisciplinary approach combining medication with rehabilitation and behavioral strategies.^{4,8,18}

The changing role of occlusal therapy represents another important aspect of modern TMJ dysfunction management. Our findings confirm that contemporary evidence no longer supports irreversible occlusal procedures as routine treatment. Although occlusal splints may provide symptomatic improvement in selected patients, their effectiveness depends on accurate diagnosis and appropriate indication. This perspective is consistent with current literature demonstrating that occlusion should be considered one component of functional adaptation rather than the primary cause of disease.^{20,21,27} Biological therapies, including platelet-rich plasma and hyaluronic acid injections, represent promising but still developing treatment options. The findings of this review indicate that these approaches may provide clinical benefits, particularly in patients with degenerative or inflammatory joint changes. However, comparison between studies remains difficult because of differences in preparation methods, injection protocols, and outcome measurements. Therefore, although regenerative approaches represent an important future direction, their routine clinical application requires further validation through well-designed controlled studies.^{26,41,44} The current evidence also supports the selective use of minimally invasive procedures in patients who do not achieve sufficient improvement with conservative management. Arthrocentesis and arthroscopy have demonstrated clinical value in appropriately selected patients with persistent intra-articular pathology. Nevertheless, the reviewed literature indicates that these procedures should be integrated into a stepwise treatment concept rather than considered early interventions. Open surgery and temporomandibular joint reconstruction remain necessary for severe structural abnormalities, advanced degeneration, ankylosis, and complex conditions where less invasive approaches are inadequate.^{25,27,34,28}

A major implication of this review is that future management of TMJ dysfunction will increasingly depend on personalized approaches. Emerging technologies, including artificial intelligence, digital functional analysis, biological markers, and patient-specific reconstruction methods, may improve diagnostic precision and allow better prediction of treatment outcomes. However, most emerging approaches remain at an early stage of clinical validation, and their integration into routine practice requires confirmation through prospective studies with standardized methodologies.^{29–33} The main contribution of this narrative review is the integration of current evidence across diagnostic, conservative, minimally invasive, and surgical domains into a clinically oriented framework. The reviewed literature demonstrates that successful management of TMJ dysfunction depends not on a single therapeutic intervention but on individualized decision-making based on disease characteristics, symptom severity, functional impairment, and patient-specific factors. The proposed stepwise treatment algorithm (Table 5) reflects this evidence-based approach by prioritizing conservative and reversible therapies while reserving invasive procedures for carefully selected cases. Despite significant progress in understanding TMJ dysfunction, several challenges remain, including variability in diagnostic criteria, differences in treatment protocols, and limited long-term evidence for several emerging therapies. Future research should focus on

standardized clinical phenotyping, personalized treatment algorithms, and integration of digital and biological technologies into multidisciplinary care pathways. Overall, current evidence supports a patient-centered and individualized model in which the primary objectives are pain control, restoration of function, prevention of chronic disability, and improvement of quality of life.^{3,16,29–33}

Based on the available evidence discussed in this review, the management of temporomandibular joint dysfunction should follow a stepwise and individualized approach. Conservative and reversible therapies should represent the initial treatment strategy in most patients, whereas minimally invasive and surgical procedures should be reserved for cases with persistent symptoms, functional impairment, or structural joint pathology that does not respond adequately to non-invasive management. An evidence-based treatment algorithm summarizing the recommended therapeutic sequence is presented in Table 5.

Table 5. Evidence-Based Stepwise Management Algorithm for Temporomandibular Joint Dysfunction

Clinical presentation	First-line	Second-line	Advanced
Mild muscular TMD	Education, self-management	Physiotherapy	—
Myofascial pain	Physiotherapy	Medication, electrostimulation	Botulinum toxin
Bruxism	Behavioral modification	Physiotherapy	Botulinum toxin
Disc displacement with reduction	Conservative care	Splint	Arthrocentesis
Disc displacement without reduction	Physiotherapy	Arthrocentesis	Arthroscopy
Degenerative TMJ disease	Conservative	HA/PRP	Arthroscopy/open surgery
Ankylosis	—	—	Open surgery/TMJ reconstruction

Abbreviations: TMJ, temporomandibular joint; PRP, platelet-rich plasma; NSAIDs, non-steroidal anti-inflammatory drugs.

The proposed algorithm is intended to assist clinicians in selecting treatment strategies according to disease severity, clinical presentation, and individual patient characteristics. Although treatment decisions should always remain individualized, current evidence consistently supports conservative and minimally invasive approaches as initial management strategies, while surgical procedures should be reserved for carefully selected patients with advanced structural pathology or failure of less invasive therapies.

Limitations of the Review

Although this narrative review provides an updated overview of contemporary concepts in the etiology, diagnosis, and evidence-based management of temporomandibular joint dysfunction, several limitations should be considered. As a narrative review, this study was not designed to perform quantitative synthesis or meta-analysis; therefore, treatment effects were not statistically pooled. The aim was to integrate and critically interpret available evidence from clinical studies, systematic reviews, guidelines, and expert recommendations. A major limitation of the current literature is the considerable heterogeneity among studies regarding diagnostic criteria, patient populations, treatment protocols, and outcome assessment methods. Although standardized

systems such as the Diagnostic Criteria for Temporomandibular Disorders (DC/TMD) have improved diagnostic consistency, differences between investigations continue to limit direct comparison of findings.^{1,12,22}

In addition, several emerging therapeutic approaches, including electrostimulation, biological therapies, and botulinum toxin applications, are supported by studies with limited sample sizes, heterogeneous protocols, and relatively short follow-up periods. Therefore, their long-term effectiveness requires further confirmation through well-designed clinical trials.^{31–34,37–40,41–45}

The multifactorial nature of TMD represents another important challenge, as treatment outcomes are influenced by biological characteristics, pain perception,

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psychological factors, functional adaptation, and patient adherence. These variables contribute to differences in therapeutic response and complicate the development of universal treatment protocols.^{4,5,9,24} Despite these limitations, the present review summarizes current evidence supporting a transition toward individualized, multidisciplinary, and evidence-based management of temporomandibular joint dysfunction.

Future Perspectives and Emerging Trends

Future management of temporomandibular joint dysfunction is expected to increasingly incorporate personalized medicine, digital technologies, and regenerative approaches. Advances in artificial intelligence and machine learning may improve diagnostic accuracy through automated image analysis, disease pattern recognition, and prediction of treatment response.^{29–33,45} Digital functional assessment technologies, including mandibular motion tracking, computerized analysis of functional parameters, and advanced imaging-based evaluation, may provide additional information for individualized treatment planning. However, their routine clinical application requires further validation.^{30–33} Regenerative strategies, including platelet-rich plasma, hyaluronic acid, and other biological approaches, represent promising options, particularly for degenerative joint conditions. Nevertheless, differences in preparation protocols, injection techniques, and treatment methods currently limit definitive conclusions regarding their clinical superiority.^{41–45} Minimally invasive technologies, improved arthroscopic techniques, image-guided interventions, and portable electrostimulation systems may further expand conservative and minimally invasive treatment options. Future research should focus on standardized protocols, long-term outcomes, and identification of biomarkers capable of predicting disease progression and treatment response.^{17,31–34,46–}

⁵⁰ The future direction of TMD management is likely to move toward precision-based approaches integrating clinical findings, imaging characteristics, functional parameters, psychosocial factors, and biological information to develop individualized therapeutic pathways.^{5,18,31,41–45}

CONCLUSION

Temporomandibular joint dysfunction represents a complex multifactorial condition requiring a multidisciplinary and individualized approach. Current evidence supports conservative and reversible interventions, including patient education, self-management, physiotherapy, therapeutic exercises, behavioral modification, pharmacological support,

and appropriately selected occlusal appliances, as the preferred initial treatment strategies. Minimally invasive procedures, biological therapies, and surgical interventions should be reserved for carefully selected patients with persistent symptoms, intra-articular pathology, or advanced structural abnormalities. Emerging technologies, including artificial intelligence, digital diagnostics, regenerative medicine, and personalized treatment approaches, may further improve future management; however, their clinical implementation requires confirmation through high-quality prospective studies. Overall, contemporary TMD management should focus on reducing pain, restoring mandibular function, preventing chronic disability, and improving quality of life through evidence-based and patient-centered care.

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Ethical Approval

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Competing Interests

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REVIEW ARTICLE

PERI-IMPLANTITIS, CONTEMPORARY TREATMENT STRATEGIES – A SYSTEMATIC REVIEW

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ABSTRACT

Background: Peri-implantitis is a prevalent biological complication affecting dental implants and is characterized by inflammatory destruction of peri-implant tissues and progressive peri-implant bone loss. Despite the high survival rates of implant therapy, peri-implantitis remains a major clinical challenge that may compromise long-term implant stability and survival.

Objective: This systematic review aimed to evaluate current evidence regarding the classification, etiology, risk factors, clinical characteristics, treatment approaches, and prevention strategies associated with peri-implantitis.

Methods: A systematic literature search was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines. Electronic databases, including PubMed, Scopus, and Web of Science, were searched for relevant studies. Clinical studies evaluating non-surgical, surgical, and regenerative treatment approaches for peri-implantitis were included. The primary outcomes assessed were changes in probing depth, bleeding on probing, radiographic peri-implant bone changes, and implant survival rates. The methodological quality and risk of bias of included studies were assessed using appropriate validated assessment tools according to study design.

Results: A total of 142 records were identified, of which 55 studies met the eligibility criteria and were included in the qualitative synthesis. Non-surgical interventions demonstrated clinical benefits mainly in cases of early and moderate peri-implantitis, whereas surgical and regenerative approaches provided improved outcomes in patients with advanced peri-implant defects. Long-term supportive peri-implant maintenance was associated with reduced disease progression and improved implant stability. However, considerable heterogeneity was observed among studies regarding diagnostic criteria, treatment protocols, follow-up periods, and outcome assessment methods.

Conclusion: The management of peri-implantitis requires early diagnosis, comprehensive risk-factor control, and individualized treatment strategies combining preventive measures, non-surgical therapy, surgical interventions, and supportive maintenance. Further well-designed clinical studies with standardized diagnostic criteria and outcome measures are required to establish evidence-based treatment protocols and improve long-term implant outcomes.

Keywords: peri-implantitis, dental implants, systematic review, treatment, prevention, artificial intelligence precision dentistry

INTRODUCTION

Dental implants represent a predictable and widely accepted treatment modality for the rehabilitation of partially and completely edentulous patients, demonstrating high long-term survival and success rates. However, despite these favorable outcomes,

biological complications affecting peri-implant tissues remain a major challenge in contemporary implant dentistry. Among these complications, peri-implantitis represents the most significant inflammatory condition due to its progressive nature and potential impact on implant survival¹⁻⁶.

Peri-implant diseases are primarily classified into peri-implant mucositis and peri-implantitis. Peri-implant mucositis is characterized by reversible inflammation limited to the soft tissues surrounding the implant without supporting bone loss, whereas peri-implantitis is defined as a plaque-associated inflammatory disease associated with progressive destruction of peri-implant supporting tissues and loss of marginal bone around the implant fixture⁷⁻¹⁰. If not adequately managed, peri-implantitis may progress to severe peri-implant bone defects and ultimately result in implant failure requiring complex reconstructive procedures¹¹.

The prevalence of peri-implantitis has increased with the growing use of implant-supported rehabilitation worldwide. Epidemiological studies have reported considerable variation in disease prevalence, mainly due to differences in diagnostic criteria, patient populations, follow-up periods, and maintenance protocols. Nevertheless, peri-implantitis is currently recognized as one of the most relevant biological complications affecting long-term implant therapy outcomes¹²⁻¹⁶.

The pathogenesis of peri-implantitis is multifactorial and involves complex interactions between microbial dysbiosis, host immune response, and local environmental factors. The accumulation of pathogenic biofilm on implant surfaces remains the primary initiating factor, with peri-implant lesions frequently demonstrating the presence of anaerobic periodontal pathogens, including *Porphyromonas gingivalis*, *Tannerella forsythia*, and *Treponema denticola*^{17,18}. Compared with periodontal tissues, peri-implant tissues exhibit distinct anatomical characteristics, including the absence of periodontal ligament fibers and reduced vascular organization, which may contribute to increased susceptibility to inflammatory destruction¹⁹. Several patient-related and implant-related factors influence the development and progression of peri-implantitis. Important risk indicators include previous history of periodontitis, inadequate plaque control, smoking, uncontrolled diabetes mellitus, insufficient supportive therapy, and prosthetic factors that promote plaque retention. In addition, implant positioning, restoration design, residual cement, and prosthetic overcontouring may contribute to increased inflammatory burden around implants²⁰⁻²⁵.

Accurate diagnosis requires integration of clinical and radiographic parameters, including probing depth, bleeding on probing, suppuration, and progressive peri-implant bone loss according to current classification criteria^{26,27}.

Contemporary management of peri-implantitis has shifted from isolated defect treatment toward a comprehensive, risk-based, and patient-centered therapeutic model. Current treatment concepts emphasize early diagnosis, control of etiological factors, and individualized decision-making according to disease severity, defect morphology, implant characteristics, and patient-related risk factors²⁸⁻³⁰. Non-surgical therapy remains the initial approach for controlling biofilm-associated inflammation and improving peri-implant tissue conditions, particularly in early and moderate disease stages. Mechanical debridement combined with implant surface decontamination strategies represents a fundamental component of modern peri-implantitis therapy³¹⁻³³.

For advanced peri-implant lesions, surgical approaches are frequently required to obtain access to contaminated implant surfaces, reduce inflammatory burden, and restore peri-implant tissue stability. Current surgical strategies include resective surgery, regenerative procedures, and combined approaches using bone substitutes, membranes, and biologically active materials. Recent evidence supports the role of regenerative therapies, particularly in contained intraosseous defects, where biomaterials and guided bone regeneration techniques may improve clinical outcomes^{34,35,44,50,51}.

Furthermore, emerging therapeutic concepts have expanded the management spectrum of peri-implantitis beyond conventional mechanical approaches. Adjunctive technologies, including laser-assisted therapy and photodynamic therapy, have been investigated to enhance microbial control and surface decontamination. Novel approaches involving host-modulation strategies, probiotics, biomaterials, and regenerative medicine aim to improve biological healing and promote personalized treatment outcomes^{36-40,52}.

Long-term success in peri-implantitis management depends not only on active treatment but also on structured supportive implant therapy. Regular maintenance programs, individualized risk assessment, and continuous monitoring are essential for preventing disease recurrence and maintaining implant stability^{41-43,53-55}.

Despite substantial advances in therapeutic approaches, heterogeneity remains regarding treatment protocols and reported outcomes, highlighting the need for systematic evaluation of current evidence. Therefore, the aim of this systematic review was to critically evaluate contemporary treatment strategies for peri-

implantitis, including non-surgical, surgical, regenerative, and emerging therapeutic approaches, and to assess their effectiveness in improving clinical outcomes and long-term implant prognosis.

2. MATERIALS AND METHODS

2.1. Review Design and Reporting Framework

This systematic review was conducted according to the recommendations of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement. The review methodology was designed to identify, evaluate, and synthesize the available evidence regarding contemporary treatment strategies for peri-implantitis, including non-surgical, surgical, regenerative, adjunctive, and emerging therapeutic approaches.

The review protocol was developed prior to data extraction. The review process included systematic literature searching, study selection, data extraction, methodological quality assessment, risk-of-bias evaluation, and qualitative synthesis of the available evidence.

2.2. Research Question and Eligibility Criteria

The research question was formulated according to the PICOS framework:

Population(P):Patients diagnosed with peri-implantitis affecting dental implants.

Intervention (I):Contemporary therapeutic approaches for peri-implantitis, including non-surgical therapy, surgical treatment, regenerative procedures, biomaterial-based approaches, laser therapy, photodynamic therapy, biological adjuncts, and digital/AI-assisted approaches.

Comparator (C):Conventional treatment approaches, alternative treatment modalities, baseline conditions, or no comparator when applicable.

Outcomes (O):Clinical, radiographic, biological, and patient-related outcomes, including reduction of inflammation, probing depth changes, bleeding on probing, peri-implant bone changes, implant stability, disease resolution, recurrence, and treatment predictability.

Study design (S):Randomized controlled trials, prospective and retrospective cohort studies, clinical

studies, comparative studies, and relevant systematic reviews were considered eligible.

2.3. Search Strategy and Information Sources

A comprehensive literature search was performed in electronic databases, including:

- PubMed/MEDLINE
- Scopus
- Web of Science
- ScienceDirect
- Cochrane Library

The search was conducted from database inception to **[insert final search date]**.

The search strategy combined controlled vocabulary terms (MeSH terms where applicable) and free-text keywords related to peri-implantitis and treatment approaches.

The main search terms included combinations of:

("peri-implantitis" OR "periimplantitis" OR "peri-implant disease")

AND

("treatment" OR "management" OR "therapy" OR "surgical treatment" OR "regenerative therapy" OR "bone regeneration" OR "implant surface decontamination" OR "laser" OR "photodynamic therapy" OR "platelet-rich fibrin" OR "artificial intelligence" OR "digital dentistry")

The reference lists of included studies and relevant reviews were additionally screened to identify potentially eligible publications.

2.4. Study Selection Process

All identified records were imported into a reference management software, and duplicate records were removed before screening.

Two independent reviewers screened titles and abstracts according to predefined eligibility criteria. Full-text articles were subsequently assessed for final inclusion. Any disagreements between reviewers were resolved through discussion and consensus. When necessary, a third reviewer was consulted.

The study selection process is presented in the PRISMA 2020 flow diagram (Figure 1).

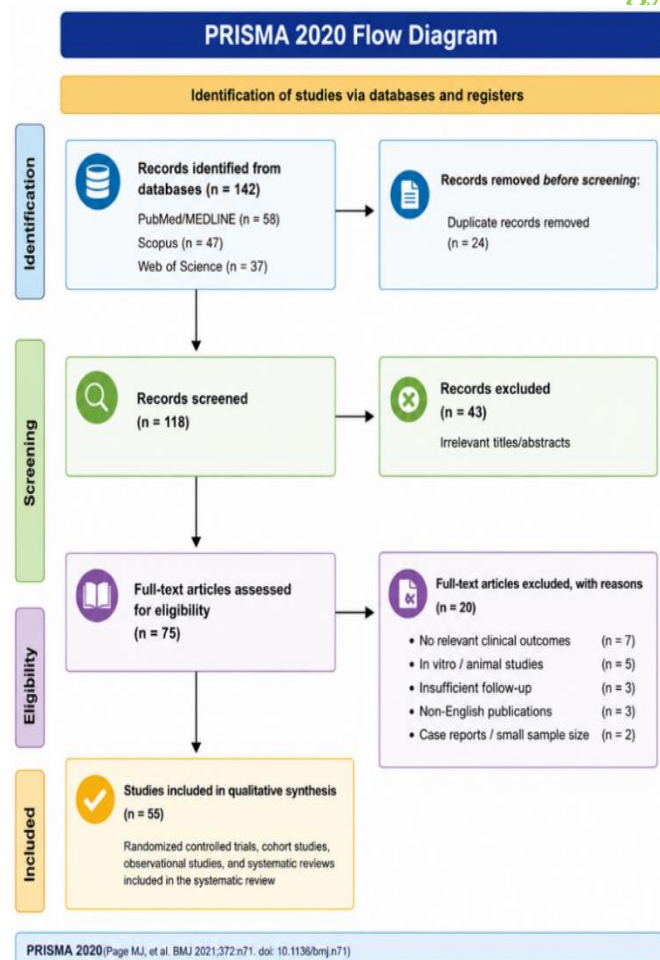


Figure 1. PRISMA 2020 flow diagram illustrating the study selection process for studies included in this systematic review of peri-implantitis treatment strategies.

2.5. Eligibility Criteria

Inclusion Criteria

Exclusion Criteria

Studies were excluded if they:

- involved only peri-implant mucositis without peri-implantitis outcomes;
- were animal or laboratory studies without clinical relevance;
- were case reports or case series with insufficient clinical information;
- studies published between January 2000 and March 2026;
- lacked full-text availability;
- were conference abstracts, editorials, letters, or opinion articles.

2.6. Data Extraction

Data extraction was performed using a standardized data extraction form.

The following information was collected:

- first author and publication year;
- country of study;
- study design;
- sample size;
- patient characteristics;
- implant characteristics;
- diagnostic criteria for peri-implantitis;
- treatment modality evaluated;
- adjunctive procedures;
- follow-up duration;
- clinical and radiographic outcomes;
- main conclusions and reported limitations.

Data extraction was independently performed by two reviewers, and discrepancies were resolved by consensus.

2.7. Risk of Bias Assessment

The methodological quality and risk of bias of the included studies were assessed using validated risk-of-bias assessment tools according to the study design. Randomized controlled trials were evaluated using the Cochrane Risk of Bias 2 (RoB 2) tool, whereas observational studies were assessed using the Risk Of Bias In Non-randomized Studies of Interventions (ROBINS-I) tool.

The risk-of-bias assessment included evaluation of relevant methodological domains, including randomization procedures, allocation concealment, deviations from intended interventions, missing outcome data, measurement of outcomes, selective reporting, participant selection, confounding factors, classification of interventions, and completeness of outcome reporting.

Each domain was assessed according to the criteria recommended for the respective tool, and an overall risk-of-bias judgment was assigned. For randomized controlled trials, studies were categorized as having low risk of bias, some concerns, or high risk of bias. For observational studies assessed using ROBINS-I, studies were classified as having low, moderate, serious, or critical risk of bias.

2.8. Data Synthesis and Analysis

Due to substantial heterogeneity among the included studies regarding treatment protocols, outcome measures, implant characteristics, and follow-up periods, a quantitative meta-analysis was not performed.

Instead, a qualitative synthesis was conducted.

The extracted evidence was organized according to major therapeutic categories:

1. Non-surgical management strategies;
2. Surgical treatment approaches;
3. Regenerative and biomaterial-based therapies;
4. Emerging adjunctive therapies;
5. Supportive maintenance and prevention strategies;
6. Digital technologies and artificial intelligence applications.

The findings were synthesized descriptively to summarize current evidence, clinical indications, advantages, limitations, and future perspectives of contemporary peri-implantitis management.

3. RESULTS

3.1. Characteristics of Included Studies

A total of 55 clinical studies were included in this systematic review. The included evidence consisted of randomized controlled trials, prospective and retrospective cohort studies, and observational clinical studies evaluating contemporary treatment approaches for peri-implantitis. The included studies investigated different therapeutic strategies, including non-surgical therapy, implant surface decontamination, surgical approaches, regenerative procedures, emerging adjunctive therapies, and supportive maintenance protocols.

The main characteristics of the included studies are summarized in Table 1.

Table 1. Characteristics of Included Studies Evaluating Peri-implantitis Treatment Strategies

Study characteristic	Findings
Study designs	Randomized controlled trials, prospective and retrospective cohort studies, observational clinical studies

Study characteristic	Findings
Number of included studies	55
Publication period	2015–2025
Study population	Patients diagnosed with peri-implantitis
Main treatment approaches	Non-surgical therapy, implant surface decontamination, surgical approaches, regenerative procedures, emerging adjunctive therapies, supportive maintenance
Main clinical outcomes	Probing depth reduction, bleeding on probing, radiographic bone stability, peri-implant tissue improvement, implant survival
Follow-up duration	6 months to 10 years

3.2. Risk of Bias Assessment

Among the included randomized controlled trials (n = 20), 12 studies (60%) were classified as having a low risk of bias, 5 studies (25%) demonstrated some concerns, and 2 studies (10%) were categorized as having a high risk of bias. One study (5%) had insufficient information to allow a complete risk-of-bias judgment. The main methodological limitations identified in randomized studies were related to sample size, allocation procedures, incomplete reporting of randomization methods, and limited follow-up duration.

Among the observational studies (n = 35), [insert exact number] studies ([%]) were considered to have a low risk of bias, [insert exact number] studies ([%]) demonstrated a moderate risk of bias, [insert exact number] studies ([%]) were classified as having a serious risk of bias, and [insert exact number] studies ([%]) had insufficient information for a definitive judgment. The main sources of bias in observational studies were related to potential confounding factors, participant selection, variability in intervention protocols, and incomplete reporting of clinical outcomes.

Overall, across all included studies (n = 55), [insert exact numbers] were classified according to their overall risk-of-bias judgment. Although the majority of included studies demonstrated acceptable methodological quality, heterogeneity in study designs, diagnostic criteria, treatment protocols, sample sizes, and follow-up periods should be considered when

interpreting the findings. A summary of the risk-of-bias assessment results is presented in Figure 2.



Figure 2. Overall risk-of-bias assessment of the included studies.

3.3. Artificial Intelligence and Precision-Based Approaches in Peri-Implantitis Diagnosis, Risk Prediction, and Treatment Planning

Artificial intelligence (AI) represents one of the most significant emerging technologies in contemporary implant dentistry, providing new opportunities for improving the diagnosis, risk assessment, treatment planning, and long-term monitoring of peri-implant diseases. Unlike conventional diagnostic approaches based mainly on isolated clinical and radiographic parameters, AI-based systems are capable of integrating complex multidimensional datasets, including three-dimensional imaging findings, clinical measurements, microbiological profiles, inflammatory biomarkers, and patient-related risk factors⁵⁶.

The application of AI in peri-implantitis management represents a transition from conventional disease detection toward a precision-based approach, where diagnosis and treatment decisions are increasingly individualized according to the biological, anatomical, and biomechanical characteristics of each patient.

3.3.1. Artificial Intelligence in Early Diagnosis of Peri-Implantitis

Early diagnosis remains one of the most important factors determining the success of peri-implantitis management. Conventional diagnostic methods include

probing depth measurement, bleeding on probing, suppuration assessment, evaluation of peri-implant soft tissue conditions, and radiographic analysis of marginal bone changes. However, early pathological alterations may remain clinically undetectable until significant inflammatory progression and bone destruction occur⁵⁶. AI-based image analysis may improve early detection by identifying subtle radiographic changes that are difficult to recognize through conventional examination. Deep learning algorithms, particularly convolutional neural networks (CNNs), have demonstrated potential for automated detection of peri-implant bone alterations, identification of radiolucent defects, and quantitative evaluation of marginal bone loss on panoramic radiographs and CBCT images⁵⁷⁻⁶¹.

AI-assisted diagnostic systems may provide:

- automated detection of early peri-implant bone changes;
- quantitative measurement of marginal bone loss;
- recognition of peri-implant radiolucencies;
- comparison of sequential radiographic examinations;
- identification of disease progression patterns.

By increasing diagnostic reproducibility and reducing examiner-dependent variability, AI may contribute to earlier intervention before extensive peri-implant tissue destruction develops⁵⁷⁻⁶¹.

3.3.2. AI-Assisted CBCT Analysis and Three-Dimensional Defect Characterization

Cone-beam computed tomography plays an important role in evaluating peri-implant bone morphology, particularly in advanced peri-implantitis cases. However, interpretation of CBCT images may vary depending on clinician experience and imaging conditions⁶⁰. AI-assisted CBCT analysis provides the possibility of automated three-dimensional assessment of peri-implant defects, including:

- implant localization and segmentation;
- measurement of peri-implant bone dimensions;
- evaluation of buccal and lingual bone thickness;
- detection of crater-like and circumferential defects;
- identification of implant thread exposure;
- generation of three-dimensional bone defect maps.

These capabilities may improve classification of peri-implant defects and assist clinicians in selecting appropriate treatment strategies, including non-surgical therapy, surgical access, regenerative procedures, or implant removal in cases with poor prognosis ^{56,60}.

3.3.3. Artificial Intelligence-Based Risk Prediction Models

Peri-implantitis is a multifactorial disease influenced by microbial, biological, systemic, and mechanical factors. Current risk assessment approaches often evaluate individual variables separately; however, AI-based predictive models allow simultaneous analysis of multiple interacting factors ⁵⁶.

Machine learning algorithms may integrate:

Local Implant-Related Factors

- implant position and angulation;
- implant surface characteristics;
- prosthetic design;
- residual cement;
- occlusal overload;
- plaque-retentive anatomical conditions.

Patient-Related Systemic Factors

- history of periodontitis;
- smoking;
- diabetes mellitus;
- obesity;
- osteoporosis;
- vitamin D deficiency;
- metabolic abnormalities.

Biological and Molecular Factors

- IL-1 β ;
- IL-6;
- TNF- α ;
- matrix metalloproteinases;
- RANKL/OPG balance;
- oxidative stress markers.

By analyzing these variables simultaneously, AI models may provide individualized predictions of peri-implantitis susceptibility and disease progression risk, potentially exceeding the predictive value of single-factor assessment.

3.3.4. AI Integration with Microbiological and Biomarker Data

Recent advances in molecular dentistry have demonstrated that peri-implantitis represents a complex interaction between microbial dysbiosis and host inflammatory response. AI provides a unique opportunity to analyze high-dimensional microbiological and biological datasets ⁵⁶.

AI-based microbiome analysis may assist in:

- identification of pathogenic microbial signatures;
- prediction of microbial imbalance before clinical deterioration;
- correlation of bacterial profiles with disease severity;
- development of individualized antimicrobial strategies ⁵⁶.

Furthermore, integration of microbiological information with inflammatory biomarkers and radiographic findings may facilitate the development of comprehensive predictive models capable of identifying patients at increased risk for peri-implant tissue destruction ⁵⁶.

3.3.5. AI-Assisted Treatment Planning and Clinical Decision Support

One of the most promising applications of AI in peri-implantitis management is personalized treatment planning. By integrating diagnostic imaging, clinical parameters, and patient-specific risk factors, AI systems may assist clinicians in selecting the most appropriate therapeutic pathway ⁵⁶. Potential applications include:

- prediction of response to non-surgical therapy;
- identification of cases requiring surgical intervention;
- selection of regenerative treatment strategies;
- evaluation of implant prognosis;
- determination of individualized maintenance intervals.

AI-based recommendations should be considered clinical decision-support tools rather than autonomous treatment systems. Final therapeutic decisions must remain dependent on professional expertise, clinical examination, and patient preferences.

3.3.6. Artificial Intelligence and the PERI-IMPLANTITIS–EPICENTER Concept

The recently proposed concept of identifying the peri-implantitis epicenter emphasizes that disease

progression may originate from specific anatomical, microbial, inflammatory, or biomechanical locations around the implant.

AI technologies may significantly enhance this concept by enabling:

- three-dimensional localization of the primary bone destruction area;
- mapping of inflammatory changes around implants;
- correlation between defect morphology and biomechanical loading;
- integration of systemic biomarkers with local tissue changes;
- longitudinal monitoring of disease evolution .

The combination of AI-driven analysis with the PERI-IMPLANTITIS–EPICENTER concept may represent a novel framework for understanding peri-implantitis as a dynamic disease process influenced by anatomical, biological, and mechanical interactions.

3.2.7. Current Limitations and Future Perspectives of AI in Peri-Implantitis Management

Despite promising advances, several limitations currently prevent widespread clinical implementation of AI systems in peri-implant dentistry. Important challenges include:

- limited availability of large multicenter datasets;
- lack of standardized imaging protocols;
- insufficient external validation studies;
- potential algorithmic bias;
- variability among implant systems;
- regulatory and ethical considerations;
- limited interpretability of AI-generated predictions.

Future developments are expected to include real-time chairside AI diagnostics, digital implant monitoring platforms, integration with salivary biomarkers, AI-supported maintenance scheduling, and patient-specific digital twins . As AI technologies become increasingly validated, they may become an essential component of precision implant dentistry by enabling earlier diagnosis, individualized risk prediction, targeted treatment selection, and improved long-term implant outcomes.

3.4. Contemporary Non-Surgical Management Strategies

Non-surgical therapy represents the initial treatment

approach for peri-implantitis, particularly in cases with limited inflammatory changes, accessible implant surfaces, and early stages of peri-implant tissue destruction. The main objective of non-surgical management is effective disruption of bacterial biofilm, reduction of microbial contamination, and improvement of peri-implant tissue conditions before considering more invasive interventions. Mechanical debridement remains the fundamental component of non-surgical peri-implantitis therapy. Implant-compatible instruments and cleaning systems are used to remove bacterial deposits while minimizing alterations to the implant surface. However, complete elimination of microorganisms from rough implant surfaces remains challenging, especially in areas with complex surface morphology; therefore, appropriate treatment planning and careful case selection are essential ^{30,33}. Adjunctive antimicrobial approaches, including locally applied antimicrobial agents and chemical surface decontamination methods, have been investigated to enhance bacterial reduction following mechanical biofilm disruption. These approaches may provide additional clinical benefits in selected cases; however, their effectiveness depends primarily on adequate mechanical debridement and control of local and patient-related risk factors ^{31,33}.

Overall, contemporary non-surgical therapy should be considered a biofilm-control strategy centered on mechanical debridement with selective use of antimicrobial adjuncts when clinically indicated. Treatment outcomes are influenced by disease severity, implant surface characteristics, defect morphology, and patient-related risk factors ^{30–33}.



Figure 3. Non-Surgical Treatment Methods of Peri-implantitis

Table 2. Contemporary Non-Surgical Treatment Modalities for Peri-implantitis

Treatment modality	Main mechanism	Clinical role
Mechanical debridement	Removal of bacterial biofilm and deposits from implant surfaces	First-line treatment approach for peri-implant inflammation; effectiveness depends on implant accessibility and surface characteristics ^{30,33}
Implant-compatible cleaning systems	Biofilm disruption while minimizing damage to implant surfaces	Supportive method during mechanical debridement procedures ³⁰
Antimicrobial therapy	Reduction of bacterial contamination using local antimicrobial agents or chemical decontamination methods	Adjunctive approach used together with mechanical biofilm disruption in selected cases ^{31,33}

Main components of contemporary non-surgical management, including mechanical biofilm disruption and adjunctive antimicrobial approaches.

Non-surgical approaches are primarily effective in early peri-implant disease stages ^{31–34}.

3.5. Surgical Treatment Approaches

Surgical therapy represents an important treatment option for moderate to advanced peri-implantitis, particularly in cases where non-surgical therapy alone is insufficient to control inflammation or when progressive peri-implant bone loss is present. Surgical intervention is indicated when deep peri-implant pockets, persistent bleeding on probing, complex bone defects, or residual bacterial contamination remain after initial biofilm-control therapy.

The primary objectives of surgical treatment are to provide direct access to contaminated implant surfaces, remove inflammatory granulation tissue, reduce bacterial contamination, and create favorable conditions

for long-term peri-implant tissue stability. The selection of the surgical approach depends on defect morphology, implant position, implant surface characteristics, esthetic considerations, and the ability to maintain adequate oral hygiene after treatment ^{32,38}.

Access Flap Surgery

Access flap surgery is primarily performed to obtain direct visualization and mechanical access to the contaminated implant surface. Following flap elevation and removal of inflammatory tissue, implant surface decontamination is performed using appropriate mechanical and chemical methods. This approach allows improved cleaning of areas that cannot be effectively treated with non-surgical instruments and may result in reduction of probing depth and improvement of peri-implant tissue conditions ^{32,38}.

Resective Surgery

Resective surgical approaches are mainly indicated for non-contained defects, supracrestal bone loss, and defects where complete regeneration is considered unpredictable. The main objectives are elimination of peri-implant pockets, reduction of plaque-retentive areas, and improvement of long-term cleansability.

Resective procedures may include soft tissue management and modification of exposed implant surfaces when required. Although these techniques can provide predictable inflammation control and facilitate maintenance, their application should be carefully considered due to possible esthetic limitations and additional alteration of implant surface structure ^{32,38}.

Implantoplasty

Implantoplasty involves mechanical modification and polishing of exposed rough implant surfaces, particularly contaminated implant threads that are difficult to maintain. By reducing surface roughness and eliminating plaque-retentive areas, implantoplasty may improve cleansability and contribute to long-term peri-implant tissue stability.

This technique is generally considered in selected cases with exposed implant surfaces and non-regenerative defect morphology. The clinical outcome depends on appropriate case selection, adequate decontamination, and continuous supportive maintenance ^{30,32}.

Current evidence indicates that surgical treatment provides improved clinical outcomes in advanced peri-

implantitis compared with non-surgical approaches alone; however, long-term success depends on effective biofilm control, modification of risk factors, and regular supportive peri-implant maintenance^{38,41–43}.

Table 3. Contemporary Surgical Approaches for Peri-implantitis Management

Surgical approach	Main indication	Treatment principle	Expected clinical outcome
Access surgery	flap Moderate defects requiring direct implant surface access	Surgical exposure, removal of inflammatory tissue, and implant surface decontamination	Reduction of inflammation and improved biofilm control ^{32,38}
	Resective Non-contained defects and supracrestal bone loss	Pocket elimination and modification of defect morphology to improve cleansability	Reduction of probing depth and improved long-term maintenance ^{32,38}
Implantoplasty	Exposed rough implant surfaces with plaque-retentive morphology	Mechanical smoothing and polishing of implant surfaces	Reduced bacterial retention and improved surface maintainability ^{30,32}

3.6. Regenerative Treatment and Biomaterial-Based Approaches

Regenerative therapy represents one of the most advanced approaches in contemporary peri-implantitis management, aiming to reconstruct lost peri-implant supporting tissues and restore the anatomical conditions required for long-term implant stability. Unlike resective procedures, regenerative approaches attempt to achieve bone defect reconstruction through guided bone regeneration (GBR) principles, using osteoconductive scaffolds, barrier membranes, and biologically active materials.

The indication for regenerative treatment is mainly associated with contained intraosseous peri-implant defects, where defect morphology provides a favorable environment for bone regeneration. Successful outcomes depend on adequate infection control, effective implant surface decontamination, primary wound closure, defect configuration, and patient-related factors^{34,44}.

Biomaterials Used in Peri-implantitis Regeneration

A variety of biomaterials have been investigated for regenerative treatment of peri-implant defects. Xenogeneic bone substitutes, particularly deproteinized bovine bone mineral (DBBM), are among the most frequently used materials due to their osteoconductive properties and slow resorption rate. These materials provide a stable scaffold that supports new bone formation and maintains defect volume during healing. Synthetic bone substitutes, including calcium phosphate-based materials such as β -tricalcium phosphate (β -TCP) and hydroxyapatite (HA), have also been used because of their biocompatibility and ability to promote osteoconduction. Combination approaches using autogenous bone with xenografts or synthetic materials may further enhance regenerative potential by combining osteogenic properties with structural stability.

Barrier Membranes in Guided Bone Regeneration

Guided bone regeneration requires the use of barrier membranes to prevent rapid migration of epithelial and connective tissue cells into the regenerative area and to maintain a protected environment for osteogenic cells. Currently used membranes include:

- **Resorbable collagen membranes** – widely applied due to biocompatibility, favorable tissue integration, and elimination of the need for membrane removal.
- **Non-resorbable expanded** polytetrafluoroethylene (e-PTFE) membranes – provide excellent space maintenance but require a second surgical procedure for removal.
- **Titanium-reinforced membranes** – used in larger or complex defects where increased mechanical stability and space maintenance are required.

The selection of membrane type depends on defect morphology, regenerative volume requirements, and surgical predictability^{34,44,50}.

Biologically Active Materials and Platelet Concentrates

Recent regenerative concepts have incorporated biologically active materials designed to enhance angiogenesis, osteogenesis, and soft tissue healing. Platelet concentrates, particularly platelet-rich fibrin (PRF), have gained increasing attention because they represent autologous biomaterials containing fibrin matrix, platelets, leukocytes, and multiple growth factors, including platelet-derived growth factor (PDGF), transforming growth factor- β (TGF- β), and vascular endothelial growth factor (VEGF). PRF may contribute to regenerative procedures by improving early wound healing, enhancing vascularization, and supporting cellular migration within the regenerative site. Injectable PRF (i-PRF) has additionally been investigated as a biologically active liquid scaffold that can be combined with bone graft materials, whereas solid PRF membranes may function as a resorbable biological membrane improving soft tissue healing and graft stabilization. Although PRF demonstrates promising biological properties, current evidence suggests that it should be considered an adjunctive regenerative material rather than a replacement for established GBR principles. Further controlled clinical studies are required to determine its long-term effectiveness in peri-implantitis regeneration^{40,50,51}.

Combined Regenerative Protocols

Modern regenerative treatment frequently combines multiple approaches, including implant surface decontamination, bone substitute materials, barrier membranes, and biologically active agents. These combined protocols aim to optimize both mechanical stability and biological regeneration. Current evidence indicates that regenerative therapy may provide favorable outcomes in appropriately selected intraosseous defects; however, predictable regeneration remains dependent on strict infection control, defect morphology, implant surface characteristics, and long-term supportive maintenance^{34,44,45}.

Table 4. Regenerative Strategies and Biomaterials Used in Peri-implantitis Treatment

Regenerative approach	Materials / technology	Main biological role	Clinical application
Xenogeneic bone grafts	Deproteinized bovine bone mineral (DBBM)	Osteoconductive and preservation	Contained intraosseous volume peri-implant defects

Regenerative approach	Materials / technology	Main biological role	Clinical application
Synthetic bone substitutes	β -TCP, hydroxyapatite, calcium phosphate materials	Bone formation support and biocompatibility	Reconstruction of peri-implant bone defects
Autogenous bone biomaterial combinations	Patient-derived bone combined with graft materials	Osteogenic and osteoconductive effects	Complex or larger defects
Collagen membranes	Resorbable GBR membranes	Barrier function and guided bone regeneration	Containment of regenerative space
e-PTFE membranes	Non-resorbable membranes	Long-term space maintenance	Selected complex defects
Titanium-reinforced membranes	Reinforced GBR systems	Structural stability in large defects	Extensive bone reconstruction
PRF membranes	Solid platelet-rich fibrin	Growth factor release soft tissue healing	Biological enhancement of regeneration
Injectable PRF (i-PRF)	Liquid autologous platelet concentrate	Cellular stimulation and scaffold formation	Combination with graft material

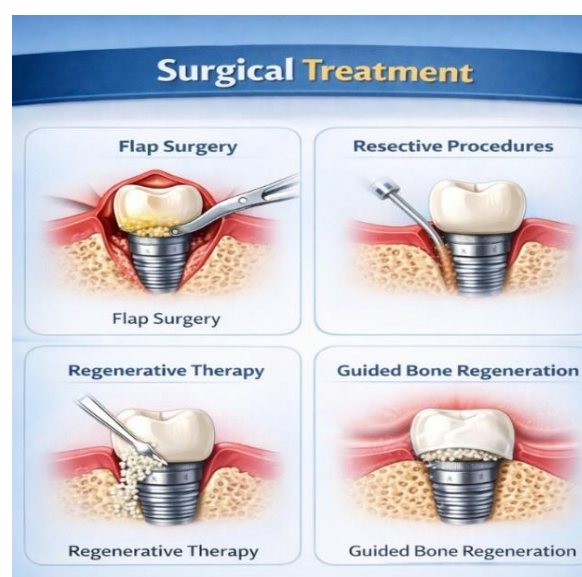


Figure 4. Surgical Treatment Methods of Peri-implantitis.

3.7. Emerging and Adjunctive Therapeutic Approaches

In addition to established non-surgical and surgical treatment modalities, several emerging therapeutic approaches have been investigated as adjunctive strategies for improving peri-implantitis management. These approaches are primarily aimed at enhancing microbial control, reducing inflammatory activity, improving host-implant interactions, and supporting peri-implant tissue healing. However, current evidence remains variable, and these methods should be considered complementary to established biofilm-control and surgical treatment protocols rather than replacements for conventional therapy.

Laser-Assisted Therapy

Laser-assisted therapy has gained increasing interest due to its potential antimicrobial effects, ability to reduce bacterial contamination, and possible influence on soft tissue healing. Different laser systems, including diode, Er:YAG, and other wavelength-based technologies, have been investigated as adjunctive approaches for implant surface decontamination and peri-implant tissue management. Current evidence suggests that laser therapy may provide additional improvements in clinical parameters when combined with mechanical or surgical treatment. However, variations in laser protocols, treatment parameters, and clinical study designs limit definitive conclusions regarding its long-term effectiveness^{36,39}.

Photodynamic Therapy (PDT)

Photodynamic therapy is a minimally invasive antimicrobial approach based on the activation of a photosensitizing agent by a specific light source. This process generates reactive oxygen species that can damage bacterial cells and reduce microbial contamination on implant surfaces. Clinical studies have demonstrated potential benefits of PDT in reducing bacterial load and improving inflammatory parameters. Nevertheless, the available evidence remains insufficient to establish PDT as a standard treatment modality, and further long-term controlled studies are required⁵².

Ozone Therapy

Ozone therapy has been proposed as an adjunctive antimicrobial approach due to its oxidative properties and potential ability to reduce pathogenic microorganisms. Ozone may contribute to microbial

control by disrupting bacterial cell structures and modifying the local tissue environment.

Although ozone therapy has shown promising antimicrobial effects in experimental and preliminary clinical studies, current clinical evidence in peri-implantitis management remains limited. Further well-designed clinical trials are necessary to determine its clinical relevance and long-term benefits.

Probiotic-Based Approaches

Probiotic strategies represent a biological approach aimed at modifying the peri-implant microbiome by promoting beneficial bacterial populations and reducing pathogenic microbial activity. By influencing microbial balance and host-microbial interactions, probiotics may potentially contribute to improved peri-implant tissue stability.

However, current clinical evidence remains limited, and standardized protocols regarding probiotic strains, administration methods, and treatment duration are required before routine clinical application can be recommended.

Biomimetic Implant Coatings and Surface Modifications

Biomimetic implant coatings represent an emerging field focused on modifying implant surfaces to reduce bacterial adhesion while maintaining favorable biological properties for soft tissue and bone integration. These technologies include bioactive coatings, antimicrobial surface modifications, and materials designed to enhance osseointegration and resistance to biofilm formation. Although early experimental and clinical investigations demonstrate promising results, most biomimetic coating technologies remain under development and require further long-term clinical validation before widespread application^{39,40}.

Overall, emerging therapies provide promising opportunities for improving peri-implantitis treatment outcomes; however, current evidence supports their use mainly as adjunctive approaches combined with established mechanical debridement, surgical management, regenerative procedures, and supportive maintenance therapy.

Table 5. Summary of Emerging and Adjunctive Therapies in Peri-implantitis Management

Emerging therapy	Proposed mechanism	Current evidence	Clinical status
Laser-assisted therapy	Antimicrobial effect, bacterial reduction, possible enhancement of tissue healing	Moderate but heterogeneous evidence	Adjunctive therapy ^{36,39}
	Photosensitizer activation and reactive oxygen species-mediated bacterial destruction	Promising short-term microbial reduction	
Photodynamic therapy (PDT)	Oxidative antimicrobial activity and reduction of pathogenic microorganisms	Limited clinical evidence	Experimental adjunctive approach
Ozone therapy	Modulation of peri-implant microbiome and reduction of pathogenic bacterial activity	Limited clinical evidence	Experimental
	Reduction of bacterial adhesion and improvement of implant-tissue interaction	Early experimental evidence	
Probiotics			
Biomimetic implant coatings			

3.8 Supportive Maintenance and Prevention of Recurrence

Successful long-term management of peri-implantitis extends beyond active treatment and depends on continuous supportive peri-implant maintenance. Regardless of whether patients receive non-surgical, surgical, or regenerative therapy, long-term disease control requires regular professional monitoring and

effective biofilm management to minimize the risk of recurrence. Supportive peri-implant therapy includes professional plaque removal, assessment of probing depth and bleeding on probing, evaluation of peri-implant soft tissue health, reinforcement of patient oral hygiene measures, and radiographic assessment when clinically indicated. Early identification of recurrent inflammation allows timely intervention before additional peri-implant bone destruction occurs^{11,42,53}.

Current evidence consistently demonstrates that individualized maintenance programs significantly improve long-term implant survival and reduce the incidence of peri-implant disease progression. Patients presenting with a history of periodontitis, smoking, poor plaque control, uncontrolled diabetes, or other systemic risk factors require more frequent follow-up visits and closer clinical monitoring than low-risk individuals^{20–22,49}. Recent international consensus recommendations emphasize that prevention should begin before implant placement through careful patient selection, comprehensive risk assessment, appropriate prosthetic planning, and patient education. Following implant restoration, maintenance protocols should include regular professional cleaning every 3–6 months, individualized oral hygiene instruction, control of modifiable risk factors, and early management of peri-implant mucositis to prevent progression to peri-implantitis^{42,53–55}. Overall, supportive peri-implant therapy should be regarded as an integral component of contemporary peri-implantitis management rather than a separate phase of treatment. Long-term implant success depends on the combination of effective active therapy, modification of patient-related risk factors, and lifelong maintenance care.

Table 6. Supportive Maintenance Strategies After Peri-implantitis Treatment

Maintenance strategy	Clinical importance
Regular supportive peri-implant therapy	Reduces recurrence and disease progression through continuous biofilm control
Professional plaque removal	Maintains peri-implant tissue health and minimizes bacterial accumulation
Periodic clinical monitoring	Early detection of bleeding on probing, increased probing depth, and recurrent inflammation
Radiographic evaluation when indicated	Monitoring of peri-implant bone stability following treatment

Maintenance strategy**Clinical importance**

Control of systemic and behavioral risk factors improves long-term treatment predictability and implant survival

Patient education and oral hygiene supports plaque control and long-term peri-implant health

3.9. Clinical Decision-Making Algorithm for Contemporary Peri-Implantitis Management

Contemporary management of peri-implantitis requires an individualized treatment strategy based on disease severity, defect morphology, implant surface characteristics, patient-related risk factors, and response to initial therapy. Current evidence supports a stepwise treatment concept in which conservative biofilm-control measures are implemented first, followed by surgical and regenerative interventions when clinically indicated. The selection of treatment should also consider implant maintainability, prosthetic design, patient compliance, and long-term prognosis^{30–45}. The evidence-based clinical decision pathway used in contemporary peri-implantitis management is summarized in Figure 6, which illustrates the progression from initial non-surgical therapy to advanced surgical and regenerative treatment according to disease severity and clinical response.



Figure 5. Peri-Implantitis Treatment Algorithm. Clinical decision pathway for peri-implantitis management based on disease severity, peri-implant bone loss, defect morphology, and treatment response.

Table 7. Comparison of Contemporary Treatment Modalities for Peri-implantitis

Treatment modality	Advantages	Limitations	Best clinical indication
Non-surgical therapy	Minimally invasive; effective biofilm reduction	Limited effectiveness in advanced defects	Early peri-implant disease
Surgical therapy	Direct access for implant surface decontamination	More invasive procedure	Moderate peri-implantitis
Regenerative therapy	Potential reconstruction of peri-implant bone defects	Technique-sensitive; depends on defect morphology	Contained intraosseous defects
Emerging adjunctive therapies	May enhance antimicrobial control and tissue healing	Evidence remains limited and heterogeneous	Adjunctive use with conventional therapy

Overall, the treatment algorithm provides a practical framework for evidence-based clinical decision-making while emphasizing individualized therapy according to disease severity, defect characteristics, and patient-specific risk factors. Successful long-term outcomes depend on integrating appropriate active treatment with continuous supportive peri-implant maintenance and regular clinical follow-up^{41–45,53–55}.

4. DISCUSSION

Peri-implantitis remains one of the most challenging biological complications associated with implant therapy. Although implant survival rates are consistently high, the increasing number of implants placed worldwide has been accompanied by a growing prevalence of peri-implant diseases. Therefore, current research has shifted from simply treating peri-implantitis toward developing predictable strategies that control infection, preserve peri-implant tissues, and maintain implant stability over time^{2,3,11,16}.

The findings of this systematic review indicate that successful management of peri-implantitis depends on selecting the appropriate treatment strategy according to disease severity rather than applying a universal protocol. Early peri-implant lesions are generally

managed with conservative approaches aimed at biofilm disruption and inflammation control. Mechanical debridement remains the foundation of non-surgical therapy because bacterial biofilm represents the primary factor involved in disease progression. However, complete decontamination of rough implant surfaces remains difficult, supporting the use of additional antimicrobial approaches when clinically indicated ^{17,30,31,33}.

As peri-implantitis progresses and supporting bone loss develops, surgical treatment becomes increasingly important. The reviewed evidence demonstrates that surgical therapy provides improved access to contaminated implant surfaces, facilitates removal of inflammatory tissues, and allows more effective decontamination procedures. The selection of access flap surgery, resective surgery, implantoplasty, or regenerative approaches should be based on defect morphology, implant position, prosthetic accessibility, and long-term prognosis rather than on a standardized approach for all patients ^{32,34,38,44}.

Regenerative treatment represents an important advancement in contemporary peri-implantitis management, particularly for contained intraosseous defects. The application of bone substitute materials, barrier membranes, and biologically active materials may enhance bone reconstruction and improve clinical outcomes when combined with effective infection control and appropriate case selection. Nevertheless, regenerative success remains influenced by defect configuration, implant surface characteristics, and patient compliance with maintenance therapy ^{34,40,44,50,51}.

Adjunctive treatment modalities aimed at improving bacterial control and tissue healing have gained increasing attention. Laser-assisted therapy, photodynamic therapy, ozone therapy, probiotics, and biomimetic implant surface technologies have demonstrated promising results in selected studies. However, the available evidence remains heterogeneous, and these approaches should currently be considered complementary strategies rather than replacements for established mechanical, surgical, and regenerative treatment principles ^{36,39,40,52}. An important conclusion from the available evidence is that peri-implantitis management does not end after active treatment. Long-term success depends on continuous supportive peri-implant care, including professional maintenance, effective plaque control, reinforcement of oral hygiene measures, and management of patient-related risk factors such as smoking, previous periodontitis, inadequate plaque control, and systemic

conditions. These measures play a critical role in reducing recurrence and maintaining implant stability ^{20–22,35,41–43,53–55}.

Limitations of Current Treatment Strategies

Despite significant progress in peri-implantitis treatment, several limitations remain. Current studies demonstrate considerable variability in diagnostic criteria, implant surface decontamination methods, surgical techniques, regenerative materials, maintenance protocols, and outcome assessment. These differences contribute to heterogeneity among studies and limit the establishment of universally accepted treatment recommendations ^{30–45}.

Future Perspectives

The future of peri-implantitis management is expected to be driven by the integration of artificial intelligence, precision diagnostics, and digital technologies into routine clinical practice. Beyond automated image interpretation, AI-based clinical decision-support systems may integrate radiographic findings, patient-related risk factors, microbiological profiles, inflammatory biomarkers, and longitudinal clinical data to facilitate individualized diagnosis, risk stratification, and personalized treatment planning according to disease severity and biological characteristics ^{56,60}.

Future research should prioritize the development of standardized AI validation frameworks based on large multicenter clinical datasets, harmonized imaging protocols, standardized diagnostic criteria, and externally validated machine learning models. In addition, the implementation of explainable artificial intelligence (XAI) algorithms will be essential to improve the transparency, reliability, and clinical acceptance of AI-assisted peri-implantitis management. Prospective randomized clinical trials with long-term follow-up are required to determine whether AI-assisted diagnostic and therapeutic strategies improve implant survival, disease prevention, and patient-reported outcomes compared with conventional approaches ^{56–61}.

Another promising direction involves integrating AI with three-dimensional CBCT analysis, digital implant monitoring systems, salivary and peri-implant crevicular fluid biomarkers, digital twins, and precision medicine concepts. These technologies may enable continuous monitoring of peri-implant tissue health, earlier prediction of disease progression, personalized maintenance protocols, and more timely therapeutic interventions. As these innovations become clinically

validated, they are expected to contribute to more predictable peri-implantitis management and improved long-term implant survival^{39-45,53-61}.

5. CONCLUSION

This systematic review demonstrates that contemporary peri-implantitis management requires an individualized treatment approach based on disease severity, defect characteristics, implant-related factors, and patient risk indicators. Mechanical biofilm control remains the basis of therapy, while surgical and regenerative approaches provide additional benefits in advanced cases. Emerging adjunctive therapies show potential but require further clinical validation. Long-term supportive maintenance and regular monitoring remain essential for preventing recurrence and preserving implant stability. Further standardized clinical studies are necessary to strengthen the evidence base and improve future treatment strategies for peri-implantitis.

DECLARATIONS

Conflict of Interest

The author declare no conflict of interest.

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Ethical Approval

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CASE REPORT

PATIENT-CENTERED VERTICAL RIDGE AUGMENTATION USING THE TENT POLE CONCEPT

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ABSTRACT

Background: Vertical ridge augmentation remains one of the most challenging procedures in implant dentistry because severe alveolar defects frequently require complex regenerative approaches, multiple surgical interventions, and prolonged treatment periods before definitive prosthetic rehabilitation. Maintaining a stable regenerative space during healing is considered a critical factor for successful three-dimensional bone reconstruction.

Case Presentation: This report presents the clinical application of the Tent Pole System, which combines implant-supported tenting abutments (SANTA®) and a wide-head tenting screw (SBB®) to maintain regenerative space during simultaneous implant placement and vertical ridge augmentation. A patient with severe posterior maxillary alveolar ridge deficiency associated with extensive horizontal and vertical bone loss underwent simultaneous implant placement, sinus augmentation, and three-dimensional ridge reconstruction. The regenerative procedure incorporated concentrated growth factor (CGF), StickyBone™, and a collagen membrane. Implant-supported tenting abutments were used in implant sites, while a wide-head tenting screw was applied in an implant-free pontic region to provide continuous space maintenance throughout the defect. Clinical, radiographic, and prosthetic outcomes were evaluated during follow-up.

Results: The Tent Pole System allowed reconstruction of the deficient alveolar ridge with stable maintenance of the augmented volume. Early provisional rehabilitation was achieved, followed by definitive prosthetic restoration with satisfactory functional and esthetic outcomes. At two-year follow-up, stable peri-implant hard and soft tissues were observed without biological or prosthetic complications. Soft tissue enhancement was successfully achieved using a minimally invasive sutureless free gingival graft technique.

Conclusion: The Tent Pole System represents a promising approach for managing severe vertical ridge defects by integrating implant-supported and implant-free space-maintaining devices within a simplified regenerative protocol. Although the presented clinical outcomes are encouraging, further prospective controlled studies with larger patient populations and longer follow-up are required to validate its predictability and long-term effectiveness.

Keywords: Vertical ridge augmentation; Tent Pole Concept; guided bone regeneration; implant dentistry; SANTA®; SBB®; concentrated growth factor

Vertical ridge augmentation remains one of the most challenging procedures in implant dentistry. Conventional techniques, including autogenous block bone grafting, distraction osteogenesis, titanium mesh, and non-resorbable membrane-guided bone regeneration, have demonstrated favorable clinical outcomes. However, these procedures are often associated with significant drawbacks, including donor-site morbidity, unpredictable graft resorption, prolonged treatment periods, multiple surgical interventions, and increased patient morbidity.¹⁻⁴⁾ Furthermore, simultaneous implant placement is frequently not feasible in severe vertical defects, resulting in an extended edentulous healing period before functional rehabilitation can be achieved. To overcome these limitations, the author developed the Tent Pole Concept, which utilizes a 2-mm-high tenting abutment (SANTA®, Biotem Implant Co., Seoul, Republic of Korea) connected directly to the platform of an implant placed

simultaneously within the bone defect. In this concept, the implant and the SANTA function together as a biological tent pole by supporting the overlying soft tissue, preventing collapse of the grafted bone, and maintaining a stable regenerative space throughout healing. This approach enables simultaneous implant placement and vertical ridge augmentation while simplifying the surgical procedure, reducing patient morbidity, and shortening the overall treatment period.⁵⁾ However, the Tent Pole Concept using the SANTA® alone cannot be applied to implant-free pontic sites or extensive vertical defects where implant placement is not feasible. To address this limitation, the authors subsequently developed the wide-head tent-pole screw (WHTPS; SBB®, Biotem Implant Co., Seoul, Republic of Korea), a wide-head tenting device specifically designed for implant-free sites. Unlike conventional mini-tenting screws, which often require the placement of multiple screws to maintain the regenerative space, the SBB® (Sohn's Bone Builder) provides a substantially larger supporting surface, allowing stable space maintenance with fewer fixation devices while simplifying the surgical procedure.⁶⁾

The present case report represents the clinical application integrating the SANTA and SBB into a unified Tent Pole System. By combining implant-supported and implant-free tenting devices, this approach aims to reconstruct extensive vertical ridge defects while maintaining regenerative space throughout the entire defect.

This report presents two patients with severe vertical ridge deficiencies treated using this integrated Tent Pole System and demonstrates the clinical feasibility of

a simplified, biologically based, and patient-centered approach for predictable three-dimensional vertical ridge augmentation.

1. CASE PRESENTATION

A 64-year-old man was referred to our department for the management of a persistent oroantral fistula that had developed following surgical treatment for maxillary sinusitis associated with a bone graft infection in the right posterior maxilla. To close the fistula, a vascularized interpositional periosteal connective tissue (VIP-CT) flap was performed, resulting in complete closure of the oroantral communication. Three months later, the patient returned for follow-up. Clinical examination confirmed complete healing of the oroantral fistula without any evidence of recurrent infection. However, severe horizontal and vertical alveolar ridge deficiencies were observed in the right posterior maxilla. Cone-beam computed tomography (CBCT) further demonstrated extensive alveolar bone loss with a persistent communication between the residual alveolar ridge and the maxillary sinus caused by severe bone resorption. (Figure 1).



Figure 1. Preoperative clinical and radiographic findings. (A) Preoperative intraoral view demonstrating severe horizontal and vertical alveolar ridge resorption in the right posterior maxilla following healing of the oroantral fistula. (B) Preoperative CBCT coronal image showing severe vertical alveolar bone loss with a large osseous communication between the alveolar ridge and the maxillary sinus. Marked thickening of the Schneiderian membrane is also evident, indicating chronic inflammatory changes.

Because the patient desired a fixed implant-supported prosthesis, simultaneous maxillary sinus augmentation and three-dimensional alveolar ridge reconstruction were planned. The surgical objectives were to eliminate the residual communication with the maxillary sinus, reconstruct the severely resorbed alveolar ridge, and create sufficient bone volume for implant-supported rehabilitation. After a comprehensive discussion with the patient, it was explained that a conventional staged guided bone regeneration (GBR) approach using an e-PTFE membrane or titanium mesh could require multiple surgical procedures and, depending on the

healing response, an overall treatment period of approximately 18 months or longer before delivery of the definitive implant-supported prosthesis. Such a treatment strategy would inevitably prolong the edentulous healing period, increase patient morbidity, and delay functional rehabilitation. Because the patient's primary goal was to regain oral function with a fixed implant-supported prosthesis as early as possible, a patient-centered treatment strategy was selected instead of the conventional staged protocol. The treatment plan was designed to minimize the number of surgical interventions while simultaneously reconstructing the severely deficient alveolar ridge and facilitating earlier prosthetic rehabilitation.

To accomplish these objectives, simultaneous maxillary sinus augmentation and three-dimensional ridge reconstruction were performed using the Tent Pole Concept. Dental implants connected to SANTA® were used as implant-supported tent poles to maintain the regenerative space at the implant sites, while a 6-mm SBB® was placed in the implant-free second premolar (pontic) region to support the grafted bone and maintain space throughout the entire defect.

This integrated approach enabled comprehensive reconstruction of the posterior maxilla while avoiding the prolonged staged treatment associated with conventional GBR.

The surgical procedure was performed under local anesthesia following the intravenous administration of preoperative antibiotics (Flomoxef, Flumarin®, Ildong Pharm, Republic of Korea). Venous blood was drawn from the patient's forearm to produce autologous fibrin glue and concentrated growth factor (CGF) membranes, used to prepare sticky bone, as originally introduced by Sohn et al.⁽⁷⁾ A crestal incision with anterior and posterior vertical releasing incisions extending into the vestibular mucosa was made, and a full-thickness buccal mucoperiosteal flap was carefully elevated. After flap reflection, a large bony communication between the posterior alveolar ridge and the maxillary sinus was clearly identified. The Schneiderian membrane was then carefully elevated using sinus elevators. To maximize the blood supply to the newly created subantral space and promote bone regeneration, the palatal bony wall of the maxillary sinus was widely exposed during membrane elevation. In addition, a bony defect was observed around the previously placed implant site in the premolar region. During elevation of the Schneiderian membrane, a small membrane perforation occurred. Rather than filling the sinus cavity with particulate bone graft material, four CGF (concentrated growth factor) blocks were placed into the elevated sinus cavity.

This approach was intended not only to facilitate repair of the Schneiderian membrane perforation but also to reduce the risk of postoperative sinusitis while promoting early new bone formation within the newly created subantral space. Following sinus augmentation, implants (Biotem Implant Co., Seoul, Republic of Korea) were placed in the canine, first premolar, and second molar regions. The implant platforms in the canine and first premolar sites were positioned approximately 2 mm apical to the proximal bone level of the adjacent healthy lateral incisor. SANTA-2 (2-mm height) abutments were connected to these implants to function as implant-supported tent poles. A SANTA-1 abutment was connected to the implant placed in the second molar region to support horizontal ridge augmentation. To maintain the regenerative space in the implant-free second premolar (pontic) region, a 6-mm-diameter SBB® was inserted on the palatal aspect of the defect at 50 rpm using a handpiece connected to an implant motor. The height of the SBB® head was adjusted to correspond precisely with the height of the SANTA® abutments, thereby creating a continuous tenting framework capable of maintaining stable three-dimensional regenerative space throughout the defect. (Figure 2)

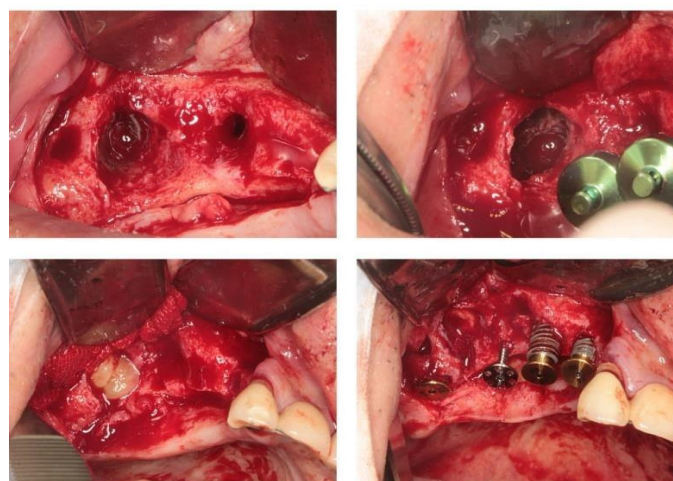


Figure 2 Surgical procedures for reconstruction using the Tent Pole System.

(A) Full-thickness buccal flap elevation revealing a large osseous communication with the maxillary sinus and severe alveolar ridge defect. (B) Schneiderian membrane elevation and implant site preparation using a Bone Pen guide. (C) Bone graft-free sinus augmentation using four CGF membranes following Schneiderian membrane perforation. (D) Placement of a 6-mm SBB® in the implant-free second premolar region and connection of SANTA® abutments to the implant platforms. The combination of the SANTA® and SBB® established the Tent Pole System.

Following implant placement, StickyBone™, prepared by mixing deproteinized bovine bone mineral with autologous fibrin, was applied generously over the reconstructed ridge to completely fill the augmented area and slightly cover the heads of both the SANTA® abutments and the SBB®. The grafted site was then covered with a 3 × 4 cm resorbable collagen membrane.

Because the Sticky Bone provided excellent graft stability, no additional membrane fixation with tacks was required. After adequate periosteal releasing incisions were performed to achieve tension-free flap advancement, the buccal flap was repositioned and primary wound closure was achieved with slight flap eversion.

Five months later, a palatal crestal incision was made to expose and remove the SANTA® and the SBB®. Scan bodies were connected to the implants for a digital impression. (Figure 3 - 5)

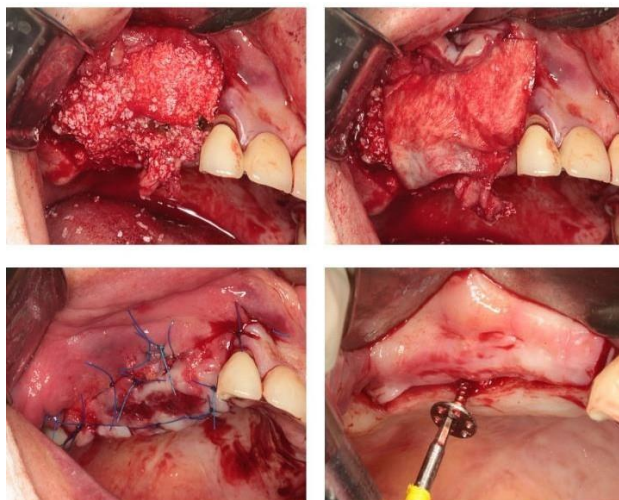


Figure 3. Figure 3. Guided bone regeneration and second-stage surgery.

(A) Sticky Bone was generously applied to reconstruct the vertical ridge defect, completely filling the augmented area and slightly covering the heads of the SANTA abutments and the SBB. (B) The grafted site was covered with a resorbable collagen membrane without additional fixation. (C) Tension-free primary wound closure was achieved following adequate periosteal releasing incisions. (D) After five months of healing, the SANTA® and the SBB® were exposed through a palatal crestal incision and removed prior to digital impression procedures.



Figure 4. Immediate postoperative CBCT evaluation. (A) Coronal CBCT image demonstrating the reconstructed maxillary ridge following simultaneous implant placement and bone graft-free sinus augmentation. (B–D) Cross-sectional CBCT images showing the three-dimensional configuration of the reconstructed ridge and maintenance of the augmented space around the implants sites.

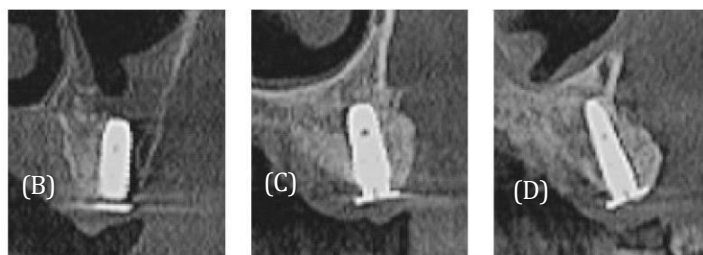


Figure 5. Five-month postoperative CBCT evaluation. (A) Panoramic CBCT image demonstrating stable vertical ridge reconstruction following application of the Tent Pole System and new bone formation with bone graft-free sinus augmentation. (B–D) Cross-sectional CBCT images confirming maintenance of the regenerated three-dimensional ridge contour around the implants and in the implant-free pontic sites.

Two weeks later, a screw-retained functional provisional restoration was delivered. Immediate functional loading was initiated while simultaneously promoting prosthetically guided soft tissue healing and peri-implant soft tissue maturation. After confirming stable osseointegration and favorable soft tissue architecture, the definitive prosthesis was delivered. At 18 months after functional loading, the peri-implant keratinized tissue around the definitive prosthesis remained insufficient.

Therefore, a sutureless free gingival graft (FGG) was performed to increase the width of keratinized tissue. In the sutureless FGG technique, the graft is stabilized with tissue cyanoacrylate adhesive instead of conventional sutures. This approach significantly simplifies the procedure, allowing completion in less than 10 minutes. Compared with the conventional sutured FGG technique, it offers several advantages, including shorter surgical time, reduced patient discomfort, minimal surgical trauma, higher patient satisfaction, and less postoperative graft shrinkage. The technique is simple, predictable, and highly efficient, making it a patient-centered approach to soft tissue augmentation.

At the 2-year follow-up, both the definitive restoration and peri-implant tissues remained stable, with satisfactory esthetic and functional outcomes and no evidence of biological or prosthetic complications. (Figure 6 and 7)

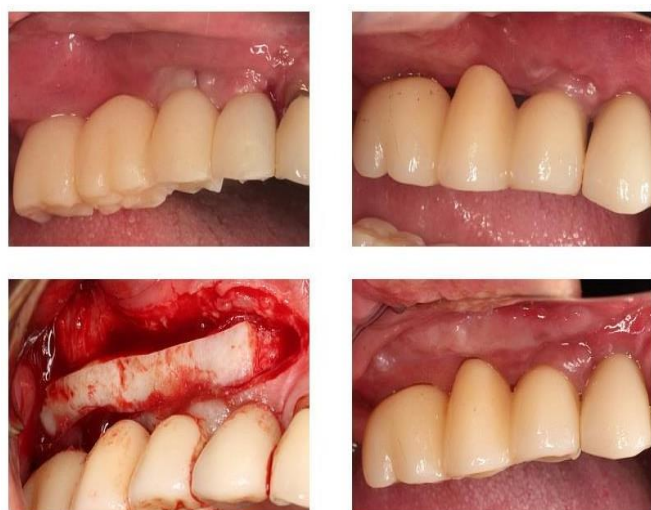


Figure 6. Clinical outcomes following prosthetic rehabilitation.

(A) Clinical view of the screw-retained functional provisional restoration delivered 2 weeks after suture removal, allowing immediate functional loading while promoting prosthetically guided soft tissue healing. (B) Definitive implant-supported restoration delivered after 1 month of functional loading with the provisional restoration. (C)

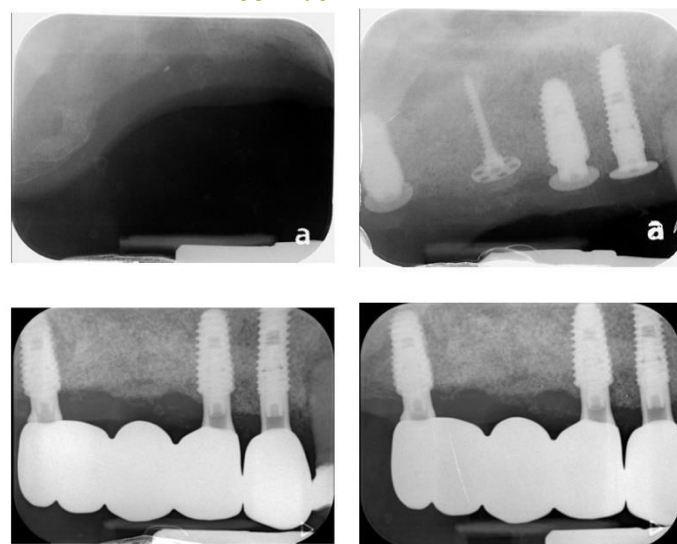


Figure 7. Radiographic evaluation throughout treatment and follow-up.

(A) Preoperative radiograph demonstrating severe vertical alveolar ridge deficiency in the right posterior maxilla. (B) Immediate postoperative radiograph following simultaneous implant placement, Tent Pole System application, and vertical ridge reconstruction. (C) Radiograph obtained at delivery of the definitive implant-supported restoration, showing successful reconstruction of the alveolar ridge and prosthetic rehabilitation.

(D) Two-year follow-up radiograph demonstrating stable peri-implant marginal bone levels and functional maintenance of the definitive restoration.

DISCUSSION

Vertical ridge augmentation continues to represent one of the greatest challenges in implant reconstruction because successful treatment requires not only sufficient bone formation but also stable maintenance of the regenerated space throughout healing. Numerous surgical techniques have been proposed to manage severe vertical ridge deficiencies; however, each has inherent limitations that may compromise treatment efficiency or increase patient morbidity. Autogenous block bone grafting has traditionally been regarded as the gold standard for vertical ridge reconstruction because of its osteogenic potential. Nevertheless, donor-site morbidity, limited graft availability, unpredictable graft resorption, and the need for a second surgical site remain significant disadvantages. In addition, implant placement is frequently delayed until graft maturation, resulting in prolonged edentulous healing periods and delayed functional rehabilitation.⁸⁾ Distraction osteogenesis provides simultaneous expansion of both hard and soft tissues and can achieve substantial vertical bone gain. However, previous systematic reviews have reported complication rates approaching 50%, including vector deviation, infection, hardware-related complications, and patient discomfort. Similarly, sandwich osteotomy is

technically demanding and carries risks of transport segment fracture, wound dehiscence, and compromised vascularity.⁹⁾ Vertical guided bone regeneration using titanium mesh or non-resorbable membranes has also demonstrated favorable regenerative outcomes. However, membrane or mesh exposure remains one of the most common complications and may adversely affect bone regeneration. Furthermore, these techniques generally require a second surgical procedure for removal of the fixation devices, thereby increasing surgical invasiveness, patient morbidity, and treatment duration. Likewise, conventional mini-tenting screw techniques often require placement of multiple screws to support large grafted areas, increasing operative time and surgical complexity.¹⁰⁻¹²⁾

The concept underlying the present technique differs fundamentally from conventional vertical augmentation procedures. Rather than focusing solely on maximizing bone volume, the Tent Pole System was developed according to a patient-centered philosophy, with the primary objectives of reducing surgical invasiveness, minimizing the edentulous healing period through simultaneous implant placement whenever feasible, simplifying the surgical procedure, and restoring oral function as early as possible. Our previous clinical study demonstrated that the SANTA® (Sohn's Augmentation New Tenting Abutment) enables simultaneous implant placement while maintaining stable regenerative space above the implant platform, allowing predictable three-dimensional bone reconstruction with a simplified surgical approach. Unlike conventional tenting devices, the SANTA functions as both a healing abutment and a biological tent pole, eliminating the need for additional fixation devices around the implant.¹³⁾

However, the original SANTA concept was limited to implant-supported regions and could not be applied to implant-free pontic sites or extensive defects where simultaneous implant placement was impossible. To overcome this limitation, we subsequently introduced the Sohn's Bone Builder (SBB®), a novel wide-head tenting screw specifically designed for implant-free regions. In our previous retrospective study, the SBB® achieved a mean vertical bone gain of 8.86 mm with only 17.8% radiographic resorption during healing.⁶⁾ Histomorphometric analysis further demonstrated newly formed bone ranging from 21.2% to 57.5% beneath the screw head without inflammatory reactions, confirming that stable maintenance of regenerative space promotes predictable vertical bone regeneration.¹⁴⁾ The present report expands these previous concepts by integrating the SANTA® and SBB into a unified Tent Pole System. Rather than functioning as independent devices, the two components complement each other according to the anatomical requirements of the defect.

The SANTA® provides space maintenance in implant-supported regions, whereas the SSBB® maintains regenerative space in implant-free pontic areas. This integrated approach enables reconstruction of extensive vertical defects with fewer fixation devices, shorter operative time, simplified surgical procedures, and simultaneous implant placement whenever clinically feasible. From a clinical perspective, the greatest advantage of the Tent Pole System is not merely the amount of regenerated bone but its ability to simplify treatment while improving the patient's overall experience. By reducing the number of surgical procedures, shortening the edentulous healing period, and facilitating earlier prosthetic rehabilitation, this strategy reflects the fundamental principles of patient-centered implant dentistry.

The limitations of this report include the small number of cases and the absence of long-term comparative data. Prospective controlled clinical studies with larger patient populations are therefore necessary to validate the long-term effectiveness, stability, and reproducibility of the Tent Pole System.

CONCLUSION

The SANTA® represents a patient-centered approach to vertical ridge augmentation by combining simultaneous implant placement with predictable space maintenance using an implant platform-connected tenting abutment.

In the case presented, favorable vertical bone regeneration and stable implant outcomes were achieved while reducing surgical complexity and overall treatment time. For implant-free sites, the SBB® extends the same biological principle by providing stable regenerative space maintenance without the need for multiple conventional mini-tenting screws. Its wide-head design simplifies the surgical procedure and may reduce operative time while maintaining graft stability.

DECLARATIONS

Ethical Approval

Not applicable.

Competing Interests

The author is the developer of the SANTA® and SBB® systems.

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None.

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REVIEW ARTICLE

ARTIFICIAL INTELLIGENCE IN DENTAL IMPLANTOLOGY: A SCOPING REVIEW.

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Abstract

Background: Artificial intelligence (AI) is rapidly transforming dental implantology by introducing advanced approaches for diagnosis, treatment planning, surgical guidance, and outcome prediction. The integration of AI with cone-beam computed tomography (CBCT), intraoral scanning, digital workflows, and computer-assisted implant surgery has created new opportunities for personalized and precision-based implant treatment. However, the current evidence remains heterogeneous, and a comprehensive mapping of AI applications in implant dentistry is needed.

Objective: This scoping review aimed to map the current evidence regarding the applications of artificial intelligence in dental implantology, with particular emphasis on diagnostic performance, digital implant planning, surgical assistance, prediction models, and future clinical perspectives.

Methods: A scoping review was conducted according to the methodological framework of the Joanna Briggs Institute (JBI) and reported following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) guidelines. A comprehensive literature search was performed in PubMed, Scopus, Web of Science, ScienceDirect, and Google Scholar. Studies investigating AI-based technologies applied to dental implantology were considered eligible. Data were extracted regarding study characteristics, AI algorithms, clinical applications, imaging modalities, outcomes, and reported limitations.

Results: The available evidence indicates that AI applications in implant dentistry are primarily focused on automated radiographic analysis, anatomical structure recognition, implant position optimization, guided surgery, and prediction of clinical outcomes. Deep learning algorithms, particularly convolutional neural networks (CNNs), have demonstrated promising performance in CBCT-based anatomical identification and treatment planning. Emerging applications include AI-assisted prosthetic design, peri-implant disease prediction, and integration with three-dimensional digital workflows. Nevertheless, limitations related to dataset quality, external validation, standardization, and clinical implementation remain.

Conclusion: Artificial intelligence represents a promising technological advancement in dental implantology, supporting a transition toward personalized, data-driven, and precision-based implant treatment. Further prospective clinical studies and standardized validation protocols are required before widespread routine application of AI systems in implant practice.

Keywords: Artificial intelligence; dental implants; implant dentistry; deep learning; digital dentistry; CBCT; computer-assisted implant surgery; scoping review.

primarily surgical discipline focused on

1. INTRODUCTION

Dental implantology has evolved considerably over the last several decades, transitioning from a

osseointegration toward a digitally integrated, patient-centered, and precision-based field. The predictability of implant-supported rehabilitation has been enhanced through advances in implant surface technology, three-dimensional imaging, guided surgery, computer-aided design and manufacturing (CAD/CAM), and biomaterial development. Nevertheless, implant treatment remains a complex clinical process that requires accurate diagnosis, comprehensive anatomical evaluation, prosthetically driven planning, and individualized decision-making.

The long-term success of dental implants depends on multiple biological, anatomical, mechanical, and patient-related factors. Accurate assessment of available bone volume, identification of critical anatomical structures, evaluation of soft tissue conditions, and appropriate implant positioning are essential components of predictable treatment outcomes. Traditionally, implant planning has relied on clinician experience combined with two-dimensional radiography, clinical examination, and manual interpretation of three-dimensional imaging data. Although these approaches remain clinically effective, they may be influenced by operator variability and limitations associated with the analysis of complex diagnostic information.

The rapid development of digital dentistry has significantly changed contemporary implant workflows. Cone-beam computed tomography (CBCT), intraoral scanners, virtual implant planning platforms, and computer-guided surgical systems have enabled clinicians to evaluate anatomical structures in three dimensions and perform prosthetically driven implant placement. However, the increasing volume of digital diagnostic information has created new challenges regarding efficient data interpretation and clinical decision support. Artificial intelligence (AI) has emerged as a promising technology capable of addressing these challenges through automated analysis, pattern recognition, and predictive modelling.

Artificial intelligence refers to computational systems capable of performing tasks traditionally associated with human cognitive functions, including learning, classification, prediction, and decision-making. In dentistry, AI applications have expanded rapidly, particularly in diagnostic imaging, radiographic interpretation, treatment planning, and prediction of clinical outcomes ¹. Machine learning and deep learning approaches allow algorithms to identify complex relationships within large datasets, potentially improving diagnostic consistency and supporting personalized treatment strategies ².

Within dental implantology, AI has gained increasing attention because implant treatment requires the integration of multiple data sources, including CBCT images, intraoral scans, clinical parameters, and prosthetic requirements. Unlike conventional software based on predefined rules, AI-driven systems can learn from large numbers of clinical examples and improve their performance through iterative training. Deep learning methods, particularly convolutional neural networks (CNNs), have demonstrated substantial potential for medical and dental image analysis due to their ability to automatically detect and classify anatomical structures within complex imaging datasets ³.

One of the most investigated applications of AI in implant dentistry is automated analysis of CBCT images. Accurate interpretation of CBCT data is fundamental for implant placement because clinicians must evaluate bone dimensions, density characteristics, alveolar ridge morphology, and anatomical limitations such as the mandibular canal and maxillary sinus. Recent studies have demonstrated that deep learning algorithms can assist in the segmentation and identification of anatomical structures, reducing manual workload and improving reproducibility of radiographic assessment ^{4,5}. These developments may be particularly valuable in complex implant cases involving severe bone deficiency or anatomically challenging regions.

AI-assisted implant planning represents another rapidly developing area. Conventional digital implant planning requires clinicians to manually determine implant position, angulation, diameter, and depth according to anatomical and prosthetic considerations. AI-based systems have the potential to automate several stages of this process by recognizing edentulous regions, analysing available bone, and generating optimized implant positioning recommendations. Current evidence suggests that AI-based planning systems may demonstrate promising technical accuracy; however, differences in datasets, validation protocols, and clinical scenarios presently limit direct comparison between studies ⁶.

The integration of artificial intelligence with digital implant workflows may contribute to the development of personalized implant dentistry. Contemporary treatment concepts increasingly emphasize individualized planning based on patient-specific anatomical characteristics rather than standardized approaches. By combining radiographic information, intraoral scanning data, and clinical variables, AI systems may support customized treatment strategies that consider both surgical and prosthetic objectives ⁷. This approach corresponds with the broader movement toward precision dentistry, where clinical decisions are supported by patient-specific biological and digital information.

Another emerging application of AI involves computer-assisted and robotic implant surgery. Navigation systems and robotic platforms aim to improve the transfer accuracy between virtual treatment planning and clinical execution. AI-enhanced surgical systems may provide real-time guidance, recognize deviations, and assist clinicians during implant placement procedures. Recent investigations have reported high accuracy of digitally guided and robotic-assisted implant placement, although additional prospective clinical studies are required to establish their routine clinical applicability⁸. It should be noted that computer-guided surgery, dynamic navigation, and robotic systems are not inherently AI-based; they were considered within the scope of this review only when an identifiable AI-component contributed to planning, analysis, guidance, or decision support.

Beyond implant placement, AI applications are also being explored in implant prosthodontics and maintenance. AI-supported systems have been investigated for prosthetic design optimization, implant component recognition, occlusal analysis, and prediction of implant-related complications. These technologies may contribute to more efficient restorative workflows and improved communication between surgical and prosthetic teams^{9,10}.

Peri-implant disease management represents another potential field for AI implementation. Peri-implantitis is a multifactorial condition influenced by microbial dysbiosis, host immune response, implant characteristics, and patient-related risk factors. AI-based predictive models may assist in identifying patients at increased risk of biological complications by integrating clinical, radiographic, and biological information. Although promising, these applications remain largely at the research stage and require further clinical validation¹¹.

Despite the considerable potential of AI in implant dentistry, several limitations must be considered. The performance of AI algorithms depends strongly on the quality, quantity, and representativeness of training datasets. Many published studies are based on retrospective datasets obtained from single institutions, which may limit external validity and generalizability. Variability in imaging protocols, annotation procedures, algorithm architecture, and outcome definitions creates additional challenges when comparing results between studies¹².

Furthermore, the clinical implementation of AI raises important ethical and practical considerations. Issues related to patient data protection, algorithm transparency, responsibility for AI-assisted decisions,

and clinician acceptance must be carefully addressed. AI should therefore be considered as an assistive technology designed to enhance clinical decision-making rather than replace professional expertise¹³.

Recent reviews have highlighted that current AI research in dentistry is characterized by rapid technological development but limited clinical translation. Most available studies focus on technical performance, image analysis accuracy, and algorithm development, whereas fewer investigations evaluate long-term clinical outcomes, cost-effectiveness, and real-world integration into routine implant practice¹⁴. Consequently, there remains a need for comprehensive evidence mapping to clarify current applications, technological trends, and future research priorities.

The continuous evolution of AI, three-dimensional imaging, and digital manufacturing suggests that implant dentistry is moving toward a more automated and personalized model of care. Future developments may involve integration of AI with virtual surgical planning, additive manufacturing, patient-specific implants, and regenerative approaches, creating highly individualized treatment pathways^{15–17}. However, standardized reporting frameworks, multicenter validation studies, and interdisciplinary collaboration between clinicians, engineers, and data scientists are essential for responsible implementation.

Although previous publications have investigated specific AI applications in dental imaging or implant planning, the available evidence remains fragmented across different clinical domains and technological platforms. A comprehensive mapping of current knowledge is therefore necessary to understand the scope of AI applications in dental implantology and identify existing evidence gaps.

Therefore, this scoping review aims to map the current literature regarding artificial intelligence applications in dental implantology, including diagnostic imaging, implant planning, surgical guidance, prosthetic workflows, predictive modelling, and future clinical perspectives. By synthesizing available evidence, this review seeks to provide a comprehensive overview of the current state of AI-driven implant dentistry and highlight directions for future research and clinical innovation (Figure 1).

AI-Enabled Dental Implant Workflow

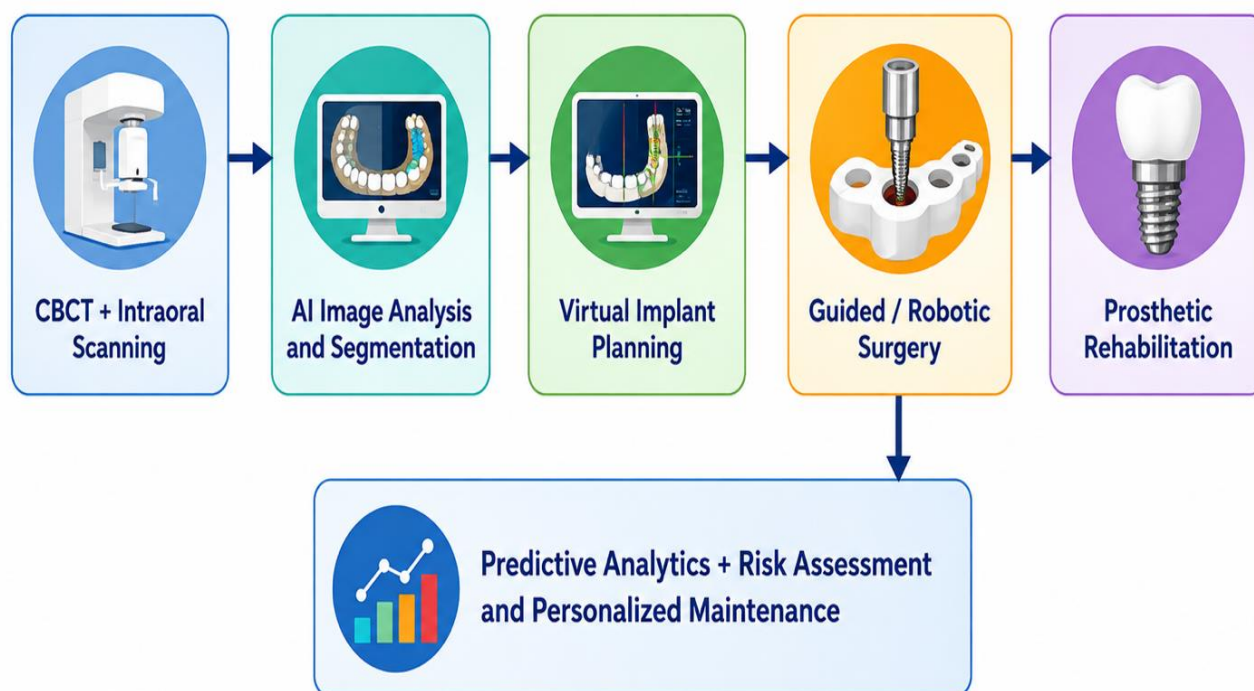


Figure 1. AI-enabled dental implant workflow integrating CBCT, intraoral scanning, AI-assisted analysis, virtual planning, computer-assisted surgery, prosthetic rehabilitation, and predictive maintenance.

3.2 Characteristics and Distribution of AI Applications in Dental Implantology

These studies represented the current evidence landscape regarding artificial intelligence applications in dental implantology, including AI-assisted imaging analysis, implant treatment planning, computer-guided surgery, prosthetic workflows, and predictive modelling approaches.

The included literature demonstrates a rapid expansion of research investigating artificial intelligence applications across different areas of dental implantology. The available evidence consisted of various study designs, including diagnostic studies, methodological investigations, retrospective analyses, clinical evaluations, and review articles.

Most studies were published within the last five years, reflecting the recent acceleration of AI integration into digital dentistry. The majority of investigations originated from countries with established digital dentistry research programs, including South Korea, China, European countries, and the United States.

The reviewed studies demonstrated considerable variation regarding AI models, datasets, imaging protocols, and clinical objectives. Deep learning approaches, particularly convolutional neural networks, represented the most frequently investigated methods, mainly because of their ability to analyse complex three-dimensional imaging data.

The included studies demonstrated that artificial intelligence applications in dental implantology are mainly concentrated in five major clinical domains: CBCT-based image analysis, implant treatment planning, computer-guided surgery, prosthetic rehabilitation, and predictive modelling. These applications reflect the increasing integration of AI into digital implant workflows and indicate its potential role in improving diagnostic accuracy, treatment personalization, and clinical decision support (Table 1).

Table 1. Main Applications of Artificial Intelligence in Dental Implantology

AI Application	Clinical Purpose	Common AI Methods	Potential Clinical Benefits
CBCT image analysis	Detection and segmentation of anatomical structures	Deep learning, CNNs	Improved radiographic interpretation, reduced observer variability
Implant treatment planning	Virtual implant positioning and bone assessment	Machine learning, computer vision	Personalized treatment planning
Guided implant surgery	Surgical navigation and accuracy improvement	AI-assisted navigation systems	Improved transfer accuracy from virtual plan to surgery
Implant prosthodontics	Automated restoration design and CAD/CAM optimization	AI-based design algorithms	More efficient restorative workflow
Predictive modelling	Prediction of implant complications and outcomes	Machine learning models	Risk assessment and personalized follow-up

3.3 Artificial Intelligence in Diagnostic Imaging and CBCT Analysis

Artificial intelligence (AI) has emerged as one of the most extensively investigated technologies in dental implantology, with diagnostic imaging representing the most mature application domain. The majority of the included studies evaluated AI-assisted interpretation of cone-beam computed tomography (CBCT) images using deep learning algorithms, particularly convolutional neural networks (CNNs), for automated detection, segmentation, and classification of anatomical structures relevant to implant treatment planning.

The principal applications included automatic identification of the mandibular canal, mental foramen, maxillary sinus boundaries, inferior alveolar nerve, alveolar crest morphology, residual ridge dimensions, and bone quality assessment. Several investigations also explored automated localization of missing teeth, assessment of available bone volume, and segmentation of cortical and cancellous bone to facilitate virtual implant planning. Compared with conventional manual image interpretation, AI-assisted systems demonstrated high reproducibility and reduced observer-dependent variability, while substantially decreasing the time required for radiographic analysis.

Despite these encouraging findings, considerable heterogeneity was observed among studies regarding CBCT acquisition protocols, annotation strategies, dataset size, AI architectures, and validation methods.

Most studies focused on algorithm development and internal technical validation, whereas relatively few evaluated diagnostic performance under routine clinical conditions or across external datasets. Consequently, although AI-assisted CBCT analysis appears highly promising, additional multicenter prospective validation studies are required before widespread clinical implementation (Figure 3).

AI-Assisted CBCT Analysis in Implant Dentistry

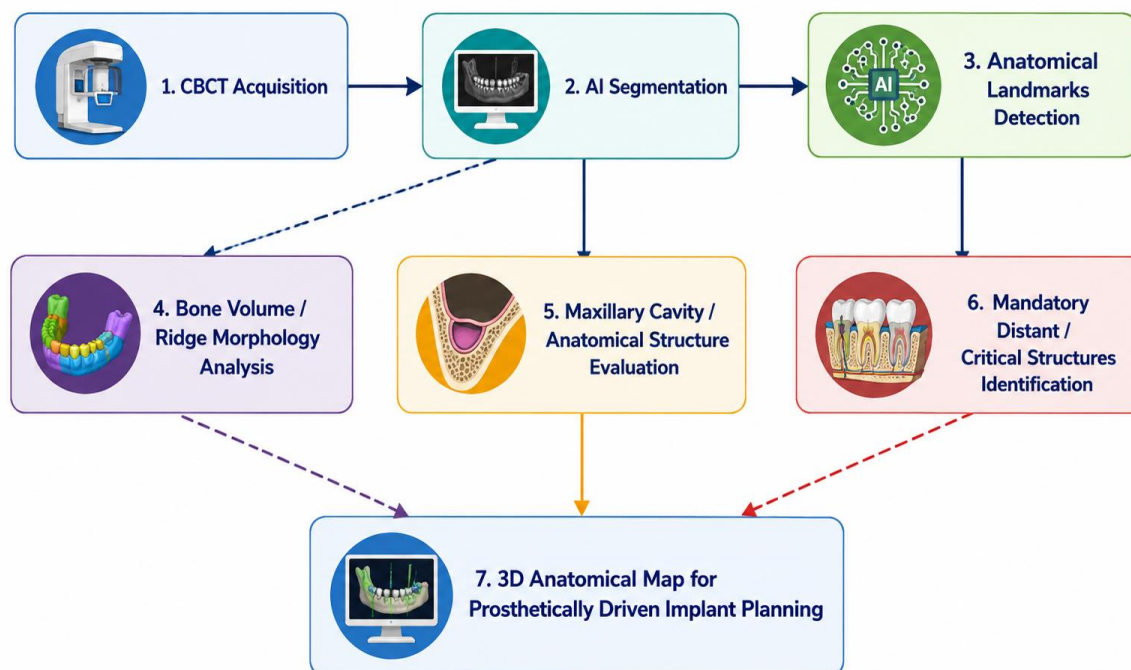


Figure 3. AI-assisted CBCT analysis for dental implantology, illustrating automated anatomical segmentation, landmark detection, and generation of a three-dimensional anatomical map for implant planning.

3.4 AI-Assisted Implant Treatment Planning

Virtual implant treatment planning represented another major research domain identified in the evidence mapping. The reviewed studies investigated the ability of AI systems to support clinicians in determining optimal implant position by simultaneously analyzing prosthetic requirements, available bone volume, anatomical limitations, implant dimensions, and occlusal relationships.

Machine learning and computer vision algorithms were integrated into digital planning software to generate treatment recommendations based on multidimensional patient-specific datasets. Several studies suggested that AI-assisted planning may improve consistency between clinicians, reduce planning time, and facilitate prosthetically driven implant placement. AI was also reported to assist in selecting implant diameter and length, evaluating bone availability, and identifying potential surgical limitations before treatment.

However, the current evidence remains heterogeneous because different commercial planning platforms employ proprietary algorithms and varying validation strategies. Furthermore, most studies assessed technical planning accuracy rather than clinically meaningful outcomes such as implant survival, surgical complications, or patient-reported satisfaction. Standardized evaluation criteria and prospective clinical trials are therefore necessary to determine the true clinical value of AI-assisted treatment planning.

3.5 AI Integration with Digital and Computer-Assisted Implant Surgery

The integration of AI-components into computer-assisted implant surgery represents an emerging area within digital dentistry. Several studies described AI-supported workflows combining CBCT imaging, intraoral scanning, virtual implant planning, CAD/CAM surgical guide fabrication, dynamic navigation systems, and robotic-assisted implant placement.

The reviewed evidence indicates that AI facilitates communication between diagnostic imaging, virtual planning, surgical execution, and prosthetic rehabilitation by improving the transfer accuracy from digital planning to clinical treatment.

Navigation-assisted and robotic implant surgery has demonstrated high placement precision in experimental and early clinical studies; however, the specific incremental contribution of AI to this accuracy remains insufficiently established.

Nevertheless, current clinical evidence remains limited. Most available studies were feasibility investigations or retrospective analyses involving relatively small patient populations. High equipment costs, increased workflow complexity, limited accessibility, and the absence of standardized clinical protocols currently restrict widespread implementation. Future multicenter clinical trials are needed to evaluate whether AI-assisted surgical systems improve long-term implant success compared with conventional guided surgery.

3.6 AI Applications in Implant Prosthodontics and Rehabilitation

Artificial intelligence applications extend beyond surgical planning into prosthetic rehabilitation and digital restorative dentistry. The reviewed studies described AI-assisted workflows for implant-supported prosthesis design, automated recognition of implant components, digital smile analysis, occlusal optimization, and CAD/CAM restoration planning.

AI algorithms were incorporated into digital design software to automate prosthetic workflows by identifying implant platforms, selecting restorative components, optimizing emergence profiles, and assisting laboratory technicians during restoration fabrication. These technologies have the potential to reduce laboratory time, improve standardization of prosthetic design, and enhance communication between clinicians and dental technicians.

Despite these advantages, evidence supporting AI-assisted implant prosthodontics remains relatively limited. Most investigations consisted of technical feasibility studies rather than controlled clinical trials. Long-term evaluation of prosthetic complications, restoration survival, maintenance requirements, and patient-centered outcomes remains insufficient, highlighting the need for well-designed prospective clinical research.

3.7 Predictive Models and Peri-implant Disease Assessment

Predictive modelling represents one of the newest applications of AI in implant dentistry. Machine learning algorithms were developed to integrate clinical variables, CBCT findings, periodontal history, systemic risk factors, smoking status, and biological markers to estimate the probability of implant failure or peri-implant disease.

Several studies demonstrated encouraging predictive performance using supervised machine learning approaches such as random forests, support vector machines, artificial neural networks, and gradient boosting algorithms. These models may assist clinicians in identifying high-risk patients, supporting individualized maintenance protocols, and improving preventive strategies.

However, important methodological limitations remain. Most predictive models were trained using retrospective datasets from single institutions, limiting external validity. Differences in patient populations, outcome definitions, follow-up duration, and predictor selection also hinder comparison across studies. Consequently, current AI prediction systems should be regarded as promising decision-support tools rather than fully validated clinical decision-making instruments. Future research should emphasize prospective multicenter validation, explainable AI methodologies, standardized reporting guidelines, and integration into routine clinical practice. AI can function as a clinical decision-support system rather than a replacement for professional judgment. A conceptual model illustrating this interaction is presented in Figure 4.

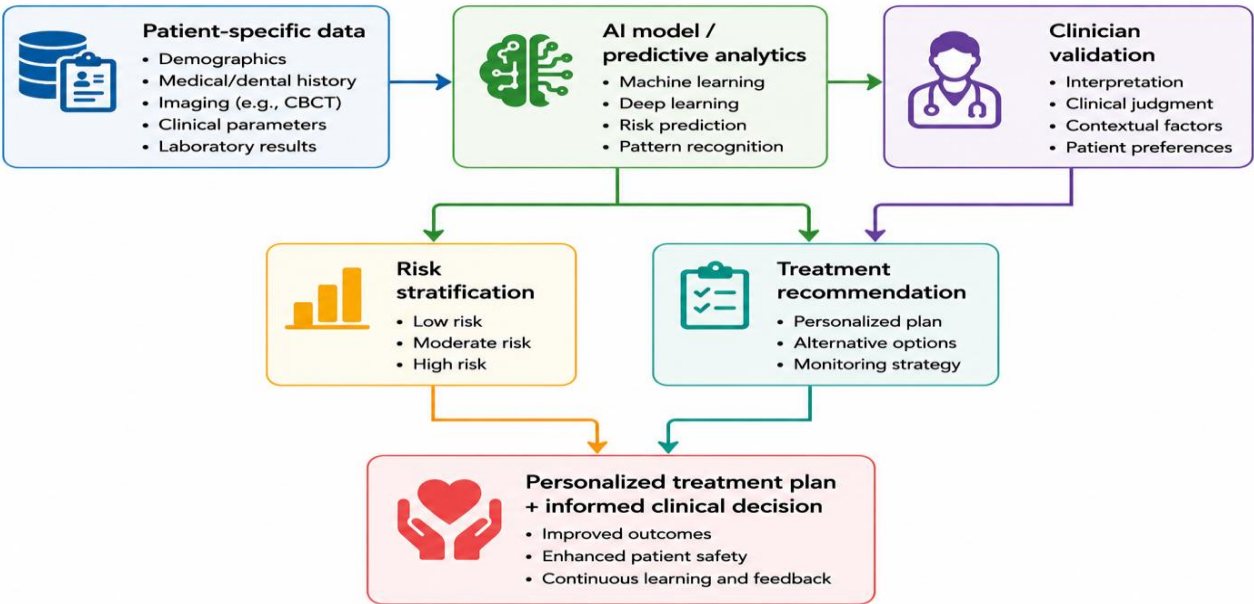


Figure 4. Conceptual model of AI as a clinical decision-support system. Patient-specific data are processed by AI models and subsequently reviewed and validated by the clinician.

Overall, the evidence synthesized in this scoping review demonstrates that artificial intelligence applications span the entire implant treatment workflow, from diagnosis and treatment planning to surgery, prosthetic rehabilitation, and long-term outcome prediction. As summarized in Table 2, the most developed body of evidence currently concerns AI-assisted diagnostic imaging and CBCT analysis, where deep learning algorithms have consistently demonstrated high technical accuracy and reproducibility. AI-assisted implant planning and digital surgical guidance have also shown promising results, particularly in improving workflow efficiency and treatment precision; however, robust clinical validation remains limited. In contrast, applications in implant prosthodontics and predictive modelling are still at an earlier stage of development, with most available studies focusing on technical feasibility rather than long-term clinical effectiveness. Collectively, these findings indicate that although AI has considerable potential to enhance clinical decision-making and personalized implant therapy, further multicenter prospective studies, standardized validation protocols, and transparent reporting are required before these technologies can be routinely integrated into evidence-based implant practice (Table 2).

Table 2. Summary of Artificial Intelligence Applications in Dental Implantology

Research Domain	Main AI Applications	Common AI Methods	Main Findings	Current Limitations	Future Research Priorities
Diagnostic imaging and CBCT analysis	Anatomical landmark detection, segmentation, bone assessment, nerve identification	Deep learning (CNN), image segmentation	Promising to high technical performance in selected diagnostic tasks	Heterogeneous datasets; limited external validation	Multicenter validation and standardized imaging datasets
Implant treatment planning	Virtual implant positioning, implant selection,	Machine learning, computer vision	Improved planning consistency and workflow efficiency	Lack of standardized planning protocols	Prospective clinical outcome studies

	bone evaluation				
Digital and computer-assisted surgery	Surgical guides, navigation systems, robotic implant placement	AI-assisted navigation, robotics	Improved transfer accuracy from virtual planning to surgery	High cost, limited clinical evidence	Randomized multicenter clinical trials
Implant prosthodontics and rehabilitation	CAD/CAM restoration design, implant recognition, occlusal optimization	AI-assisted CAD/CAM algorithms	More efficient digital restorative workflow	Predominantly technical studies	Long-term prosthetic outcome evaluation
Predictive modelling and peri-implant disease	Implant failure prediction, peri-implant disease risk assessment	Random forests, neural networks, SVM, gradient boosting	Personalized risk prediction and maintenance planning	Retrospective datasets and limited external validation	Explainable AI, prospective validation, real-world implementation

3.8 Evidence Gaps and Future Research Needs

The evidence mapping identified several important limitations in the current literature on artificial intelligence (AI) in dental implantology. First, most available studies are based on retrospective datasets or single-center experiences, limiting the generalizability of their findings. Second, considerable heterogeneity exists in AI model development, validation strategies, and reporting methodologies, making comparisons across studies difficult. Third, despite encouraging technical performance, relatively few investigations have evaluated clinically relevant outcomes, cost-effectiveness, patient-centered benefits, and long-term performance under routine clinical conditions.

Overall, the current evidence suggests that AI has substantial potential to improve implant diagnosis, treatment planning, surgical guidance, prosthodontic rehabilitation, and outcome prediction. However, the level of clinical evidence remains variable across different application domains. As summarized in Table 3, future research should prioritize multicenter prospective clinical studies, external validation of AI models, standardized reporting frameworks, and the integration of explainable and clinically validated AI systems into routine implant workflows.

Table 3. Evidence Mapping of AI Applications in Dental Implantology.

Domain	Current maturity of evidence	Main Findings	Evidence Gaps / Future Directions
Imaging analysis	Relatively developed	Strong technical performance of deep learning models	External multicenter validation and evaluation across different CBCT systems
Implant planning	Developing	Promising planning accuracy but limited clinical validation	Prospective clinical trials and standardized outcome measures
Surgical guidance	Early to developing	Improved digital workflow integration	Long-term clinical effectiveness and cost-

		and surgical precision	effectiveness studies
Implant prosthodontics	Early-stage	Early-stage evidence for AI-assisted CAD/CAM restoration design	Clinical validation and integration into routine prosthodontic workflows
Prediction models	Developing	Machine learning shows potential for predicting implant outcomes and complications	Prospective validation, explainable AI models, and real-world implementation

4. DISCUSSION

Artificial intelligence has rapidly evolved from an experimental technology into a clinically relevant tool in dentistry, particularly in implant dentistry, where accurate diagnosis, three-dimensional planning, and individualized treatment strategies are essential for predictable outcomes. The present review highlights that AI applications in implant dentistry extend beyond automated image interpretation and increasingly integrate radiographic analysis, anatomical segmentation, implant planning, surgical guidance, and digital workflow optimization. These findings are consistent with previous reports demonstrating that AI may improve diagnostic performance, workflow efficiency, and clinical decision support while simultaneously introducing challenges related to validation, transparency, and implementation into routine practice ^{1,2,18,20}.

Previous systematic reviews have primarily focused on AI performance in diagnostic imaging and implant-related radiographic assessment. Hung et al. reported that AI applications in implant dentistry demonstrated promising accuracy, particularly in image-based tasks such as implant detection, anatomical landmark identification, and risk assessment; however, they emphasized the limited availability of high-quality clinical validation studies ¹⁸. Similarly, Revilla-León et al. demonstrated that AI has substantial potential in implant dentistry but concluded that most available evidence remains based on retrospective datasets rather than prospective clinical outcomes ²⁰. In comparison, the current evidence landscape suggests a progressive shift from isolated diagnostic applications toward integrated AI-assisted workflows that combine imaging, digital planning, and personalized treatment strategies.

The role of AI in dental imaging represents one of the most mature areas of application. Deep learning algorithms, particularly convolutional neural networks (CNNs), have demonstrated high performance in detecting anatomical structures, pathological findings, and implant-related conditions on radiographic images ^{6,22}. Studies evaluating CBCT-based AI models have shown reliable performance in segmentation and three-dimensional reconstruction of anatomical structures, which are critical for implant placement planning ^{15,23}. These findings support the concept that AI may reduce operator-dependent variability and enhance precision during complex implant procedures. However, unlike traditional diagnostic studies, implant dentistry requires not only image recognition accuracy but also clinical relevance, surgical applicability, and measurable improvement in patient outcomes.

Recent investigations have expanded AI applications toward fully digital implant workflows. Wang et al. demonstrated that deep learning technologies could facilitate automated analysis of dental imaging data and improve integration between radiographic information and treatment planning [9]. Similarly, Ying et al. emphasized that AI-assisted workflows may influence multiple stages of implant prosthodontics, including diagnosis, prosthetic design, and treatment optimization ¹¹. These developments correspond with broader trends in digital implant dentistry, where intraoral scanning, computer-guided surgery, and virtual planning have become increasingly integrated into clinical practice ^{26,27}. Nevertheless, AI should currently be considered an assisting technology rather than a replacement for clinician expertise, as final treatment decisions remain dependent on biological considerations, patient preferences, and surgical judgment.

A major difference between early AI studies and contemporary applications is the movement from algorithm performance toward clinical integration. Earlier investigations predominantly evaluated whether AI systems could correctly identify structures or conditions, whereas newer research focuses on how AI can support personalized treatment planning and improve predictability. For example, three-dimensional reconstruction models and automated landmark detection systems have demonstrated potential for improving implant positioning and anatomical evaluation

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²⁵. However, similar to findings reported in other medical fields, technical accuracy does not necessarily translate into improved clinical outcomes without prospective validation and standardized implementation protocols ^{31,40}.

Despite encouraging developments, several challenges remain. One of the major limitations identified across the literature is the lack of external validation and standardized datasets. Many AI models are trained using single-center datasets, which may reduce generalizability across different populations, imaging devices, and clinical environments ^{10,41}. Furthermore, differences in CBCT acquisition parameters, image quality, annotation protocols, and algorithm architecture make direct comparison between studies difficult. Similar concerns have been reported in healthcare AI research, where reproducibility, transparency, and responsible implementation remain essential requirements for clinical adoption ^{39,44}.

The practical implementation of AI in implant dentistry involves a balance between technological advantages and current limitations. AI provides significant benefits in rapid image interpretation, personalized treatment planning, digital surgical workflows, and predictive decision support. However, barriers including limited external validation, lack of standardized protocols, economic considerations, technical complexity, and ethical concerns continue to restrict widespread clinical adoption. The major advantages and challenges associated with AI implementation across different clinical domains are summarized in Table 4.

Table 4. Advantages and Challenges of Artificial Intelligence Implementation in Implant Dentistry.

Aspect	Advantages	Current Challenges
Diagnosis	Rapid analysis of complex imaging data	Limited external validation
Treatment planning	Patient-specific planning support	Lack of standardized protocols
Surgery	Improved digital workflow integration	Cost and technical complexity
Prosthetic workflow	Automated design assistance	Limited clinical outcome studies
Decision support	Predictive analysis	Explainability and ethical issues

Another important consideration is explainability. Although deep learning models may achieve high predictive performance, their decision-making processes are often difficult to interpret. Explainable artificial intelligence (XAI) approaches have therefore gained increasing attention to improve clinician trust and facilitate safe clinical adoption ^{32,33}. In implant dentistry, where surgical decisions involve irreversible interventions and anatomical risks, transparent AI systems that provide understandable rationale for recommendations will likely be essential.

The economic and ethical aspects of AI implementation should also be considered. Although AI may reduce planning time and improve workflow efficiency, adoption requires investment in infrastructure, software validation, clinician training, and data security systems.

Previous healthcare analyses have emphasized that successful AI integration depends not only on technological performance but also on regulatory frameworks, interdisciplinary collaboration, and appropriate clinical governance ³⁶⁻³⁸.

Limitations

Several limitations should be acknowledged. First, despite the rapidly expanding literature on AI in implant dentistry, many available studies remain retrospective and heterogeneous, limiting direct comparison of reported outcomes. Differences in AI algorithms, imaging modalities, clinical indications, and evaluation metrics contribute to variability between studies.

Second, the majority of published investigations focus on technical performance parameters, such as accuracy, sensitivity, specificity, or segmentation quality, rather than clinically meaningful outcomes including implant survival, complication rates, patient satisfaction, or long-term functional results. Therefore, the current evidence supports the potential of AI but does not yet establish definitive superiority over conventional clinical workflows.

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Third, AI models are highly dependent on the quality and diversity of training datasets. Models developed from limited institutional datasets may demonstrate reduced performance when applied to different populations or imaging systems. Future research should prioritize multicenter datasets, standardized reporting frameworks, and prospective clinical validation.

Finally, ethical considerations related to patient data protection, algorithm transparency, responsibility for AI-assisted decisions, and regulatory approval remain important barriers to widespread clinical implementation.

Future Perspectives and Emerging Trends

The future development of AI in implant dentistry is expected to move toward fully integrated, intelligent digital ecosystems. Future AI platforms may combine CBCT imaging, intraoral scanning, facial analysis, clinical history, biological parameters, and patient-specific risk factors to generate comprehensive predictive models for implant treatment planning.

A major emerging direction is the development of multimodal AI systems capable of integrating different sources of clinical information rather than relying on isolated imaging data. Such systems may enable personalized implant strategies by predicting anatomical limitations, biological risks, and potential treatment outcomes.

Another important trend is the expansion of explainable and responsible AI. Future systems will likely incorporate XAI methodologies to provide clinicians with interpretable recommendations rather than purely automated decisions^{32,33}. This approach may improve clinician acceptance and facilitate regulatory approval.

Generative artificial intelligence and large language models may also contribute to future clinical workflows by assisting with treatment documentation, clinical decision support, patient communication, and evidence-based treatment recommendations. However, these applications require careful validation to ensure reliability and prevent inappropriate clinical recommendations.

Furthermore, integration between AI and robotic or computer-guided implant surgery may represent an important future direction. Combining AI-based planning with dynamic navigation and robotic assistance could potentially improve surgical precision, particularly in complex anatomical cases.

The expected clinical impact of these emerging technologies is summarized in Table 5.

Table 5. Future Directions of AI in Dental Implantology.

Future Development	Expected Clinical Impact
Multimodal AI systems (CBCT + intraoral scans + clinical data)	Comprehensive personalized implant planning
Explainable AI (XAI)	Increased clinician confidence and transparency
AI combined with 3D printing	Patient-specific surgical guides and implants
AI-assisted robotic surgery	Increased procedural precision
Predictive implant models	Early identification of complications
Digital twins in implant dentistry	Simulation-based treatment optimization

Overall, the future role of AI in implant dentistry is unlikely to involve replacement of clinicians; rather, AI will function as an advanced decision-support system that enhances human expertise and enables more predictable, personalized, and efficient treatment **Figure 5**.

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Future Directions of AI in Dental Implantology

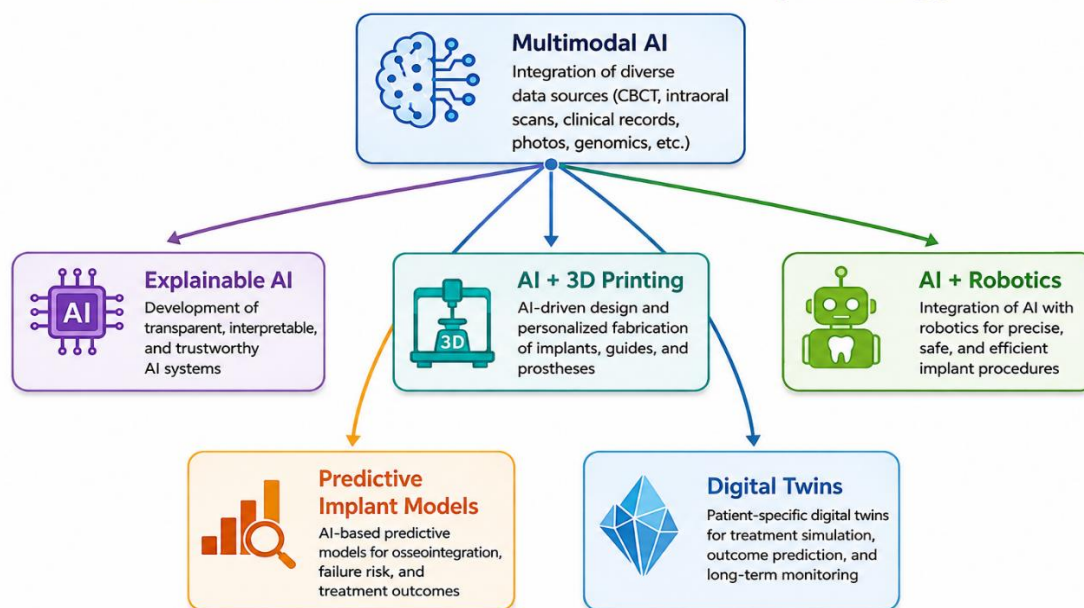


Figure 5. Future directions of AI in dental implantology, including multimodal AI, explainable AI, three-dimensional printing, robotic surgery, predictive models, and digital twins.

5. CONCLUSION

Artificial intelligence represents a transformative development in implant dentistry, with applications ranging from radiographic interpretation and anatomical segmentation to digital implant planning and personalized treatment optimization. Current evidence suggests that AI technologies may improve diagnostic performance, enhance workflow efficiency, and support clinical decision-making in selected implant-related applications.

However, the available evidence remains limited by methodological heterogeneity, insufficient prospective validation, and a lack of standardized clinical outcome assessment. Future research should focus on multicenter clinical studies, explainable AI approaches, integration of multimodal patient data, and evaluation of long-term treatment outcomes.

Rather than replacing clinical expertise, AI should be considered a complementary technology that enhances precision, predictability, and personalization in modern implant dentistry. With appropriate validation and responsible implementation, AI has the potential to become an integral component of future digital implant workflows.

DECLARATIONS

Ethical Approval

Not applicable.

Competing Interests

The authors declare no conflict of interest.

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REVIEW ARTICLE

ORAL MANIFESTATIONS OF FAMILIAL MEDITERRANEAN FEVER: A NARRATIVE REVIEW

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ABSTRACT

Background: Familial Mediterranean fever (FMF) is the most common inherited autoinflammatory disorder characterized by recurrent episodes of fever and systemic inflammation caused primarily by pathogenic variants in the *MEFV* gene encoding the pyrin protein. Although FMF predominantly affects serosal membranes, joints, and skin, increasing evidence suggests that chronic inflammatory activation may also influence oral tissues and contribute to a variety of oral manifestations. Recognition of these findings is clinically relevant because oral lesions may represent early or accompanying manifestations of systemic inflammatory activity and may overlap with other inflammatory and autoimmune disorders.

Objective: This narrative review aimed to summarize the current evidence regarding oral manifestations associated with familial Mediterranean fever, including mucosal lesions, periodontal alterations, temporomandibular joint involvement, oral manifestations related to systemic complications, and treatment-associated oral findings.

Methods: A narrative literature review was performed using available publications from major biomedical databases, including PubMed/MEDLINE, Scopus, and Web of Science. Relevant studies describing oral manifestations, inflammatory mechanisms, clinical characteristics, and dental considerations in patients with FMF were analyzed. Due to the limited and heterogeneous nature of available evidence, including case reports, observational studies, and clinical reviews, a narrative synthesis approach was applied.

Results: The available literature indicates that recurrent oral ulcerations, particularly aphthous-like lesions, represent the most frequently reported oral finding in patients with FMF. These lesions may occur independently or during periods of increased inflammatory activity and may create diagnostic challenges due to clinical similarity with Behçet disease and other immune-mediated disorders. Additional reported findings include gingival inflammatory changes, altered periodontal responses, temporomandibular joint symptoms associated with inflammatory arthritis, and oral manifestations related to systemic complications such as AA amyloidosis. Long-term colchicine therapy may influence oral health indirectly through modulation of inflammatory activity; however, specific oral adverse effects in FMF patients remain insufficiently investigated.

Conclusions: Although oral manifestations are not considered primary diagnostic criteria for familial Mediterranean fever, they represent clinically relevant findings that may reflect systemic inflammatory activity and influence patient quality of life. Dentists and oral healthcare professionals should be aware of the potential oral presentations of FMF to facilitate early recognition, appropriate differential diagnosis, and multidisciplinary patient management. Further prospective studies are required to better define the prevalence, clinical significance, and biological mechanisms underlying oral involvement in FMF.

Keywords: Familial Mediterranean fever; FMF; oral manifestations; aphthous ulcers; autoinflammatory disease; *MEFV* gene; periodontal inflammation; colchicine.

1. INTRODUCTION

Familial Mediterranean fever (FMF) is the most

prevalent monogenic autoinflammatory disease and represents a prototypical disorder of innate immune dysregulation. It is characterized by recurrent, self-

limited inflammatory attacks accompanied by fever, serosal inflammation, arthritis, and cutaneous manifestations. The disease predominantly affects populations originating from the Mediterranean basin, including Armenians, Turks, Arabs, etc.; however, with increased migration and improved genetic recognition, FMF has been identified worldwide. Although the clinical spectrum of FMF is primarily associated with systemic manifestations, emerging evidence suggests that chronic inflammatory activation may influence multiple tissues, including oral and maxillofacial structures; however, the extent and clinical significance of oral involvement remain incompletely characterized.¹⁻³

Historically, FMF was described as a familial condition characterized by recurrent episodes of fever and abdominal pain, but advances in molecular genetics and immunology have significantly expanded the understanding of its pathogenesis. FMF is currently classified among hereditary autoinflammatory disorders, which are distinguished from autoimmune diseases by predominant involvement of innate immune pathways rather than antigen-specific adaptive immune responses. The central pathological mechanism involves dysregulation of inflammasome-mediated inflammation, resulting in excessive production of pro-inflammatory cytokines, particularly interleukin-1 β (IL-1 β), and uncontrolled activation of neutrophil-dependent inflammatory pathways.^{4,5}

The genetic basis of FMF is strongly associated with pathogenic variants in the MEFV gene, located on chromosome 16p13.3. The MEFV gene encodes pyrin, a 781-amino-acid protein expressed mainly in innate immune cells, particularly neutrophils, monocytes, and macrophages. Pyrin functions as a critical regulator of inflammatory signaling by controlling assembly and activation of the pyrin inflammasome. Under physiological conditions, pyrin participates in mechanisms that limit inappropriate inflammatory activation. However, disease-associated mutations may impair this regulatory function, resulting in abnormal inflammasome activation and excessive inflammatory responses.^{6,7}

More than 300 variants of the MEFV gene have been described; however, only a subset has been clearly associated with FMF susceptibility and disease severity. The most frequently reported pathogenic variants include M694V, M680I, M694I, and V726A, which are primarily located within exon 10 encoding the B30.2/SPRY domain of pyrin. The M694V variant is considered one of the most clinically significant mutations and has been associated with

earlier disease onset, more severe inflammatory attacks, and increased risk of AA amyloidosis. However, genotype-phenotype correlations remain complex, as clinical expression is influenced by additional genetic modifiers, environmental factors, epigenetic mechanisms, and variations in inflammatory regulation.⁸⁻¹⁰

The pathogenesis of FMF involves abnormal regulation of the inflammasome pathway, a molecular platform responsible for activation of inflammatory caspases and maturation of IL-1 β . In healthy individuals, pyrin activation is tightly controlled through phosphorylation-dependent mechanisms involving regulatory proteins such as 14-3-3. Mutations affecting pyrin function reduce this inhibitory regulation and promote spontaneous inflammasome assembly. The resulting activation of caspase-1 leads to increased conversion of pro-IL-1 β into biologically active IL-1 β , which stimulates recruitment and activation of neutrophils and amplifies inflammatory responses.^{11,12}

IL-1 β represents a central mediator in FMF pathogenesis and contributes to many clinical manifestations of the disease. Increased IL-1 signaling promotes endothelial activation, leukocyte recruitment, vascular permeability, and tissue inflammation. These mechanisms explain the episodic inflammatory attacks affecting serosal membranes, synovial tissues, and skin. Furthermore, persistent subclinical inflammation between attacks may contribute to long-term complications, particularly AA amyloid deposition resulting from chronic elevation of serum amyloid A protein.^{13,14}

The clinical phenotype of FMF is highly variable. Typical attacks usually develop during childhood or adolescence and are characterized by episodes of fever lasting 12–72 hours, accompanied by sterile inflammation of the peritoneum, pleura, or synovial membranes. Abdominal attacks resembling acute surgical conditions are among the most common manifestations, while recurrent monoarthritis and erysipelas-like erythema represent other characteristic features. The severity and frequency of attacks vary considerably between patients, even among individuals carrying identical genetic variants, emphasizing the contribution of additional modifying factors.^{1,3,15}

The oral cavity has increasingly been recognized as a potential site influenced by systemic inflammatory disorders. Oral tissues represent an immunologically active environment where epithelial barriers, resident immune cells, microbiota, and connective tissues continuously interact. Since FMF is characterized by excessive innate immune activation and neutrophil-driven inflammation, theoretical mechanisms exist through which systemic inflammatory dysregulation may

influence oral mucosal integrity, periodontal tissues, and healing responses. However, direct clinical evidence linking FMF with specific oral changes remains limited.^{16,17}

Among reported oral findings in patients with FMF, recurrent oral ulcerations represent the most frequently described manifestation. These lesions may resemble recurrent aphthous stomatitis and may create diagnostic challenges, particularly because oral aphthous lesions are also common in Behçet disease, another inflammatory disorder prevalent in Mediterranean populations. Differentiating FMF-associated oral findings from Behçet-related manifestations is clinically important, as the two conditions differ in systemic involvement, diagnostic criteria, and therapeutic strategies.^{18–20}

The relationship between FMF and periodontal tissues remains an emerging area of investigation. Periodontal tissues are highly responsive to systemic inflammatory mediators, and increased circulating levels of IL-1 β , tumor necrosis factor- α (TNF- α), and other cytokines may influence periodontal immune responses. Although definitive evidence establishing FMF as an independent risk factor for periodontal disease is lacking, the biological plausibility of interaction between FMF-associated inflammation and periodontal homeostasis has stimulated further research.^{21,22}

Another important aspect of FMF relevant to oral health is the development of systemic complications. Chronic uncontrolled inflammation may lead to AA amyloidosis, which can occasionally involve oral and maxillofacial tissues. Amyloid deposition may result in soft tissue enlargement, tongue involvement, altered mucosal characteristics, and functional disturbances. Although these findings are uncommon, they represent clinically relevant manifestations requiring recognition.²³

The management of FMF has been revolutionized by colchicine therapy, which remains the cornerstone of disease prevention. Colchicine reduces inflammatory attacks and prevents amyloid deposition by inhibiting microtubule polymerization and neutrophil-mediated inflammatory activity. More recently, biologic therapies targeting IL-1 pathways, including anakinra and canakinumab, have provided therapeutic options for patients with colchicine-resistant or colchicine-intolerant disease.^{24–26}

From a dental perspective, awareness of FMF-associated oral findings is important because oral lesions may accompany systemic inflammatory activity or complicate differential diagnosis with

other immune-mediated conditions. Dentists and oral healthcare professionals may encounter patients presenting with recurrent unexplained oral ulcers, inflammatory oral changes, or unusual healing patterns and should consider systemic inflammatory disorders within the diagnostic process when appropriate.^{18,27}

Despite increasing knowledge regarding the molecular mechanisms of FMF, oral findings remain insufficiently characterized. Current evidence is limited by the predominance of case reports, small clinical series, and heterogeneous diagnostic approaches. The prevalence, pathophysiological mechanisms, and clinical significance of oral involvement in FMF remain incompletely defined.^{18,27}

This narrative review aims to provide a comprehensive overview of reported oral findings associated with familial Mediterranean fever, integrating current knowledge regarding genetic mechanisms, immunopathogenesis, clinical presentation, diagnostic considerations, and future perspectives. A better understanding of these findings may contribute to earlier recognition of systemic disease, improved interdisciplinary collaboration, and more comprehensive patient management.

2. MATERIALS AND METHODS

2.1 Literature Search Strategy

A narrative literature review was conducted to evaluate the available scientific evidence regarding reported oral findings associated with familial Mediterranean fever (FMF), with particular emphasis on clinical characteristics, genetic background, molecular mechanisms, inflammatory pathways, and implications for oral healthcare. The methodology was designed to provide a comprehensive interpretation of the available literature while considering the heterogeneous and predominantly descriptive nature of evidence related to oral involvement in this rare autoinflammatory disorder.

A structured literature search was performed in the electronic databases PubMed/MEDLINE, Scopus, and Web of Science. Publications available from database inception until 2026 were considered. The search strategy was developed using a combination of controlled vocabulary terms (including MeSH terms where applicable) and free-text keywords related to familial Mediterranean fever, genetic mechanisms, inflammation, and oral findings.

The following search terms and their combinations were used:

“familial Mediterranean fever”,
“FMF”,
“MEFV gene”,
“MEFV mutation”,
“pyrin”,
“pyrin inflammasome”,
“autoinflammatory disease”,
“innate immunity”,
“interleukin-1 β ”,
“IL-1 β ”,
“oral manifestations”,
“oral findings”,
“oral involvement”,
“oral ulceration”,
“aphthous ulcers”,
“recurrent oral ulcers”,
“periodontal inflammation”,
“oral mucosa”,
“temporomandibular joint”,
“colchicine therapy”.

Boolean operators (AND, OR) were applied to combine search terms and improve identification of relevant publications. Additional studies were identified through manual screening of reference lists from relevant articles to ensure inclusion of important publications not retrieved through the primary database search.

2.2 Study Selection and Data Synthesis

The initial literature search identified 73 potentially relevant publications from the selected electronic databases. Retrieved records were evaluated according to their relevance to the objectives of the present narrative review. The selection process included assessment of article titles, abstracts, and, when necessary, full-text evaluation to determine whether publications provided clinically or biologically meaningful information regarding FMF and its reported oral findings.

Publications were considered eligible when they addressed one or more of the following aspects: genetic mechanisms associated with FMF, particularly MEFV gene variants and pyrin-mediated inflammatory regulation; molecular mechanisms involved in inflammasome activation and IL-1 β -mediated inflammation; clinical characteristics of FMF; reported oral and maxillofacial findings; differential diagnostic considerations involving oral lesions; systemic complications with possible oral implications; and therapeutic approaches relevant to disease control.

Studies were excluded when they lacked direct relevance to FMF, did not provide sufficient

information regarding disease mechanisms or oral findings, represented duplicate publications, or focused exclusively on unrelated autoimmune or autoinflammatory disorders. Publications without accessible full-text information or without clinically meaningful data were also excluded.

Following qualitative assessment of the available literature, 31 articles were selected for the final narrative synthesis. The included publications represented a heterogeneous range of evidence, including clinical studies, case reports, observational investigations, molecular genetic studies, and review articles. Due to the limited number of studies specifically addressing oral findings in FMF and the substantial variability in study designs, patient populations, and reported outcomes, quantitative statistical analysis was not performed.

The extracted information was analyzed using a descriptive narrative approach. The available evidence was organized into the following major thematic domains:

- genetic basis and molecular mechanisms of familial Mediterranean fever;
- role of MEFV mutations and pyrin inflammasome activation;
- inflammatory pathways contributing to systemic disease manifestations;
- reported oral and maxillofacial findings;
- possible mechanisms linking systemic inflammation with oral tissue responses;
- differential diagnosis of oral lesions associated with FMF;
- clinical considerations for dental practitioners and multidisciplinary management.

2.3 Eligibility Criteria

Inclusion Criteria

Articles were included if they met the following criteria:

- studies involving patients with clinically or genetically confirmed familial Mediterranean fever;
- publications describing reported oral findings or oral-related clinical observations in FMF patients;
- studies investigating the genetic and molecular basis of FMF, including MEFV gene variants and inflammatory mechanisms;
- publications addressing clinical characteristics, diagnosis, treatment, or systemic complications relevant to oral healthcare;
- peer-reviewed articles published in English;
- clinical studies, observational studies, case reports, molecular investigations, and relevant review articles.

Exclusion Criteria

Articles were excluded if they:

- focused on inflammatory diseases unrelated to FMF;
- investigated general oral ulcerative disorders without an association with FMF;
- lacked information regarding clinical characteristics, genetic mechanisms, or inflammatory pathways relevant to FMF;
- were conference abstracts, unpublished materials, or non-peer-reviewed sources;
- represented duplicated or overlapping reports.

2.4 Data Extraction and Analysis

Relevant information from the included publications was extracted and organized according to predefined categories. Extracted variables included:

- first author and year of publication;
- country and population characteristics;
- study design;
- genetic findings, including reported MEFV mutations;
- molecular mechanisms and inflammatory pathways investigated;
- reported oral findings;
- associated systemic manifestations;
- treatment approaches and potential clinical implications.

Because the available evidence demonstrated substantial heterogeneity in study methodology and outcome reporting, data were synthesized qualitatively rather than quantitatively. The narrative synthesis focused on identifying recurring patterns, clinically relevant observations, possible biological mechanisms, and current limitations in understanding oral involvement in FMF.

2.5 Methodological Considerations

This review was conducted as a narrative review due to the rarity of reported oral findings associated with FMF and the predominance of descriptive evidence. Unlike systematic reviews designed to provide quantitative estimates or evaluate comparative treatment effects, narrative reviews allow integration of diverse evidence sources, including clinical observations, genetic investigations, and mechanistic studies. The selected methodology enabled a broader interpretation of the relationship between FMF-

related inflammatory dysregulation and oral health while identifying areas requiring further investigation. Future prospective studies using standardized oral examination protocols, inflammatory biomarker assessment, and genetically characterized FMF cohorts are necessary to clarify the prevalence, clinical significance, and biological mechanisms underlying oral findings in patients with familial Mediterranean fever.

3 RESULTS

3.1 Overview of the Included Literature

The initial literature search identified 73 potentially relevant publications addressing different aspects of familial Mediterranean fever (FMF), including genetic mechanisms, inflammatory pathways, clinical characteristics, systemic complications, and possible oral involvement. All retrieved records were assessed according to their relevance to the objectives of the present narrative review. Following evaluation of titles, abstracts, and available full-text publications, studies lacking clinically or biologically relevant information regarding FMF or its potential oral manifestations were excluded.

After qualitative assessment of the available evidence, 31 articles were included in the final narrative synthesis. The included publications represented a heterogeneous body of evidence comprising clinical studies, case reports, observational investigations, molecular genetic studies, and review articles. The majority of available literature focused on the genetic basis, immunopathogenesis, and systemic manifestations of FMF, whereas a smaller proportion specifically addressed oral and maxillofacial findings.

The available evidence indicates that oral manifestations are not established diagnostic criteria or classical features of FMF. However, several reports have described oral findings occurring in patients with FMF, suggesting that oral involvement may represent an additional clinical observation associated with systemic inflammatory activity. Among the reported oral findings, recurrent oral ulcerations and aphthous-like lesions were the most frequently described. Other less consistently reported manifestations included inflammatory mucosal changes, periodontal alterations, temporomandibular joint symptoms, and oral manifestations associated with systemic complications such as AA amyloidosis.^{18,19,21,23}

The reviewed literature also highlighted the complexity of genotype–phenotype relationships in FMF. Although specific *MEFV* variants, particularly exon 10 mutations such as M694V, have been associated with increased disease severity, earlier onset, and higher inflammatory burden, clinical expression remains influenced by

multiple genetic, environmental, and immunological factors. The main genetic and immunological mechanisms associated with FMF pathogenesis are summarized in Table 1. Whether these factors directly influence the development or severity of oral manifestations remains unclear.^{3,8-10}

Table 1. General Characteristics of Included Publications (n = 31)

Characteristic	Findings
Initial records identified	73
Articles included in final narrative synthesis	31
Publication types	Clinical studies, case reports, observational studies, molecular genetic studies, review articles
Main investigated topics	Genetic mechanisms, inflammatory pathways, oral manifestations, systemic complications, treatment considerations
Disease investigated	Familial Mediterranean fever (FMF)
Main genetic focus	MEFV gene variants and pyrin protein dysfunction
Main inflammatory mechanism	Pyrin inflammasome activation and IL-1β-mediated inflammation
Most frequently reported oral findings	Recurrent oral ulcerations, aphthous-like lesions, mucosal inflammatory changes
Overall evidence characteristics	Heterogeneous, predominantly descriptive clinical evidence

3.2 Genetic and Molecular Characteristics of Familial Mediterranean Fever

The included literature consistently identified FMF as a hereditary autoinflammatory disorder primarily associated with pathogenic variants in the MEFV gene located on chromosome 16p13.3. The MEFV gene encodes pyrin, an intracellular protein that plays a central role in regulating innate immune responses through modulation of inflammasome activation.^{6,7}

The reviewed studies demonstrated that pathogenic alterations affecting pyrin function may result in dysregulated activation of the pyrin inflammasome, leading to increased caspase-1 activity and enhanced processing of pro-interleukin-1β (pro-IL-1β) into biologically active IL-1β. This inflammatory cascade promotes neutrophil recruitment and contributes to the recurrent inflammatory episodes characteristic of FMF.^{1,12,28,29}

Among the reported MEFV variants, M694V, M680I, M694I, and V726A are among the most frequently described pathogenic mutations. Several studies have associated the M694V variant with a more severe clinical phenotype, earlier disease onset, increased frequency of inflammatory attacks, and a higher risk of AA amyloidosis. Nevertheless, genotype alone does not completely determine clinical expression, and

disease severity is influenced by additional modifying genetic and environmental factors.^{3,8-10}

The relevance of FMF-related inflammatory mechanisms to oral tissues remains hypothetical but biologically plausible. IL-1β signaling and neutrophil-mediated inflammatory responses, which play central roles in FMF pathogenesis, are also involved in mucosal immune regulation, periodontal inflammatory processes, and tissue repair mechanisms. However, direct evidence linking specific MEFV mutations with oral manifestations remains insufficient.^{13,14,16}

Among the reported MEFV variants, M694V, M680I, M694I, and V726A are among the most frequently described pathogenic mutations. Several studies have associated the M694V variant with a more severe clinical phenotype, earlier disease onset, increased frequency of inflammatory attacks, and a higher risk of AA amyloidosis. Nevertheless, genotype alone does not completely determine clinical expression, and disease severity is influenced by additional modifying genetic, epigenetic, environmental, and immunological factors.^{3,8-10}

The main genetic and immunological characteristics reported in patients with FMF are summarized in Table 2.

Table 2. Genetic and Immunological Findings Reported in Included Studies

Parameter	Findings
Disease category	Monogenic autoinflammatory disorder
Main genetic alteration	Pathogenic variants of the MEFV gene
Chromosomal location	16p13.3
Encoded protein	Pyrin
Primary molecular abnormality	Dysregulated pyrin inflammasome activation
Major cytokine involved	Interleukin-1β (IL-1β)
Main inflammatory cells involved	Neutrophils, monocytes, and macrophages
Frequently reported mutations	M694V, M680I, M694I, V726A
Genotype–phenotype association	M694V is frequently associated with increased disease severity, earlier onset, and higher inflammatory burden
Major systemic complication	AA amyloidosis
Clinical implication	Variable genotype–phenotype expression influenced by genetic, environmental, and immunological modifiers

The relevance of FMF-related inflammatory mechanisms to oral tissues remains hypothetical but biologically plausible. IL-1β signaling and neutrophil-mediated inflammatory responses, which play central roles in FMF pathogenesis, are also involved in mucosal immune regulation, periodontal inflammatory processes, and tissue repair mechanisms. However, direct evidence linking specific *MEFV* mutations with oral manifestations remains insufficient.^{13,14,16}

3.3 Oral Manifestations Associated with Familial Mediterranean Fever

The reviewed literature indicates that oral manifestations have been reported in patients with familial Mediterranean fever (FMF); however, compared with the well-established systemic features of the disease, oral involvement remains insufficiently characterized. Available evidence is derived mainly from clinical observations, case reports, and limited observational studies, making accurate estimation of prevalence and determination of clinical significance challenging. Among the reported oral findings, recurrent oral ulcerations and aphthous-like lesions represent the most frequently described manifestations.^{18,19}

Reported oral ulcerations were generally described as painful, recurrent lesions resembling recurrent aphthous stomatitis and involving predominantly non-keratinized mucosal surfaces, including the labial mucosa, buccal mucosa, tongue, and soft palate. In

some reports, oral lesions appeared during periods of increased inflammatory activity; however, a consistent association between the presence of oral ulcers and the severity or frequency of systemic FMF attacks has not been established.^{18,19}

A major diagnostic consideration is the clinical similarity between FMF-associated oral ulcers and oral manifestations observed in Behçet disease. This overlap is particularly important in populations with a high prevalence of FMF, including Mediterranean populations. Therefore, recurrent oral ulcerations in patients with suspected FMF should not be interpreted as an isolated diagnostic finding but should be evaluated together with systemic manifestations, family history, genetic findings, and other clinical criteria.^{19,20}

Beyond mucosal lesions, limited reports have described possible periodontal and maxillofacial involvement in patients with FMF. Although periodontal disease is not recognized as a primary manifestation of FMF, systemic inflammatory activation may theoretically influence periodontal immune responses through shared inflammatory pathways involving IL-1β, TNF-α, and neutrophil-mediated mechanisms. Nevertheless, current evidence remains insufficient to establish FMF as an independent risk factor for periodontal disease.^{16,17,21,22}

The main oral manifestations reported in FMF patients and their proposed biological mechanisms are summarized in Table 3.

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Table 3. Oral Manifestations Reported in Patients with FMF

Oral manifestation	Clinical characteristics	Possible pathogenic mechanism
Recurrent oral ulcerations	Painful aphthous-like lesions with episodic recurrence, mainly affecting non-keratinized mucosal surfaces	IL-1 β -mediated inflammatory activation and neutrophil-mediated immune responses [18,19]
Oral mucosal inflammation	Erythema, mucosal sensitivity, and inflammatory changes	Systemic inflammatory activation associated with FMF episodes [18]
Aphthous-like lesions	Recurrent ulcerative lesions involving labial mucosa, buccal mucosa, tongue, and soft palate	Altered mucosal immune regulation and inflammatory susceptibility [18–20]
Gingival inflammatory changes	Increased gingival inflammatory response and possible enhanced susceptibility to inflammation	Cytokine-mediated immune dysregulation involving IL-1 β and TNF- α pathways [13,14]
Periodontal alterations	Limited clinical observations suggesting possible inflammatory periodontal changes	Interaction between systemic inflammatory pathways and periodontal immune responses [16,17,21,22]
Temporomandibular symptoms	Rare inflammatory joint manifestations associated with FMF-related arthritis	FMF-associated inflammatory arthritis affecting the temporomandibular joint region [1,15]
Amyloidosis-related oral changes	Possible soft tissue enlargement or altered tissue consistency in advanced disease	AA amyloid deposition associated with chronic uncontrolled inflammation [23]

Summary of oral manifestations reported in patients with familial Mediterranean fever (FMF), including clinical characteristics and proposed inflammatory mechanisms. Current evidence suggests that recurrent oral ulcerations are the most frequently described oral finding; however, the prevalence, pathogenesis, and direct relationship with *MEFV* mutations or systemic disease activity remain insufficiently established.

3.4 Recurrent Oral Ulcerations and Diagnostic Considerations

Recurrent oral ulcerations represent the most consistently reported oral finding among patients with FMF. Although these lesions are not specific for FMF, their presence in individuals with recurrent fever episodes, serositis, arthritis, or a positive family history may provide additional clinical information supporting

evaluation for an underlying autoinflammatory disorder.^{18,19}

The reviewed evidence emphasizes the importance of distinguishing FMF-associated oral lesions from other inflammatory and immune-mediated conditions, particularly Behçet disease. Both disorders may present with recurrent oral ulcerations; however, their underlying pathogenic mechanisms and associated systemic manifestations differ substantially.²⁰ In FMF, oral manifestations are considered potentially related to dysregulated innate immune activation and IL-1 β -driven inflammatory pathways. In contrast, Behçet disease represents a complex inflammatory vasculitic disorder involving both innate and adaptive immune mechanisms, with oral ulcerations forming one of its major diagnostic features.

Therefore, differential diagnosis requires comprehensive assessment of clinical presentation, genetic background, systemic manifestations, and laboratory findings rather than evaluation of oral lesions alone.^{11,12,20}

The main clinical differences between FMF-associated oral ulcerations and other ulcerative disorders are summarized in Table 4.

Table 4. Clinical differences between FMF-associated oral ulcerations and other ulcerative disorder

Feature	FMF	Behçet Disease	Recurrent Aphthous Stomatitis
Main mechanism	Autoinflammatory process mediated predominantly by IL-1β and innate immune dysregulation [11,12]	Systemic inflammatory vasculitis involving innate and adaptive immune pathways [20]	Localized mucosal immune reaction with multifactorial etiology [27]
Genetic association	Pathogenic MEFV variants, particularly exon 10 mutations [6–10]	Association with HLA-B51 and other immune-related genetic factors [20]	Multifactorial genetic susceptibility [27]
Oral ulcers	Reported with variable frequency; usually aphthous-like and recurrent [18,19]	Frequent, recurrent, and often a major clinical manifestation [20]	Common recurrent oral ulcerations without systemic disease [27]
Typical systemic findings	Recurrent fever attacks, serositis, arthritis, and inflammatory episodes [1,15]	Ocular involvement, genital ulcers, vascular manifestations, and systemic inflammation [20]	Usually absent or limited to oral mucosal involvement [27]
Diagnostic role of oral lesions	Supportive clinical finding; not considered a diagnostic criterion for FMF [18,19]	Major diagnostic component and characteristic clinical feature [20]	Represents the primary clinical manifestation [27]

Comparison of recurrent oral ulcerative manifestations observed in familial Mediterranean fever (FMF), Behçet disease, and recurrent aphthous stomatitis. The table highlights differences in underlying inflammatory mechanisms, genetic associations, systemic manifestations, and the diagnostic significance of oral lesions. Although oral ulcerations may occur in FMF, they lack specificity and should be interpreted within the broader clinical and genetic context.

3.5 Periodontal and Maxillofacial Findings

The relationship between FMF and periodontal tissues remains an emerging field with limited available evidence. Theoretically, chronic inflammatory activation associated with FMF may influence periodontal homeostasis through shared inflammatory mediators, including IL-1β, TNF-α, and other

cytokines involved in immune regulation, tissue destruction, and repair processes.^{16,17,21,22}

However, current evidence does not support considering periodontal disease as a direct manifestation of FMF. Reported periodontal alterations may reflect increased inflammatory susceptibility in genetically predisposed individuals rather than a specific FMF-associated periodontal phenotype. Future investigations involving genetically confirmed FMF cohorts, comprehensive periodontal examinations, and standardized inflammatory assessments are required to clarify this potential association.^{21,22}

Temporomandibular joint involvement has been rarely described in patients with FMF. When present, it may represent part of the broader musculoskeletal inflammatory manifestations of the disease rather than

a specific oral complication. Clinical findings may include joint pain, restricted mandibular movement, and symptoms associated with inflammatory arthritis.
1,15

3.6 Treatment-Related Oral Considerations

The reviewed literature confirms colchicine as the cornerstone therapy for FMF, with established efficacy in reducing inflammatory attacks and preventing AA amyloidosis. Colchicine acts primarily through inhibition of microtubule polymerization and suppression of neutrophil-mediated inflammatory

activity. However, its specific effects on FMF-associated oral manifestations have not been systematically investigated.²⁴

Patients with colchicine-resistant or colchicine-intolerant FMF may receive targeted biological therapies, particularly IL-1 inhibitors such as anakinra and canakinumab. These agents effectively reduce systemic inflammatory activity; however, their influence on oral manifestations, mucosal lesions, and periodontal inflammatory responses remains insufficiently studied.²⁵⁻²⁷

Potential therapeutic approaches and their possible oral implications are summarized in Table 5.

Table 5. Therapeutic Approaches in FMF and Potential Oral Implications

Treatment	Mechanism of action	Possible oral relevance
Colchicine	Inhibition of microtubule polymerization and suppression of neutrophil-mediated inflammatory activity	Reduction of systemic inflammatory activity and attack frequency; possible indirect improvement of inflammation-associated oral manifestations [24]
Anakinra	IL-1 receptor blockade leading to inhibition of IL-1-mediated inflammatory signaling	Potential reduction of IL-1-driven inflammatory responses affecting systemic and possibly oral tissues [25,27]
Canakinumab	Selective neutralization of IL-1β	Suppression of systemic inflammatory activation; potential influence on inflammation-related oral manifestations requires further investigation [26,27]
Dental supportive management	Symptomatic oral care, preventive dental therapy, and management of oral discomfort	Improvement of oral health status, patient comfort, and quality of life; supportive role in patients with recurrent oral lesions

Therapeutic strategies used in FMF and their potential implications for oral health. While colchicine and IL-1-targeted biological therapies effectively control systemic inflammation, their direct effects on FMF-associated oral manifestations remain insufficiently characterized. Supportive dental management remains important for maintaining oral health and improving patient quality of life.

3.7 Summary of Main Findings

The synthesis of available evidence indicates that oral findings may represent an underrecognized aspect of

FMF; however, their role within the overall disease phenotype remains incompletely defined. Oral manifestations are not included among the established diagnostic criteria of FMF, and current evidence is insufficient to determine their prevalence or prognostic significance.^{18,19}

Among the reported oral findings, recurrent oral ulcerations and aphthous-like lesions represent the most frequently described manifestations. These findings may occur in association with systemic inflammatory activity, although a direct causal relationship has not been conclusively demonstrated.

The available literature suggests that potential oral involvement may be biologically plausible due to the central role of pyrin inflammasome dysregulation, IL-1 β signaling, and neutrophil-mediated inflammation in

FMF pathogenesis. Nevertheless, the limited number of dedicated oral studies and the predominance of descriptive evidence prevent definitive conclusions regarding mechanisms, frequency, and clinical relevance.^{11–14,18,21,22}

Future prospective investigations involving standardized oral examinations, inflammatory biomarker analysis, and genetically characterized FMF

cohorts are required to clarify whether oral manifestations represent independent clinical features, indicators of systemic inflammatory activity, or secondary consequences of chronic inflammation. The figure 1 summarizes the potential oral manifestations reported in FMF, including recurrent aphthous-like ulcerations, possible periodontal inflammatory changes, temporomandibular joint involvement, treatment-related considerations, and oral implications of systemic complications. The central panel illustrates FMF as a monogenic autoinflammatory disorder driven by *MEFV* mutations, pyrin inflammasome dysregulation, IL-1 β activation, and systemic inflammatory responses. Current evidence suggests biological plausibility of oral involvement; however, the frequency, mechanisms, and clinical significance of oral manifestations remain insufficiently established.

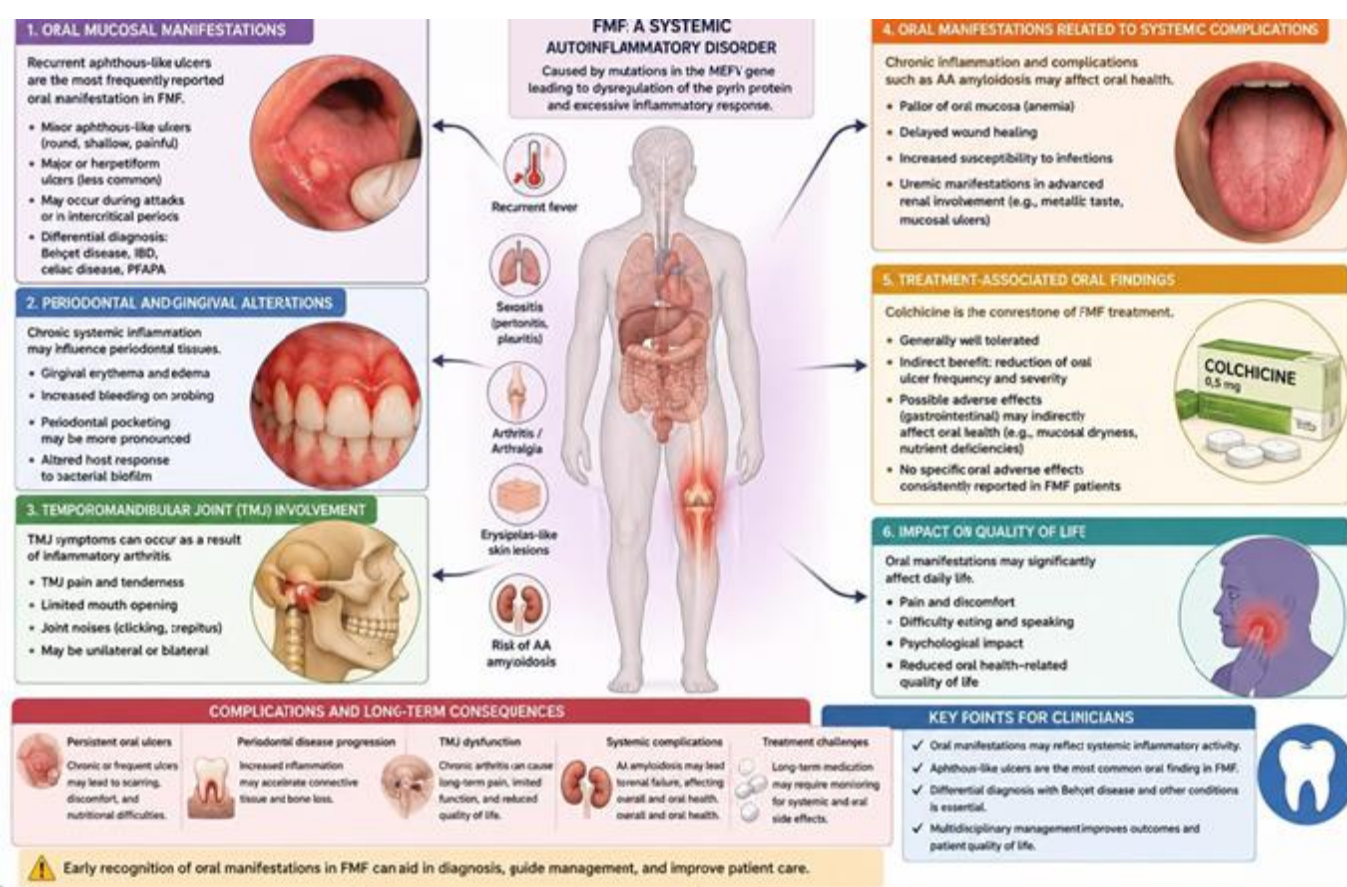


Figure 1. Oral manifestations and complications associated with FMF

4 DISCUSSION

The present narrative review synthesized the available evidence regarding oral manifestations associated with FMF, with particular emphasis on the relationship between genetic abnormalities, innate immune dysregulation, and potential oral and

maxillofacial involvement. Although FMF is primarily recognized as a systemic autoinflammatory disorder characterized by recurrent fever episodes, serosal inflammation, arthritis, and the risk of AA amyloidosis, the reviewed literature indicates that oral manifestations may represent an additional, although incompletely defined, component of the disease spectrum. The current

evidence remains limited; however, the reported findings suggest that oral involvement may reflect the broader inflammatory phenotype of FMF rather than a distinct primary oral manifestation of the disease.^{1-5,18,19} The biological plausibility of oral involvement in FMF is supported by the central role of pyrin inflammasome dysregulation and excessive IL-1 β -mediated inflammation in disease pathogenesis. Pathogenic variants of the MEFV gene result in impaired regulation of pyrin activity, leading to uncontrolled inflammasome activation, increased caspase-1 activity, and enhanced production of IL-1 β . This inflammatory pathway promotes neutrophil recruitment and persistent activation of innate immune responses. Because oral mucosal tissues and periodontal structures are continuously influenced by immune-mediated inflammatory processes, systemic abnormalities in innate immunity may theoretically contribute to altered oral tissue responses in genetically susceptible individuals. However, the currently available clinical evidence does not allow definitive conclusions regarding the extent or clinical importance of this association. Among the oral manifestations reported in FMF patients, recurrent oral ulcerations represent the most frequently described finding. These lesions are generally characterized as painful, aphthous-like ulcers affecting non-keratinized mucosal surfaces. Nevertheless, their prevalence, recurrence pattern, and relationship with systemic inflammatory attacks remain insufficiently established. Unlike Behçet disease, in which recurrent oral ulcerations represent a major diagnostic component, oral ulcers are not included among the diagnostic criteria for FMF. Therefore, their presence should be interpreted as a possible supportive clinical feature rather than a specific diagnostic marker.^{18,19} The differential diagnosis between FMF-associated oral ulcerations and Behçet disease represents an important clinical challenge, particularly in Mediterranean populations where both conditions are relatively prevalent. Although both disorders may present with recurrent oral lesions, their immunological mechanisms differ considerably. FMF is primarily characterized by dysregulated innate immunity involving pyrin inflammasome activation and IL-1 β overproduction, whereas Behçet disease involves a complex inflammatory process with vasculitic features and interaction between innate and adaptive immune pathways. Consequently, evaluation of recurrent oral ulcers in suspected FMF patients should include comprehensive assessment of systemic manifestations, family history, genetic findings, and other clinical characteristics rather than relying solely on oral findings.^{11,12,20} The relationship between FMF and periodontal health remains one of the least explored areas. The available literature suggests a

possible interaction between systemic inflammatory activity and periodontal immune responses, mainly because several inflammatory mediators involved in FMF, including IL-1 β and TNF- α , also participate in periodontal tissue inflammation and destruction. However, current evidence does not support considering periodontal disease as a direct manifestation or diagnostic feature of FMF. Instead, periodontal alterations may represent increased inflammatory susceptibility associated with chronic immune activation. Future investigations involving standardized periodontal examinations, inflammatory biomarker assessment, and genetically confirmed FMF cohorts are required to clarify this potential association.^{13,14,16,17,21,22}

The possible involvement of maxillofacial structures in FMF appears to be uncommon but clinically relevant. Temporomandibular joint symptoms have occasionally been described as part of the musculoskeletal manifestations of FMF, particularly in patients with inflammatory arthritis. These findings should be interpreted within the context of systemic inflammatory activity rather than as isolated oral manifestations. Similarly, oral findings related to AA amyloidosis, including soft tissue enlargement or macroglossia, are rare but may indicate advanced systemic disease and require appropriate medical evaluation. The management of FMF has substantially improved with the widespread use of colchicine and the introduction of targeted biological therapies. Colchicine remains the cornerstone of treatment because of its ability to reduce inflammatory attacks and prevent AA amyloid deposition through inhibition of neutrophil activity. Although effective control of systemic inflammation may theoretically reduce inflammatory oral manifestations, direct evidence evaluating the effect of colchicine on oral outcomes is currently lacking. Similarly, IL-1-targeted therapies, including anakinra and canakinumab, have demonstrated effectiveness in colchicine-resistant FMF; however, their specific influence on oral manifestations requires further investigation.^{24-27,30,31} From a clinical dental perspective, awareness of possible oral manifestations associated with FMF is important for early recognition of systemic inflammatory disease. Patients presenting with recurrent unexplained oral ulcerations accompanied by fever episodes, abdominal attacks, arthritis, or relevant family history may benefit from interdisciplinary assessment involving dental specialists, oral medicine clinicians, and rheumatologists. Recognition of potential systemic associations may prevent repeated symptomatic treatment of oral lesions without addressing the underlying inflammatory disorder.¹⁸⁻²⁰ Despite advances in understanding FMF pathogenesis, the clinical significance of oral involvement remains uncertain. The majority of available publications consist of case reports, small observational studies, and descriptive clinical observations rather than large controlled investigations.

Consequently, important questions remain unanswered, including the true prevalence of oral manifestations, their association with specific MEFV variants, their relationship with inflammatory activity, and their potential value as indicators of disease severity.^{3,8–10,18,19}

Future Perspectives

Future research should focus on establishing a more comprehensive understanding of oral involvement in FMF through multidisciplinary clinical studies integrating rheumatological and oral medicine perspectives. Prospective investigations involving genetically confirmed FMF patients should include standardized assessment of oral mucosal lesions, periodontal parameters, salivary inflammatory markers, and correlations with disease activity. The evaluation of molecular biomarkers may provide valuable insights into whether oral tissues reflect systemic inflammatory status in FMF. Particularly, analysis of salivary cytokines such as IL-1 β and other inflammatory mediators may contribute to understanding the biological relationship between systemic autoinflammation and oral tissue responses. Genotype–phenotype correlation studies represent another important research direction. Determining whether specific MEFV variants are associated with increased frequency or severity of oral manifestations may improve clinical characterization of FMF and contribute to personalized patient monitoring strategies. Further studies are also required to evaluate whether effective suppression of systemic inflammation through colchicine or IL-1-targeted therapies influences the development, recurrence, or progression of oral manifestations. Incorporating oral outcomes into future therapeutic studies may provide additional information regarding the broader clinical impact of disease control.

5 CONCLUSIONS

FMF is a hereditary autoinflammatory disorder primarily associated with pathogenic MEFV gene variants and dysregulation of pyrin inflammasome-mediated inflammatory pathways. Although oral manifestations are not considered classical diagnostic features of FMF, current evidence suggests that oral tissues may be affected as part of the systemic inflammatory phenotype of the disease. Recurrent oral ulcerations represent the most frequently reported oral finding, whereas periodontal alterations, temporomandibular manifestations, and amyloidosis-related oral changes appear to occur less commonly. These findings should be interpreted within the broader clinical context of FMF, including systemic

symptoms, genetic characteristics, and inflammatory activity. The current evidence remains limited by the predominance of descriptive studies and the absence of standardized approaches for evaluating oral involvement. Further prospective investigations incorporating genetic analysis, inflammatory biomarkers, and comprehensive oral assessment are required to determine the prevalence, mechanisms, and clinical significance of oral manifestations in FMF. Improved recognition of potential oral manifestations may contribute to earlier diagnosis of systemic inflammatory disease, strengthen collaboration between dental and medical specialists, and support a more integrated approach to the long-term management of patients with FMF.

DECLARATIONS

Ethical Approval

Not applicable.

Competing Interests

The authors declare no conflict of interest.

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REVIEW ARTICLE

MODERN LASER TECHNOLOGIES IN DENTISTRY: A STATE-OF-THE-ART NARRATIVE REVIEW

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Abstract

Background: Laser technologies have become increasingly important in modern dentistry due to their selective interaction with biological tissues, minimally invasive characteristics, and wide range of clinical applications. The appropriate selection of a laser system requires a comprehensive understanding of laser–tissue interactions, wavelength-dependent absorption mechanisms, and the specific biological effects associated with different technologies. This narrative review aims to summarize current knowledge regarding the physical principles, clinical applications, safety aspects, and future perspectives of erbium, Nd:YAG, CO₂, and diode laser systems, with particular emphasis on recent advances and clinical experience reported in the Russian Federation.

Materials and Methods: A narrative literature review was conducted to evaluate the physical properties, mechanisms of biological interaction, clinical effectiveness, and safety characteristics of erbium, Nd:YAG, CO₂, and diode lasers used in dentistry. The review included evidence related to their applications in restorative dentistry, oral surgery, periodontology, endodontics, pediatric dentistry, therapeutic procedures, and photobiomodulation. Publications describing technological developments and clinical experiences from Russia were also analyzed.

Results: Erbium lasers (2780/2940 nm) demonstrate strong absorption by water and hydroxyapatite, enabling selective hard tissue ablation with minimal thermal effects. They allow caries removal without smear layer formation, enhance microbial reduction, and improve adhesion of restorative materials. Nd:YAG lasers (1064 nm) are selectively absorbed by hemoglobin and melanin, producing coagulative and antibacterial effects. Their applications include periodontal therapy and root canal disinfection, contributing to microbial reduction and improved treatment outcomes. CO₂ lasers (10,600 nm) exhibit high water absorption and remain highly effective for soft tissue surgery, including frenectomy, gingivectomy, and lesion removal, providing precise cutting, excellent hemostasis, and favorable healing. Diode lasers (450–980 nm) interact primarily with melanin and hemoglobin and are widely used for soft tissue procedures, periodontal de-epithelialization, hypersensitivity management, and photobiomodulation. Despite their advantages, all dental lasers are classified as Class IV devices, requiring strict safety measures, protective eyewear, and effective aspiration systems. Limitations include equipment costs and the need for specialized training. Russian developments, including L'Med-1 and ALTA Blue, demonstrate important contributions to domestic laser dentistry.

Conclusion: Laser technologies significantly enhance conventional dental approaches by improving precision, hemostasis, disinfection, and tissue response. Future progress will depend on multi-wavelength systems, digital integration, standardized clinical protocols, professional education, and further clinical research

Keywords: erbium lasers, Nd:YAG laser, CO₂ laser, diode laser.

1 INTRODUCTION

The term “laser” is an abbreviation derived from *Light Amplification by Stimulated Emission of Radiation*, describing a technology based on the generation of

coherent electromagnetic radiation through stimulated emission. Since its introduction, laser technology has become an important advancement in modern medicine and dentistry, providing precise, minimally invasive, and biologically controlled treatment approaches. The first

medical applications of lasers began in the 1960s with ruby laser use in ophthalmology, followed by the first experimental application of laser energy to dental enamel in 1964, which initiated the development of dental laser science.^{1,2} Continuous progress in laser physics and optical engineering has resulted in the development of multiple dental laser systems with different wavelengths, energy delivery modes, and clinical indications. The principal factor determining laser–tissue interaction is wavelength, as it defines the absorption of radiation by specific biological chromophores, including water, hydroxyapatite, hemoglobin, and melanin.³ Selective absorption of laser energy allows controlled photothermal, photomechanical, and photobiomodulatory effects, forming the scientific basis for modern laser applications in dentistry.⁴

Erbium lasers, including Er:YAG (2940 nm) and Er,Cr:YSGG (2780 nm), demonstrate high absorption by water and hydroxyapatite, enabling precise ablation of dental hard tissues with minimal thermal damage. These properties have established erbium lasers as valuable tools in restorative dentistry, minimally invasive cavity preparation, caries removal, and pediatric dental procedures.^{5,6} Their ability to modify dentin morphology, reduce smear layer formation, and provide antimicrobial effects contributes to improved clinical outcomes in adhesive restorative and surgical procedures.^{7–9}

Nd:YAG lasers operate at 1064 nm and interact primarily with melanin and hemoglobin, producing photothermal effects such as coagulation and microbial reduction. Due to their tissue penetration characteristics, Nd:YAG lasers have been widely investigated in periodontal therapy, endodontics, and soft tissue procedures.¹⁰ Their antimicrobial activity and ability to reduce bacterial contamination in root canals and periodontal tissues represent important clinical advantages; however, appropriate parameter selection is required to avoid excessive thermal effects.^{11–13}

CO₂ lasers (10,600 nm) demonstrate strong absorption by water, resulting in superficial and controlled soft tissue vaporization. This characteristic makes them highly effective for oral soft tissue surgery, including frenectomy, gingivectomy, biopsy procedures, and removal of benign lesions.^{14,15} CO₂ lasers provide excellent hemostasis, improved surgical visibility, reduced postoperative discomfort, and favorable wound healing, although clinical success depends on accurate adjustment of energy parameters.^{16,17}

Diode lasers (450–980 nm) represent compact and versatile systems widely used in contemporary dental

practice. Their primary chromophores are melanin and hemoglobin, allowing applications in soft tissue surgery, gingival depigmentation, periodontal de-epithelialization, antimicrobial therapy, and aesthetic procedures.^{18,19} Although diode lasers offer significant clinical advantages, careful control of power, exposure time, and irradiation parameters is necessary to prevent excessive thermal accumulation.²⁰

Laser-assisted periodontal therapy has been extensively studied due to the potential antimicrobial and biological effects of laser irradiation. Diode lasers, in particular, have demonstrated potential as adjunctive methods to conventional periodontal treatment by reducing bacterial load and influencing inflammatory responses.^{21,22} In addition, photobiomodulation represents an expanding field of laser application, with evidence suggesting effects on cellular metabolism, tissue repair, inflammation modulation, and postoperative recovery.²³

Laser technologies have also been investigated for the management of dentin hypersensitivity through modification of dentinal tubules and reduction of fluid movement within dentin. Diode and erbium lasers have demonstrated promising results; however, clinical effectiveness depends on appropriate treatment protocols and patient-related factors.^{24,25}

Despite their clinical benefits, dental lasers require strict safety measures. All dental laser systems are classified as Class IV devices and require appropriate protective eyewear, controlled operating conditions, adequate training, and effective aspiration systems.²⁶ Laser-generated plume and aerosols represent additional occupational concerns, emphasizing the importance of high-volume evacuation and appropriate safety protocols.²⁷

The widespread implementation of laser dentistry remains limited by equipment costs, maintenance requirements, and the need for specialized education. Variations in clinical protocols and outcome assessment methods further highlight the necessity for evidence-based recommendations and standardized approaches.²⁸

Laser dentistry has also developed significantly in the Russian Federation, where researchers have contributed to clinical studies and technological innovations involving erbium, Nd:YAG, CO₂, and diode lasers. Russian developments, including L'Med-1 and ALTA Blue, represent important contributions aimed at expanding access to laser-assisted dental procedures and improving clinical integration of these technologies.^{29–31}

Despite extensive research, available evidence remains heterogeneous, with many studies focusing on individual laser systems or specific clinical applications. Therefore,

a comprehensive synthesis of current knowledge regarding laser physics, biological interactions, clinical indications, safety considerations, and future perspectives remains necessary.

The aim of this narrative review was to analyze and summarize current evidence regarding the physical principles, clinical applications, advantages, limitations, and future perspectives of major dental laser systems, including erbium, Nd:YAG, CO₂, and diode lasers, with particular emphasis on recent developments and clinical experience reported in the Russian Federation.

2. MATERIALS AND METHODS

A narrative review of the scientific literature was conducted to evaluate current knowledge regarding the physical characteristics, biological interactions, clinical effectiveness, safety aspects, and future perspectives of major dental laser systems. The review included Russian and international publications focusing on erbium, Nd:YAG, CO₂, and diode lasers used in different fields of dentistry, including restorative dentistry, oral surgery, periodontology, endodontics, pediatric dentistry, and therapeutic applications. The analysis was performed with particular attention to the mechanisms of laser–tissue interaction, wavelength-dependent absorption properties, clinical indications, advantages, limitations, and safety requirements. Special emphasis was placed on scientific publications describing the development and clinical implementation of laser technologies in the Russian Federation, including domestic laser systems and research contributions.

The aim of this narrative review was to systematize current evidence regarding the physical principles, clinical applications, safety considerations, and future development trends of erbium, Nd:YAG, CO₂, and diode laser systems, with particular emphasis on Russian clinical experience and technological advances.

3. RESULTS

3.1. Clinical Applications of Erbium Laser Systems

Erbium laser systems, including Er:YAG (2940 nm) and Er,Cr:YSGG (2780 nm), represent highly selective laser technologies widely applied in modern dentistry. Their biological effects are mainly determined by strong absorption of laser radiation by water molecules and hydroxyapatite crystals, which are the principal chromophores of dental hard tissues. This specific interaction allows controlled ablation of

enamel and dentin while minimizing thermal damage to surrounding structures. The selective mechanism of erbium laser action represents one of its most important clinical advantages. Carious dentin contains a higher proportion of water compared with healthy mineralized tissues; therefore, laser energy is preferentially absorbed by infected and demineralized areas. This allows selective removal of pathological tissue while preserving intact dental structures, supporting the principles of minimally invasive dentistry.¹²

An important advantage of erbium laser-assisted cavity preparation is the modification of the dentin surface without formation of a conventional smear layer. Laser ablation produces a micro-irregular surface with exposed dentinal tubules, which may improve the micromechanical interaction between restorative materials and dental tissues. In addition, erbium laser irradiation demonstrates antimicrobial activity through photothermal and photomechanical mechanisms, contributing to reduction of bacterial contamination during restorative procedures.¹³

Clinical studies have demonstrated the effectiveness of Er:YAG and Er,Cr:YSGG lasers in the treatment of early carious lesions, minimally invasive cavity preparation, fissure sealing, and restorative dentistry procedures.^{14–16} Furthermore, erbium lasers have shown particular value in pediatric dentistry due to reduced noise and vibration compared with conventional rotary instruments, potentially improving patient acceptance and reducing dental anxiety.¹⁷

The clinical effectiveness of erbium lasers depends on appropriate selection of operating parameters, including pulse energy, repetition rate, irradiation time, and water cooling. Optimization of these parameters is essential to achieve effective tissue removal while preventing excessive thermal effects and maintaining biological safety.⁹

3.2. Nd:YAG Lasers in Periodontology and Endodontics

Nd:YAG laser systems operate at a wavelength of 1064 nm and demonstrate optical characteristics different from erbium lasers. Their radiation is primarily absorbed by pigmented chromophores, particularly hemoglobin and melanin, while water absorption remains relatively limited. This interaction allows deeper penetration into soft tissues and determines their application in periodontal therapy, endodontics, and soft tissue procedures requiring coagulation and antimicrobial effects.^{18–20}

The biological effects of Nd:YAG laser irradiation are primarily associated with photothermal mechanisms. Absorption of laser energy by pigmented bacterial

structures results in rapid temperature elevation, protein denaturation, and destruction of microbial cell membranes.

Within periodontal pockets, these effects contribute to reduction of pathogenic microorganisms and modification of inflamed tissues. At the same time, coagulation of small blood vessels improves surgical visibility and provides a relatively bloodless operating field.²¹

Nd:YAG laser-assisted periodontal therapy has been investigated as an adjunctive approach to conventional mechanical treatment. Studies have demonstrated its potential for microbial reduction, improvement of periodontal tissue conditions, and enhancement of clinical outcomes when appropriate protocols are followed.^{21,22}

Another clinically relevant advantage of Nd:YAG laser application is the potential reduction of bacteremia associated with periodontal procedures. The coagulative effect of laser irradiation may limit bleeding and reduce microbial dissemination into the bloodstream, which may be particularly important in medically compromised patients.²²

In endodontics, Nd:YAG lasers are used primarily as an adjunctive method for root canal disinfection. Delivery of laser energy through flexible fiber-optic systems allows irradiation of areas that may remain inaccessible to conventional instrumentation and irrigation, including dentinal tubules and lateral canal structures. The generated thermal effect contributes to bacterial elimination and improved canal decontamination.^{23–25}

However, the clinical application of Nd:YAG lasers requires careful control of energy parameters. Excessive power or inappropriate irradiation protocols may result in undesirable temperature increases and potential damage to surrounding periodontal tissues. Therefore, successful implementation depends on adequate training, knowledge of laser physics, and adherence to evidence-based protocols.

3.3. CO₂ Lasers in Dentistry

Carbon dioxide (CO₂) lasers represent one of the most established and clinically effective laser systems used in oral and maxillofacial surgery. These systems generate infrared radiation mainly at wavelengths of 9300 nm, 9600 nm, and 10,600 nm, which demonstrate extremely high absorption by water molecules. Since oral soft tissues contain a high proportion of water, this specific interaction provides controlled superficial tissue vaporization with limited

penetration depth and predictable thermal effects. The mechanism of CO₂ laser action is based on rapid absorption of laser energy by intracellular water, resulting in instantaneous vaporization and photothermal destruction of targeted tissues. This process allows precise incision, ablation, and coagulation with minimal mechanical trauma. Due to these properties, CO₂ lasers have become widely used in soft tissue procedures where accurate cutting and effective hemostasis are required.^{26,27}

CO₂ laser technology has been extensively incorporated into oral surgery and maxillofacial procedures. Its clinical indications include frenectomy, vestibuloplasty, gingivectomy, excision of benign soft tissue lesions such as papillomas, fibromas, and epulides, as well as treatment of pathological mucosal alterations, including leukoplakia and oral lichen planus.^{28–31}

One of the major advantages of CO₂ laser surgery is the simultaneous cutting and coagulation effect. The sealing of small blood vessels and lymphatic structures provides improved visualization of the surgical field, reduced intraoperative bleeding, and decreased postoperative edema and discomfort. In addition, the limited zone of thermal injury surrounding the incision contributes to favorable wound healing and satisfactory esthetic results.^{32–35}

Compared with conventional surgical techniques, CO₂ lasers may provide improved patient comfort due to reduced tissue manipulation and decreased postoperative pain. However, the clinical outcome depends strongly on appropriate selection of laser parameters, including power density, pulse duration, focusing conditions, and exposure time. Excessive energy delivery may result in unnecessary thermal damage, whereas insufficient energy may reduce tissue cutting efficiency. Therefore, although CO₂ lasers remain one of the most effective systems for oral soft tissue surgery, their application requires adequate knowledge of laser–tissue interactions and strict control of operational parameters.

3.4. Diode Lasers: Versatility and Accessibility

Diode lasers represent one of the most commonly used laser technologies in contemporary dental practice due to their compact design, operational simplicity, relatively low cost, and broad range of clinical applications. These semiconductor-based systems generate radiation within a wavelength range of approximately 450–980 nm, with melanin and hemoglobin acting as the principal tissue chromophores. Their physical characteristics determine their widespread use in soft tissue surgery, periodontal therapy, aesthetic dentistry, and photobiomodulation.^{36,37}

Unlike erbium and CO₂ lasers, diode lasers demonstrate deeper penetration into soft tissues due to their lower

absorption by water. This property enables effective interaction with vascular and pigmented tissues and provides advantages in procedures requiring coagulation, bacterial reduction, and tissue biostimulation. One of the main clinical advantages of diode lasers is their accessibility. The compact size, flexible fiber delivery system, relatively simple maintenance requirements, and lower equipment cost allow their implementation in various dental settings. These characteristics have contributed to their increasing popularity among general dental practitioners.³⁸

In surgical dentistry, diode lasers are used for soft tissue incision, frenectomy, gingivoplasty, gingival contouring, and removal of selected benign lesions. Their interaction with hemoglobin-rich tissues produces effective coagulation, reduction of bleeding, and improved visualization of the operative field. Diode lasers have also demonstrated therapeutic potential in inflammatory oral mucosal conditions. Their biological effects include analgesic action, modulation of inflammatory mediators, and stimulation of epithelial repair. Clinical studies and systematic reviews have reported that diode laser application in recurrent aphthous stomatitis may reduce pain intensity, accelerate healing, and improve patient comfort.^{39,40}

In periodontal therapy, diode lasers are mainly used as adjunctive procedures combined with conventional mechanical treatment. Their antimicrobial activity is associated with photothermal effects that may reduce bacterial load within periodontal pockets and influence inflammatory tissue responses. Systematic reviews indicate potential clinical benefits when diode lasers are combined with scaling and root planing; however, they cannot replace mechanical periodontal therapy and should be considered supportive treatment methods.^{41,42}

An important limitation of diode lasers is the possibility of excessive thermal accumulation when

inappropriate parameters are selected. Continuous-wave operation, excessive power, prolonged irradiation, or improper fiber positioning may increase the risk of tissue overheating. Comparative studies have demonstrated that diode laser application may produce greater thermal alteration than conventional scalpel techniques under certain conditions, emphasizing the importance of accurate parameter selection.⁴³

Another important application of diode lasers is the treatment of dentin hypersensitivity. Laser irradiation may reduce dentinal fluid movement through partial occlusion or modification of dentinal tubules, leading to decreased sensitivity symptoms. Clinical studies have demonstrated immediate improvement after treatment, with effects potentially maintained over several months depending on individual patient characteristics and treatment protocols.^{44,45}

Low-level diode laser irradiation has further expanded the role of these systems through photobiomodulation therapy. The proposed mechanisms include stimulation of mitochondrial activity, increased ATP production, enhancement of cellular metabolism, improved microcirculation, activation of fibroblasts, stimulation of collagen synthesis, and modulation of inflammatory responses. These biological effects support the use of diode lasers in postoperative wound healing, periodontal tissue recovery, pain management, and supportive treatment of oral mucosal disorders.⁴⁶

The main clinical characteristics of dental laser systems are determined by their wavelength-dependent absorption properties, tissue chromophores, and biological effects. Erbium lasers demonstrate high selectivity for hard-tissue procedures, Nd:YAG lasers are primarily indicated for pigmented soft tissues and microbial reduction, CO₂ lasers remain highly effective for oral soft-tissue surgery, whereas diode lasers provide versatile applications in soft-tissue management, periodontal therapy, and photobiomodulation.^{5,10,18,26,36}

protective eyewear for the clinician, dental staff, and patient, are mandatory during every laser procedure.

The optical density and protective characteristics of the eyewear must correspond precisely to the wavelength of the laser system being used to ensure adequate protection.^{4,47}

In addition to eye protection, effective organizational and environmental safety measures are essential for minimizing occupational risks. Laser operating areas should be clearly identified with appropriate warning signs, and access should be restricted to trained personnel only. The clinical team must receive specialized

3.5. Safety Considerations and Limitations of Dental Laser Technologies

The clinical implementation of laser systems in dentistry requires strict adherence to established safety principles because all surgical and high-power dental lasers are classified as Class IV laser devices, representing the highest level of biological hazard. The primary concern associated with dental laser use is potential ocular injury caused by direct or reflected exposure to laser radiation. Therefore, appropriate protective measures, including wavelength-specific

education regarding laser physics, tissue interaction mechanisms, operational parameters, and emergency procedures. Such training is particularly important because inappropriate selection of power settings, exposure time, pulse characteristics, or irradiation technique may result in excessive thermal accumulation and undesirable tissue damage.⁴⁷

An additional safety issue associated with laser-assisted procedures is the formation of laser plume and biological aerosols during tissue vaporization. Surgical smoke generated during laser ablation may contain cellular debris, microorganisms, and potentially harmful chemical compounds. Although the concentration and composition of laser-generated aerosols vary according to the tissue type and laser parameters, continuous evacuation systems with high-volume aspiration are recommended to reduce exposure risks for both patients and healthcare professionals.^{48,49}

One of the important advantages of laser technology is its non-contact mode of action. Unlike conventional mechanical instruments, laser systems transfer energy through optical fibers, articulated arms, or scanning systems without direct physical contact with the tissue surface. This characteristic contributes to improved procedural precision, reduced mechanical trauma, and better control of the surgical field. In addition, the simultaneous coagulative and antimicrobial effects observed with many laser systems may contribute to improved intraoperative conditions and postoperative healing.

Despite these advantages, several limitations continue to influence the widespread adoption of laser technologies in dental practice. The high initial cost of equipment, maintenance requirements, need for specialized training, and variability in clinical protocols remain significant barriers. Furthermore, differences in laser parameters among studies, including wavelength, energy density, pulse duration, and treatment protocols, make direct comparison of clinical outcomes difficult. Therefore, standardized clinical guidelines and well-designed controlled studies remain necessary to establish evidence-based recommendations for routine dental applications.¹

3.6. Development of Laser Technologies and Future Perspectives in Dentistry

The evolution of dental laser technology has progressed from experimental applications toward increasingly sophisticated clinical systems characterized by improved precision, reduced device dimensions, enhanced safety features, and broader therapeutic capabilities. Modern developments are

focused not only on improving laser sources but also on integrating advanced digital technologies, automated control systems, and personalized treatment approaches.⁵⁰

In recent years, the Russian Federation has demonstrated significant scientific and technological activity in the field of laser medicine and dentistry. Russian researchers have contributed to the development of laser devices, clinical protocols, and experimental investigations evaluating the effects of different wavelengths on biological tissues. However, despite the recognized clinical advantages of laser technologies, their implementation in routine dental practice remains slower compared with several international healthcare systems. This limitation is mainly associated with economic factors, including the high cost of equipment, insufficient availability of specialized training programs, and the absence of unified national clinical protocols regulating laser applications.²⁰ The development of domestic laser systems represents an important direction for expanding access to laser-assisted dental treatment. The Russian-made “L’Med-1” CO₂ laser system has been investigated for surgical applications and demonstrated potential advantages related to precise tissue incision, coagulation, antimicrobial effects, and favorable postoperative healing. These characteristics highlight the clinical potential of domestic laser technologies in oral surgery and maxillofacial practice.⁵¹ The historical development of Russian laser medicine includes the creation of early CO₂ laser systems such as “Romashka,” “Skalpel-1,” and “Skalpel-2,” followed by

more advanced platforms incorporating erbium, Nd:YAG, and diode technologies. These developments contributed to the expansion of laser-assisted procedures in various medical disciplines, including dentistry and maxillofacial surgery.⁵²

Recent technological progress has also introduced new wavelength ranges and improved semiconductor laser systems. Investigations of blue laser technology, particularly 450 nm diode systems, demonstrate increased absorption by pigmented biological tissues, enabling precise selective ablation and coagulation. The ability to combine surgical laser effects with low-intensity photobiomodulation represents a promising direction for future clinical applications.^{53, 54}

Future developments in dental laser technology are expected to focus on several major areas. One important trend is the creation of multi-wavelength laser platforms capable of combining different wavelengths within a single device. Such systems may allow clinicians to selectively target different tissue components, including water, hemoglobin, melanin, and hydroxyapatite, thereby expanding therapeutic versatility.⁵⁵ Another promising direction is the integration of laser systems with digital dentistry, computer-assisted navigation, and artificial

intelligence-based technologies. Automated monitoring of tissue characteristics, real-time adjustment of irradiation parameters, and computer-assisted control of treatment boundaries may improve accuracy, reproducibility, and patient safety.⁵⁶

Furthermore, advances in ultrafast laser technologies, including femtosecond laser systems, provide new opportunities for extremely precise tissue modification at microscopic and nanoscopic levels. These technologies may contribute to the development of minimally invasive procedures with reduced thermal effects and improved biological outcomes.⁵⁷ Future progress in laser dentistry, particularly in Russia, will depend on expanding clinical research, establishing evidence-based national protocols, improving professional education, and increasing accessibility of modern laser equipment. Integration of technological innovation with high-quality clinical evidence will be essential for achieving broader acceptance and predictable implementation of laser-assisted dentistry.

4. DISCUSSION

4.1. Clinical Interpretation and Significance of Dental Laser Technologies

The findings of this narrative review demonstrate that laser technologies have become an important component of contemporary dentistry by providing minimally invasive, precise, and biologically oriented treatment approaches. The clinical significance of dental lasers extends beyond simple tissue removal and includes improved surgical control, reduction of microbial contamination, enhanced patient comfort, and potential support of tissue healing processes.

The main advantage of laser technology compared with conventional mechanical instruments is the ability to selectively interact with biological tissues according to specific optical characteristics. This selectivity allows clinicians to preserve healthy structures, reduce mechanical trauma, and perform procedures with improved control. However, current evidence indicates that successful laser application depends not only on the characteristics of the device but also on correct clinical indications, operator experience, and integration within comprehensive treatment protocols.

Modern laser dentistry should therefore be considered an advanced complementary approach rather than a replacement for conventional dental methods. The highest clinical benefit is achieved when laser systems are incorporated into multidisciplinary treatment strategies combining mechanical, chemical, surgical, and biological approaches.

4.2. Clinical Role of Different Dental Laser Systems

The available evidence demonstrates that erbium, Nd:YAG, CO₂, and diode lasers occupy different but complementary positions in contemporary dental practice according to their wavelength-dependent biological interactions.

Erbium lasers (Er:YAG and Er,Cr:YSGG) have particular importance in minimally invasive dentistry because of their strong absorption by water and hydroxyapatite. Their ability to selectively remove altered dental tissues while preserving healthy structures supports conservative treatment concepts and makes them valuable in restorative dentistry, caries management, and selected surgical procedures.^{10–12} However, their broader implementation remains influenced by equipment cost, technical requirements, and the necessity for standardized clinical protocols.

Nd:YAG lasers demonstrate specific advantages related to their interaction with pigmented tissues and deeper penetration characteristics. Their antimicrobial and coagulative effects explain their continued use in periodontal and endodontic procedures. Nevertheless, current evidence supports their role mainly as adjunctive tools that enhance conventional treatment rather than replace mechanical instrumentation.^{18, 21, 23}

CO₂ lasers remain among the most predictable systems for oral soft tissue surgery because of their high absorption by water and controlled superficial tissue interaction. Their ability to provide precise incision, coagulation, reduced bleeding, and favorable postoperative healing explains their continued relevance in oral surgery and maxillofacial procedures.^{27, 29}

Diode lasers represent a different technological direction characterized by accessibility, portability, and versatility. Their relatively low cost and simple operation have contributed to their increasing adoption in periodontal therapy, soft tissue procedures, aesthetic dentistry, and photobiomodulation. However, their widespread availability emphasizes the importance of adequate training because inappropriate parameter selection may increase the risk of thermal tissue damage.^{36, 43}

4.3. Integration of Laser Technologies into Evidence-Based Dental Practice

A major challenge in contemporary laser dentistry is the establishment of standardized evidence-based clinical protocols. Although numerous studies demonstrate beneficial effects, the available literature remains heterogeneous because of differences in laser parameters, treatment indications, study designs, and evaluation methods.

The current evidence suggests that laser selection should be based on specific clinical objectives rather than the assumption that one laser system is universally superior. Successful treatment requires individualized consideration of tissue characteristics, disease conditions, patient factors, and clinician experience.

An additional important aspect is patient-centered care. Reduced vibration, decreased bleeding, improved surgical visibility, and potentially improved postoperative comfort represent important advantages that may increase patient acceptance, particularly in pediatric dentistry and minimally invasive procedures.¹⁷

4.4. Safety Considerations and Clinical Limitations

Despite significant advances, several factors continue to restrict the widespread adoption of laser technologies. The high initial cost of equipment, maintenance requirements, and the need for specialized education remain important barriers, particularly in general dental practice.¹

Another limitation is the lack of universally accepted clinical guidelines for many laser applications. Although numerous investigations have demonstrated positive outcomes, variations in operational parameters and treatment protocols limit direct comparison between studies.

Safety remains a fundamental component of laser dentistry. Dental lasers belong to high-risk device categories, requiring appropriate protective measures, including wavelength-specific protective eyewear, controlled clinical environments, and strict adherence to safety protocols.^{26, 47}

Laser-generated plume represents an additional occupational concern. During tissue ablation, aerosols containing biological particles and potentially harmful components may be produced; therefore, effective evacuation systems and infection-control measures are necessary to protect both dental professionals and patients.^{48, 49}

4.5. Development of Laser Technologies in Russian Dentistry

The development of laser dentistry in the Russian Federation represents an important part of the global evolution of medical laser technologies. Russian researchers have contributed to the development, investigation, and clinical application of CO₂,

Er:YAG, Nd:YAG, and diode laser systems in dentistry and maxillofacial surgery.

Historical progress in Russian laser medicine included the development of early CO₂ surgical systems, including devices such as “Romashka”, “Skalpel-1”, and “Skalpel-2”, which formed the basis for further clinical applications of laser surgery. Later, more advanced technologies, including Er:YAG, Nd:YAG, and diode systems, expanded the possibilities of minimally invasive surgical and dental procedures.⁵²

Studies evaluating domestic CO₂ laser systems, including the “L’Med-1” device, demonstrated the advantages of laser-assisted surgery, including improved hemostasis, reduced tissue trauma, precise incision, and favorable wound healing characteristics.⁵¹

More recent Russian developments, including semiconductor laser technologies such as ALTA Blue, demonstrate the potential of modern blue-spectrum lasers for selective tissue interaction and combination of ablative and photobiomodulatory effects.⁵⁴ However, despite these achievements, the implementation of laser technologies in Russian dentistry remains limited by

economic factors, insufficient standardization, and the need for specialized training programs. Expansion of clinical research and development of national recommendations are necessary for broader integration of laser systems into routine dental practice.^{20, 50}

4.6. Future Perspectives and Emerging Trends

The future development of dental laser technologies is expected to focus on improved selectivity, automation, and integration with digital dentistry.

Multi-wavelength laser systems represent a promising direction because they may allow clinicians to address different tissue components using a single platform.⁵⁵ The combination of lasers with artificial intelligence, computer-assisted navigation, and digital treatment planning may further improve precision through automated adjustment of irradiation parameters and real-time control of treatment boundaries.⁵⁶

Another important future direction is the development of ultrashort pulse technologies, including femtosecond lasers, which provide highly precise interaction with biological tissues at microscopic and nanoscopic levels while minimizing collateral damage.⁵⁷

For Russian dentistry, future progress requires strengthening collaboration between research institutions, engineers, and clinicians, expanding multicenter clinical

studies, developing standardized protocols, and improving professional education in laser medicine.

Limitations of the Review

This narrative review has several limitations. The available literature demonstrates considerable heterogeneity regarding laser parameters, treatment protocols, clinical indications, and outcome assessment methods, which complicates direct comparison between studies.

Many investigations include limited patient populations, single-center designs, and relatively short follow-up periods. Therefore, additional high-quality clinical trials with standardized methodologies are required to confirm long-term effectiveness.

Furthermore, comparative studies evaluating different laser systems under identical clinical conditions remain limited. Future research should focus on evidence-based comparisons, standardized outcome measures, and clinically relevant long-term results.

5.CONCLUSION

Laser technologies have become an important component of modern dentistry by providing precise, minimally invasive, and biologically controlled treatment approaches. Erbium lasers demonstrate significant advantages in conservative treatment of dental tissues, Nd:YAG lasers provide valuable antimicrobial and coagulative effects, CO₂ lasers remain highly effective for soft tissue surgery, and diode lasers offer accessibility and versatility for routine clinical applications. Lasers should not replace conventional dental methods but should be considered complementary technologies that enhance treatment accuracy, patient comfort, and clinical outcomes.

The international and Russian experience confirms that further development of laser dentistry will depend on technological innovation, evidence-based clinical protocols, professional education, and integration with digital technologies. These advances may contribute to the transition toward more personalized, minimally invasive, and biologically guided dental care.

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Competing Interests

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REVIEW ARTICLE

SURGICAL MANAGEMENT OF A GIANT MAXILLARY AMELOBLASTOMA USING NAVIGATION-GUIDED ENDOSCOPIC ASSISTANCE AND TITANIUM MESH RECONSTRUCTION COMBINED WITH A PEDICLED BUCCAL FAT PAD: NARRATIVE LITERATURE REVIEW SUPPORTED BY AN ILLUSTRATIVE CLINICAL CASE

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Abstract

Background:Maxillary ameloblastoma is an uncommon but locally aggressive odontogenic tumor that presents substantial surgical challenges because of its proximity to the maxillary sinus, nasal cavity, orbit, and other critical midfacial structures. Extensive tumors may require radical resection followed by complex skeletal and soft-tissue reconstruction. Contemporary surgical navigation and endoscopic visualization may improve intraoperative anatomical control, whereas titanium mesh and vascularized soft-tissue techniques can facilitate restoration of complex maxillary defects.

Objective:To review the contemporary literature concerning the surgical management of extensive maxillary ameloblastoma, with particular emphasis on computer-assisted navigation, endoscopic assistance, titanium mesh reconstruction, and pedicled buccal fat pad reconstruction, and to illustrate the clinical application of this combined strategy through a representative case.

Narrative Literature Review:A narrative review of the contemporary literature was performed using PubMed, Scopus, and Web of Science, focusing on maxillary ameloblastoma, navigation-assisted surgery, endoscopic resection, titanium mesh reconstruction, and buccal fat pad flap techniques. The review focused on the anatomical and oncological challenges of maxillary ameloblastoma, the potential role of computer-assisted intraoperative navigation and endoscopic visualization, and reconstructive strategies for complex postoperative defects.

Illustrative Clinical Case:A 48-year-old man presented with a 1.5-year history of progressive right-sided facial asymmetry, swelling, mild pain, and ipsilateral nasal obstruction. Imaging demonstrated a 45 × 38 × 32 mm right maxillary lesion involving the alveolar process, maxillary sinus, and orbital floor. Histopathological examination confirmed follicular ameloblastoma. Three-dimensional virtual planning was performed before surgery. Tumor resection was subsequently carried out using intraoperative navigation combined with endoscopic visualization. The resulting skeletal defect was reconstructed using a pre-contoured three-dimensional titanium mesh and covered with a pedicled buccal fat pad flap.

Clinical Outcome of the Illustrative Case:The operative duration was 210 minutes, with an estimated blood loss of approximately 180 mL. No intraoperative complications were reported. Postoperative imaging demonstrated satisfactory positioning of the reconstructive titanium mesh. During 12 months of follow-up, no clinically evident tumor recurrence, titanium mesh exposure, or infection was observed. Complete intraoral epithelialization of the exposed buccal fat pad was achieved within four weeks, with preservation of mastication, swallowing, speech, and satisfactory facial symmetry.

Conclusions:The contemporary literature supports a multidisciplinary approach to extensive maxillary ameloblastoma in which precise tumor resection is combined with individualized reconstruction. The illustrative case demonstrates the practical integration of navigation-guided endoscopic surgery with titanium mesh reconstruction and pedicled buccal fat pad coverage. This combination may represent a useful reconstructive strategy for selected complex maxillary defects, although the favorable outcome of a single case cannot establish comparative efficacy or generalizability.

Keywords: Temporomandibular joint dysfunction; Temporomandibular joint; Orofacial pain; Diagnosis; Conservative treatment; Arthrocentesis; Multidisciplinary management.

1. INTRODUCTION

Ameloblastoma is a benign odontogenic neoplasm characterized by locally aggressive and infiltrative growth and a clinically significant risk of local recurrence.^{1,2,5} Although the mandible is the predominant site of occurrence, maxillary ameloblastomas represent a particularly challenging subgroup because of the complex three-dimensional anatomy of the maxilla and its close relationship with the orbit, nasal cavity, maxillary sinus, pterygopalatine and infratemporal regions, and skull base.^{3,6,7} These anatomical characteristics have important implications for both oncological control and reconstructive planning and distinguish the surgical management of maxillary ameloblastoma from that of more readily accessible mandibular lesions.^{4,6,7}

The clinical presentation of maxillary ameloblastoma may be deceptively inconspicuous during the early stages of disease. Because of the relatively thin cortical boundaries of the maxilla and its communication with several air-containing spaces, tumors may expand within the maxillary sinus or adjacent anatomical compartments before producing prominent external facial deformity.^{6–8} Patients may therefore present with nonspecific manifestations, including swelling, facial asymmetry, dental displacement, nasal obstruction, epistaxis, pain, or tooth mobility.^{6–8} Consequently, some lesions are diagnosed only after extension into multiple anatomical compartments rather than while remaining confined to a localized intraosseous site.^{6–8}

Advanced maxillary ameloblastomas may involve the alveolar process, hard palate, maxillary sinus, nasal cavity, orbital floor, and posterior maxillary structures, creating a complex surgical problem in which adequate tumor removal must be balanced against preservation or restoration of critical midfacial anatomy.^{4,6–8,39} The fundamental objective of treatment remains complete and appropriately planned surgical removal of the tumor while minimizing the risk of local recurrence.^{5,38} Although conservative procedures may be appropriate for selected lesions, the infiltrative behavior of ameloblastoma and the anatomical characteristics of maxillary tumors may limit the applicability of conservative treatment in extensive disease.^{5,6,38} Large or anatomically advanced lesions may consequently require substantial maxillary resection to achieve adequate oncological clearance.^{4,6–8,38}

Extensive maxillary resection transforms tumor removal into a combined oncological and reconstructive procedure. The resulting defect may

involve several anatomical and functional compartments and require restoration of the three-dimensional architecture of the midface as well as separation of the oral cavity from the sinonasal spaces.^{4,9,10} Reconstruction is particularly important because the maxilla contributes to facial contour, orbital support, nasal architecture, mastication, speech, swallowing, and subsequent dental rehabilitation.^{9,10,17} Loss of the maxillary walls, alveolar process, sinus boundaries, or orbital floor may therefore result in substantial functional and aesthetic impairment when appropriate reconstruction is not achieved.^{9,10,17}

Communication between the oral cavity and the maxillary sinus or nasal cavity may further complicate postoperative healing and predispose to persistent oroantral or oronasal fistula, contamination, chronic sinonasal symptoms, and impaired tissue healing.^{12–14} Reconstruction should consequently provide both adequate skeletal stability and reliable soft-tissue coverage capable of establishing biological separation between the involved anatomical spaces.^{9,10,12–14}

Titanium mesh is an established reconstructive option for complex maxillofacial defects because of its mechanical strength, rigidity, relatively low weight, and adaptability to patient-specific three-dimensional anatomy.^{15–17} Titanium mesh can facilitate restoration of maxillary and orbital contours while providing a stable structural framework for overlying soft tissues.^{15–17} Computer-assisted fabrication and individualized mesh design may further improve the anatomical conformity of reconstruction in extensive maxillectomy defects.^{16,17,34} However, a rigid reconstructive framework alone does not address all biological requirements of a complex surgical site. Exposure of titanium mesh to the oral or sinonasal environment may predispose to contamination, soft-tissue dehiscence, and delayed healing, emphasizing the importance of reliable soft-tissue coverage in defects involving communication with the oral cavity or paranasal spaces.^{16–18}

The buccal fat pad (BFP) represents a useful autologous option for intraoral reconstruction because it is readily accessible, has a rich vascular supply, can be mobilized without creating a distant donor-site defect, and can conform to irregular maxillofacial defects.^{19–22} Its use as a pedicled flap provides vascularized soft-tissue coverage and may facilitate closure of communications between the oral cavity and deeper anatomical spaces.^{19–22} Clinical experience and reported reconstructive applications have demonstrated the utility of the BFP in maxillary and intraoral defects, including defects reconstructed in combination with titanium mesh.^{36–38} When combined with a rigid titanium framework, these components serve complementary purposes: titanium mesh restores structural support and three-dimensional skeletal contour, whereas the vascularized BFP provides biological

The technical difficulty of extensive maxillary tumor resection is further increased by limited visualization of deep and anatomically concealed regions. Conventional open approaches provide broad surgical access but may not always allow optimal direct visualization of the posterior maxillary sinus, superior recesses, nasal cavity, or other difficult-to-access surfaces.^{23_25} Endoscopic techniques can improve visualization of restricted anatomical spaces, although endoscopy alone may not provide sufficient exposure or control for extensive maxillary tumor resection.^{23_25,33,35} A combined open and endoscopic approach may therefore offer complementary advantages by providing adequate access for major tumor resection while allowing direct endoscopic inspection of otherwise concealed regions and assessment of the operative field.^{23_25,29,32,33,35}

Computer-assisted surgical navigation provides an additional means of intraoperative anatomical orientation. By registering the patient to preoperative three-dimensional imaging, navigation allows the surgeon to correlate the position of surgical instruments with the patient's computed tomography-based anatomy.^{27_32} This capability may be particularly useful in extensive maxillary tumors in which normal anatomical landmarks are displaced, distorted, or destroyed by tumor growth.^{27_32} Navigation can assist with maintenance of spatial orientation, identification of critical anatomical structures, and execution of a preoperatively defined surgical plan.^{27_32,35} Nevertheless, navigation should be considered a decision-support and orientation technology rather than a substitute for surgical judgment, pathological assessment, or appropriate oncological margins.^{27,29,35}

The combination of navigation and endoscopic visualization may be particularly relevant in anatomically complex maxillary surgery because the two technologies provide complementary information. Navigation provides three-dimensional spatial orientation derived from preoperative imaging, whereas endoscopy provides direct visualization of the operative surface and concealed anatomical compartments.^{23,27,29,32_35} Their integration may therefore reduce uncertainty regarding anatomical orientation during resection of tumors occupying the maxillary sinus and extending toward the nasal, orbital, or posterior maxillary regions.^{28,29,32_35} Importantly, the available evidence does not establish that navigation or endoscopic assistance independently improves oncological outcomes; rather, these technologies may facilitate accurate execution of an appropriately planned surgical procedure.^{27,29,32_35}

Despite advances in digital surgical planning, computer-assisted navigation, endoscopic techniques, and reconstructive materials, extensive maxillary ameloblastoma remains a technically demanding condition.^{6,7,27_29,33,34} Existing literature has largely addressed individual components of management, including surgical resection, computer-assisted navigation, endoscopic maxillectomy, titanium mesh reconstruction, or buccal fat pad reconstruction.^{26_37} However, comparatively limited clinical literature describes the practical integration of these technologies and reconstructive principles within a single treatment pathway for extensive maxillary ameloblastoma.^{33,36_38}

The clinical relevance of such integration extends beyond the size or rarity of the tumor. An extensive maxillary lesion requires coordinated consideration of oncological resection, three-dimensional anatomical orientation, visualization of concealed surgical regions, restoration of the facial skeleton, and reliable soft-tissue coverage.^{6,7,9,10,26,29,33,36_38} The potential value of the combined approach therefore lies in its technical and conceptual integration rather than in any single component. Navigation may support three-dimensional intraoperative orientation and execution of the planned resection; endoscopic assistance may enhance visualization of anatomically restricted regions; titanium mesh may restore the structural framework of the maxilla and orbital region; and a pedicled BFP may provide vascularized soft-tissue coverage of the reconstructive field.^{15_21,26_37}

Accordingly, the present report describes the surgical management of an extensive maxillary ameloblastoma using navigation-guided tumor resection with endoscopic assistance, immediate three-dimensional titanium mesh reconstruction, and pedicled buccal fat pad coverage. The case is presented within a narrative review of the contemporary literature to contextualize the anatomical challenges, surgical principles, reconstructive options, potential advantages, and limitations of this integrated approach.

Rather than suggesting that this combined technique is superior to established surgical strategies, the present report aims to illustrate how contemporary image-guided surgery, endoscopic visualization, and defect-specific reconstruction can be coordinated within a single operative pathway for a complex maxillary tumor. The favorable outcome of an individual case should be interpreted as illustrative rather than comparative and cannot establish oncological superiority, comparative efficacy, or generalizability. The case therefore serves as a clinical example of the potential integration of contemporary surgical technologies and reconstructive principles in the management of extensive maxillary ameloblastoma.

2.1. Narrative Literature Review

A structured narrative literature review was conducted to provide contemporary clinical and technical context for the surgical management and reconstruction of extensive maxillary ameloblastoma. The review focused on the biological and anatomical characteristics of maxillary ameloblastoma, principles of oncological resection, computer-assisted surgical navigation, endoscopic-assisted maxillectomy, three-dimensional surgical planning, titanium mesh reconstruction, and pedicled buccal fat pad (BFP) reconstruction.

The literature search was performed using PubMed/MEDLINE, Scopus, and Web of Science Core Collection. Publications indexed between January 2015 and July 2026 were considered to capture contemporary developments in image-guided surgery, endoscopic techniques, digital surgical planning, and maxillofacial reconstruction. Selected earlier publications were also considered when they represented seminal or technically important studies establishing the principles of maxillary ameloblastoma treatment, surgical navigation, titanium mesh reconstruction, or BFP flap surgery.

The search strategy combined controlled vocabulary and free-text terms related to the disease, surgical technology, and reconstructive procedures. The principal search terms included “maxillary ameloblastoma,” “maxillary ameloblastoma surgery,” “maxillectomy,” “navigation-assisted surgery,” “computer-assisted surgery,” “image-guided surgery,” “endoscopic-assisted maxillectomy,” “endoscopic resection,” “three-dimensional surgical planning,” “titanium mesh reconstruction,” “maxillary reconstruction,” “buccal fat pad,” “pedicled buccal fat pad flap,” and “oral and maxillary defect reconstruction.” Boolean operators (AND/OR) were used to combine the principal concepts and refine the search strategy.

Titles and abstracts were initially screened for relevance to the clinical and technical objectives of the review. Publications were considered relevant when they addressed one or more of the following domains: (1) clinical behavior, anatomical extension, or surgical management of maxillary ameloblastoma; (2) principles and technical considerations of maxillary resection; (3) computer-assisted navigation and three-dimensional surgical planning; (4) endoscopic assistance in maxillary or sinonasal tumor surgery; (5) titanium mesh or other rigid materials for maxillary and midface reconstruction; or (6) vascularized BFP

flap reconstruction of maxillary, oral, sinonasal, or oroantral defects.

Priority was given to clinical studies, systematic reviews, narrative reviews, technical reports, case series, and representative case reports providing clinically or technically relevant information for the surgical approach described in the present case. Studies unrelated to maxillary or maxillofacial surgery, focused exclusively on mandibular ameloblastoma without transferable surgical relevance, or lacking clinically relevant information for the objectives of the review were excluded. Reference lists of relevant publications were also manually examined to identify additional seminal or highly relevant studies not retrieved through the primary database search.

Because the purpose of this work was to provide a narrative synthesis rather than a systematic evidence synthesis, no formal risk-of-bias assessment, meta-analysis, or quantitative evidence grading was undertaken. The literature was synthesized thematically according to oncological management, anatomical and surgical considerations, image-guided navigation, endoscopic visualization, skeletal reconstruction, vascularized soft-tissue coverage, and integration of these modalities. The findings of the literature review were subsequently used to contextualize the clinical decision-making, operative strategy, and reconstructive principles applied in the illustrative clinical case.

2.2. Illustrative Clinical Case

A 48-year-old man was referred to the Department of Maxillofacial Surgery at “Izmirlan” Medical Center with a 1.5-year history of progressive right-sided facial asymmetry, mild pain, swelling of the right maxillary region, and ipsilateral nasal obstruction. Clinical examination demonstrated visible asymmetry of the middle third of the face and expansion of the right maxillary region. Preoperative computed tomography (CT) demonstrated a large expansile osteolytic lesion involving the right maxilla, with extension into the maxillary sinus and involvement of the orbital floor. The lesion involved the maxillary alveolar process and the anterior and posterolateral walls of the maxilla. The maximum recorded tumor dimensions were 45 × 38 × 32 mm Table 1.

Histopathological examination established the diagnosis of follicular ameloblastoma. Based on the clinical, radiological, and histopathological findings, extensive surgical resection was planned. Three-dimensional virtual reconstruction of the maxillofacial skeleton was performed preoperatively to define the extent of resection, establish the intended osteotomy planes, and facilitate subsequent reconstruction.

Table 1. Preoperative Clinical and Radiological Characteristics

Parameter	Findings
Age/Sex	48-year-old male
Symptom duration	Approximately 1.5 years
Clinical symptoms	Progressive facial asymmetry, mild pain, right maxillary swelling, ipsilateral nasal obstruction
Anatomical location	Right maxilla with extension into the maxillary sinus and orbital floor
Tumor dimensions	45 × 38 × 32 mm
Bone involvement	Maxillary alveolar process, anterior and posterolateral maxillary walls, and orbital floor
Histopathological diagnosis	Follicular ameloblastoma
Preoperative imaging	High-resolution maxillofacial CT with three-dimensional reconstruction
Virtual surgical planning	Three-dimensional computer-assisted planning with predefined resection margins of approximately 5–8 mm
Planned reconstruction	Three-dimensional titanium mesh with pedicled BFP coverage

The preoperative three-dimensional plan was subsequently incorporated into the intraoperative navigation workflow. The surgical objective was complete tumor removal with appropriately planned resection margins while preserving uninvolved adjacent structures whenever anatomically and oncologically feasible.

The patient's clinical presentation, including right-sided facial asymmetry and expansion of the maxillary region, is shown in Figure 1.

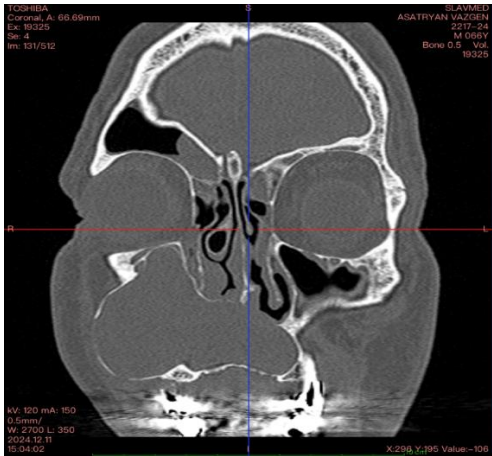


Figure 1. Preoperative clinical presentation of the patient with extensive right maxillary ameloblastoma, demonstrating right-sided facial asymmetry and expansion of the maxillary region.

2.3. Surgical Technique

2.3.1. Navigation Registration

Before tumor resection, a patient-tracking frame was secured to the cranial region to establish a stable reference for intraoperative navigation. Registration was performed by correlating selected anatomical landmarks with the preoperative high-resolution CT dataset. The reported registration error was less than 0.8 mm. Registration accuracy was verified before initiation of the osteotomies.

2.3.2. Surgical Access and Endoscopic Visualization

Surgical access was obtained through a transoral approach using a modified Weber–Ferguson mucosal incision.

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Following exposure of the maxillary surgical field, rigid 30° and 45° endoscopes were introduced to provide direct visualization of anatomically restricted regions, particularly the posterior maxillary area and orbital floor. Endoscopic visualization was used as an adjunct to the open surgical field rather than as an independent surgical approach.

2.3.3. Navigation-Guided Tumor Resection

The planned osteotomies were performed under real-time computer-assisted navigation. The navigation system was used to correlate the position of the surgical instruments with the preoperative three-dimensional reconstruction and predefined resection planes.

During tumor resection, computer-assisted navigation was used to maintain three-dimensional anatomical orientation, while endoscopic visualization was used to inspect anatomically concealed regions, particularly the posterior maxillary area and orbital floor (Figure 2A,B).

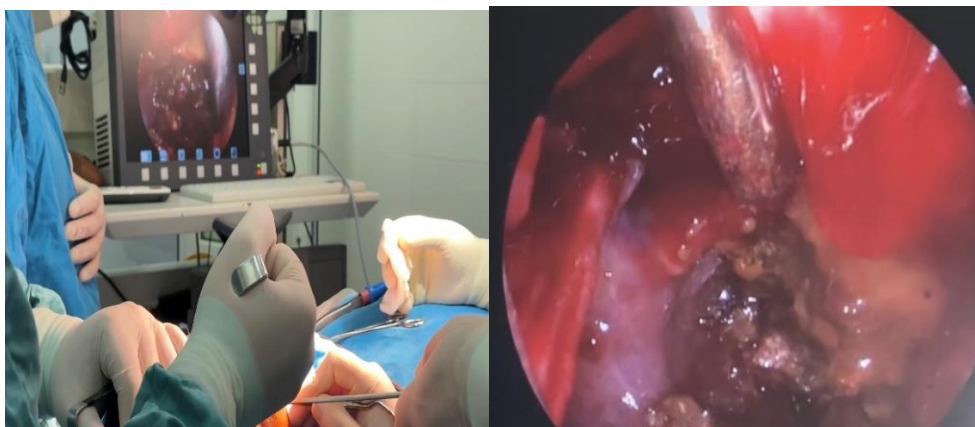


Figure 2. Navigation-guided tumor resection with endoscopic assistance. **(A)** Intraoperative navigation system demonstrating registration of the patient to the preoperative three-dimensional CT dataset and real-time localization of the surgical instruments. **(B)** Endoscopic inspection of the surgically treated maxillary region, demonstrating visualization of anatomically restricted areas following tumor resection.

Osteotomies were performed approximately 5–8 mm beyond the visible tumor boundaries according to the preoperative surgical plan and intraoperative anatomical assessment. Where the orbital floor was involved, selective resection of the affected segment was performed, while uninvolved adjacent structures were preserved whenever this was considered oncologically appropriate.

Following completion of the planned osteotomies, the tumor was removed en bloc and submitted for histopathological examination (Figure 3).



Figure 3. Resected maxillary tumor specimen following completion of the planned maxillary resection and prepared for histopathological examination.

After removal of the tumor specimen, the operative field was inspected both directly and endoscopically to assess the resection boundaries and identify any grossly apparent residual pathological tissue. The exposed maxillary surgical field before reconstruction is shown in Figure 4.

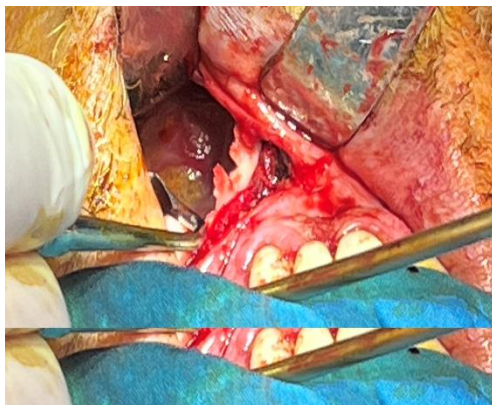


Figure 4. Intraoperative view of the maxillary surgical field following tumor removal, demonstrating the resulting surgical defect before completion of reconstruction.

2.3.4. Skeletal Reconstruction

Following completion of tumor resection, the resulting maxillary defect was reconstructed using a pre-contoured three-dimensional titanium mesh. The mesh was adapted to the planned anatomical contours of the maxilla and midface to restore the structural framework and facial contour.

The titanium mesh was rigidly secured to the remaining stable maxillary bone using microscrews. Particular attention was given to restoration of the anterior maxillary contour and the inferior orbital region.

The intraoperative positioning of the pre-contoured three-dimensional titanium mesh within the maxillary defect is shown in Figure 5.



Figure 5. Intraoperative reconstruction of the maxillary defect using a pre-contoured three-dimensional titanium mesh. The mesh is positioned within the defect and rigidly fixed to the remaining maxillary structures to restore the skeletal framework and facial contour.

2.3.5. Pedicled Buccal Fat Pad Reconstruction

A pedicled buccal fat pad (BFP) flap was subsequently harvested through the adjacent intraoral approach. The vascularized fat pad was carefully mobilized while maintaining its vascular pedicle and was transposed over the reconstructed defect and titanium mesh.

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The BFP was secured with absorbable 4-0 Vicryl sutures, providing vascularized soft-tissue coverage of the reconstructive field. The flap was positioned to facilitate biological coverage of the titanium framework and to establish separation between the oral cavity and the deeper reconstructed maxillary region.

2.3.6. Integrated Surgical Strategy

The operative sequence consisted of four complementary components: (1) navigation-guided oncological resection; (2) endoscopic visualization of anatomically concealed regions; (3) immediate three-dimensional titanium mesh reconstruction; and (4) vascularized pedicled BFP coverage.

This integrated strategy was designed to address the oncological and reconstructive requirements of the procedure within a single operative pathway. Navigation and endoscopy served as adjunctive technologies for anatomical orientation and visualization, whereas the titanium mesh and pedicled BFP provided complementary structural and biological reconstruction.

2.3.7. Postoperative Radiological Assessment

Postoperative maxillofacial CT with three-dimensional reconstruction was performed to assess the position of the titanium mesh, the reconstructed maxillary contour, and the postoperative surgical field. The postoperative three-dimensional reconstruction demonstrated satisfactory positioning of the titanium mesh and restoration of the reconstructed maxillary contour, with no radiologically apparent residual tumor (Figure 6).

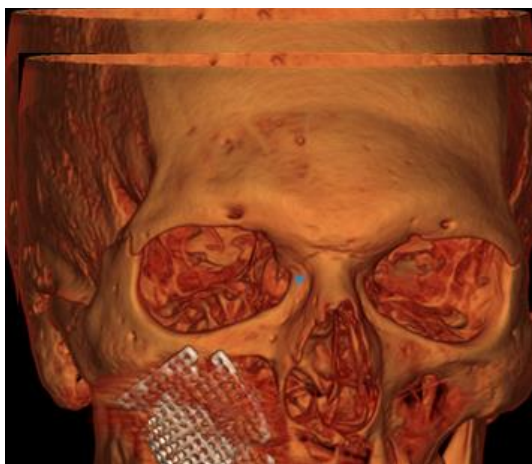


Figure 6. Postoperative three-dimensional computed tomography reconstruction demonstrating satisfactory positioning of the titanium mesh, restoration of the reconstructed maxillary contour, and no radiologically apparent residual tumor.

3. RESULTS

3.1. Findings of the Narrative Literature Review

The narrative synthesis identified several consistent themes relevant to the management of extensive maxillary ameloblastoma. Maxillary ameloblastomas represent a particularly demanding surgical subgroup because of their proximity to the maxillary sinus, nasal cavity, orbit, pterygopalatine region, and skull base. Compared with mandibular lesions, maxillary tumors may remain clinically inconspicuous during their early course and can extend into adjacent anatomical compartments before producing prominent external manifestations.⁶⁻⁹

Across the reviewed literature, complete surgical removal with appropriately planned resection margins remained the fundamental objective in the management of locally aggressive and extensive ameloblastoma. Although conservative procedures may be appropriate for selected lesions, the available evidence indicates that extensive maxillary disease frequently requires a more comprehensive resection because of its infiltrative growth pattern and the anatomical limitations of the maxilla.^{4-7,38,39}

A further recurring theme was the increasing use of three-dimensional imaging and computer-assisted surgical

planning. CT-based three-dimensional reconstruction can assist in defining tumor extent, identifying relevant anatomical structures, planning osteotomy lines, and anticipating the reconstructive requirements associated with extensive maxillary resection.^{16,27–29,32,34} Computer-assisted navigation provides additional intraoperative anatomical orientation by correlating the position of surgical instruments with the preoperative three-dimensional imaging dataset. This may be particularly useful when normal anatomical landmarks have been distorted or removed by tumor growth.^{26–32,34,35} Importantly, navigation functions as an adjunct to surgical decision-making and does not replace appropriate oncological planning or histopathological assessment of resection margins.^{26,27,35} The reviewed literature also supports the complementary role of endoscopic visualization in selected maxillary and sinonasal procedures. Endoscopic assistance can improve visualization of posterior, superior, medial, and otherwise concealed regions that may be difficult to inspect adequately through an open operative field.^{22–25,29,33,35} At the same time, the available literature generally supports endoscopy as an adjunct to an appropriately selected surgical approach rather than as a substitute for adequate oncological exposure.^{23–25,29,33,35}

With respect to reconstruction, extensive maxillary defects commonly require restoration of both skeletal architecture and soft-tissue coverage. Titanium mesh has been used for reconstruction of complex maxillary, midface, and orbital defects because of its rigidity, adaptability, and ability to provide a stable three-dimensional framework.^{15–18,34,36,37} However, rigid skeletal reconstruction alone may be insufficient when the operative defect communicates with the oral cavity or sinonasal spaces, where reliable soft-tissue coverage is important for protection of the reconstructive material and separation of anatomical compartments.^{15–18} The pedicled BFP has been described as a useful vascularized local tissue for reconstruction of oral, maxillary, palatal, and oroantral defects. Its intraoral accessibility, vascular supply, mobility, and ability to conform to irregular defects make it suitable for coverage of selected maxillofacial defects.^{19–22,36–38} The combination of titanium mesh and a vascularized BFP therefore provides complementary functions, with the mesh restoring skeletal support and the BFP providing biological soft-tissue coverage.^{36–38}

Overall, the literature indicates that the individual components of the present surgical strategy—oncological resection, three-dimensional planning, computer-assisted navigation, endoscopic visualization, titanium mesh reconstruction, and pedicled BFP coverage—are established techniques supported by clinical and technical literature.^{15–38} However, the available literature contains comparatively limited documentation of their coordinated use within a single operative strategy specifically for extensive maxillary ameloblastoma. This observation provided the clinical rationale for the integrated approach applied in the present case.

Table 2. Narrative Synthesis of the Main Surgical and Reconstructive Evidence

Domain	Main findings from the literature	Clinical relevance to the present case
Maxillary ameloblastoma	Locally aggressive behavior with potential extension into multiple anatomical compartments	Supported extensive and carefully planned resection
Oncological surgery	Complete tumor removal with appropriately planned margins remains the fundamental treatment objective	Guided the planned resection
3D surgical planning	CT-based reconstruction facilitates assessment of tumor extent and preoperative surgical planning	Used to define osteotomy planes and reconstructive requirements
Computer-assisted navigation	Provides intraoperative three-dimensional anatomical orientation	Used to support the planned osteotomies
Endoscopic assistance	Improves visualization of posterior, superior, and otherwise concealed anatomical regions	Used to inspect difficult-to-access areas
Titanium mesh	Provides rigid three-dimensional skeletal reconstruction	Used to restore maxillary and orbital contours
Pedicled BFP	Provides vascularized local soft-tissue coverage	Used to cover the reconstructive field
Integrated approach	Individual components are established, whereas their coordinated application in extensive maxillary ameloblastoma is less frequently documented	Provided the rationale for the present case

3.2. Clinical Case Findings

The patient underwent the planned integrated surgical procedure consisting of navigation-guided resection of the right maxillary ameloblastoma with endoscopic assistance, followed by immediate three-dimensional titanium mesh reconstruction and pedicled BFP coverage.

The total operative time was 210 minutes, with an estimated intraoperative blood loss of approximately 180 mL. No intraoperative complications were documented. In particular, no intraoperative injury to the orbit or other adjacent critical structures was observed.

Real-time navigation was used during the planned osteotomies, while endoscopic visualization provided additional assessment of the posterior maxillary region and orbital floor. Following tumor removal, the surgical field was inspected directly and endoscopically before reconstruction.

The resulting maxillary defect was reconstructed using a pre-contoured three-dimensional titanium mesh, which was rigidly fixed to the remaining maxillary structures. A pedicled BFP flap was subsequently mobilized and positioned over the reconstructive field to provide vascularized soft-tissue coverage. The flap was secured intraorally with absorbable sutures.

A postoperative CT examination performed on postoperative day 7 demonstrated satisfactory restoration of the reconstructed maxillary contour and appropriate positioning of the titanium mesh, with no radiologically apparent residual tumor (Figure 6).

3.2.1. Histopathological Assessment

Histopathological examination of the resected specimen confirmed the diagnosis of follicular ameloblastoma.

The postoperative CT finding of no radiologically apparent residual tumor was considered separately from histopathological assessment of the surgical margins. A definitive histopathological assessment of all surgical margins was not available in the documentation reviewed for the present report. Therefore, the postoperative radiological finding was not interpreted as evidence of histopathological R0 resection.

Microscopic examination demonstrated proliferating odontogenic epithelial islands and follicles within a fibrous stromal background, with peripheral palisading of columnar to cuboidal cells, reverse nuclear polarity, and central stellate-reticulum-like areas, consistent with follicular ameloblastoma (Figure 7A–C).

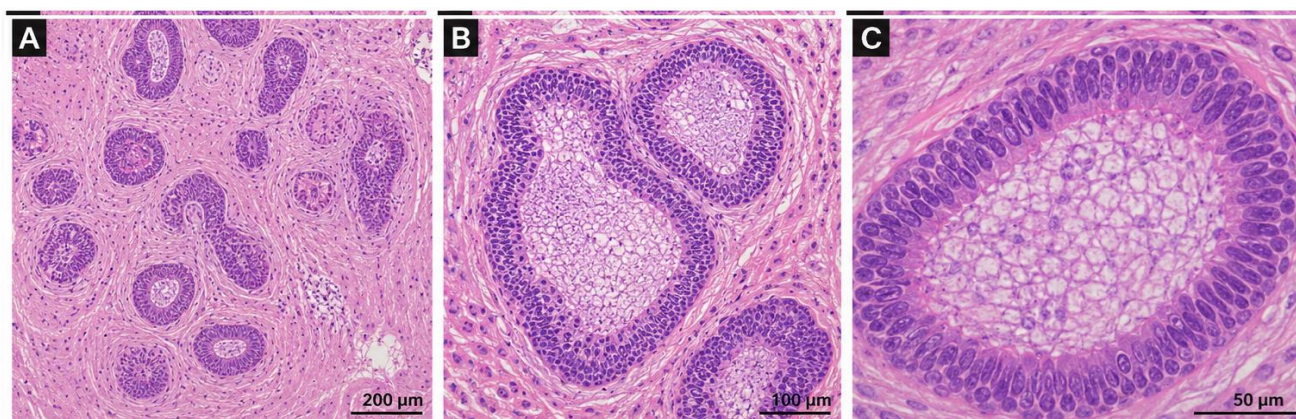


Figure 7. Histopathological features of follicular ameloblastoma. (A) Low-power view demonstrating multiple odontogenic epithelial islands and follicles within a fibrous stromal background (hematoxylin and eosin [H&E], ×40). **(B)** Intermediate-power view showing ameloblastomatous epithelial follicles with peripheral palisading of columnar to cuboidal cells (H&E, ×100). **(C)** High-power view demonstrating peripheral palisading with reverse nuclear polarity and central stellate-reticulum-like areas (H&E, ×400).

3.2.2. Twelve-Month Clinical Outcome

During the 12-month follow-up period, no clinically evident local recurrence was observed. The titanium mesh remained completely covered without clinically apparent exposure or infection. Complete intraoral epithelialization of the BFP was achieved within approximately 4 weeks.

The reconstructed facial contour remained satisfactory, with improvement in the preoperative facial asymmetry. Mastication, swallowing, and speech were preserved throughout the follow-up period. No postoperative visual deterioration or diplopia was reported Table 3.

Table 3. Twelve-Month Postoperative Clinical and Functional Outcomes

Clinical outcome	12-month finding
Local tumor control	No clinically evident local recurrence
Titanium mesh	No exposure or clinical evidence of infection
BFP healing	Complete intraoral epithelialization within approximately 4 weeks
Facial contour	Satisfactory restoration of facial symmetry
Mastication	Preserved
Deglutition	Preserved
Speech	Preserved
Visual function	No postoperative visual deterioration reported
Diplopia	Not reported
Postoperative CT	Satisfactory reconstructed maxillary contour and titanium mesh position; no radiologically apparent residual tumor on postoperative day 7 CT
Follow-up duration	12 months

3.2.3. Summary of the Clinical Outcome

Overall, the integrated surgical approach resulted in satisfactory short- and intermediate-term clinical outcomes in this patient. Navigation-guided resection and endoscopic visualization were used together to facilitate tumor removal and assessment of the complex maxillary operative field, while titanium mesh reconstruction restored the skeletal framework and the pedicled BFP provided vascularized soft-tissue coverage.

At 12 months, the patient demonstrated satisfactory facial symmetry, preserved oral functions, stable soft-tissue coverage, and no clinically evident local recurrence. The postoperative CT demonstrated satisfactory positioning of the reconstructive titanium mesh without radiologically apparent residual tumor at postoperative day 7.

These findings represent the outcome of a single illustrative clinical case and should therefore not be interpreted as evidence of comparative superiority of the integrated technique over alternative surgical or reconstructive approaches.

4. DISCUSSION

The management of an extensive maxillary

ameloblastoma is challenging because successful treatment depends on more than tumor removal alone. The surgeon must achieve adequate oncological clearance while preserving uninvolved anatomical structures and, at the same time, restoring the three-dimensional architecture and function of the maxilla. This is particularly important in maxillary ameloblastomas because the tumor may extend into the maxillary sinus, nasal cavity, orbit, posterior maxillary spaces, and, in advanced cases, toward the skull base. Because the maxilla provides relatively little resistance to tumor spread, substantial extension may occur before the external clinical findings become pronounced.^{1,5-9,39,40}

The primary objective of treatment remains complete surgical removal of the tumor with an appropriately planned margin. The extent of surgery should be determined by the biological behavior and anatomical spread of the lesion rather than by the desire to preserve structures that are already involved by tumor. Although conservative treatment may have a role in selected ameloblastomas, the available evidence generally supports more extensive surgery for large, infiltrative, or anatomically advanced lesions because conservative treatment may be associated with a greater risk of residual disease and recurrence.^{4-6,12,39} In maxillary lesions, this consideration is particularly important because the thin surrounding bone and proximity of the orbit, nasal cavity, and skull base may make apparently limited disease more extensive than suggested by the clinical examination

alone.^{6-9,40} The surgical approach in the present case was therefore planned according to the radiological extent of the tumor, the structures involved, and the anticipated three-dimensional defect that would remain after resection.

Computer-assisted navigation was incorporated into the present procedure to improve three-dimensional orientation during tumor removal. This was especially useful because the lesion involved the maxillary sinus and orbital floor, where tumor expansion can alter or obscure the normal anatomical landmarks used during conventional surgery. Navigation systems allow the surgeon to correlate the operative field with the preoperative three-dimensional imaging dataset and can therefore provide useful spatial information during complex cranio-maxillofacial procedures.^{27-29,31,32,34}

The value of navigation, however, should be interpreted appropriately. It is an adjunct to surgery and does not replace direct anatomical assessment, surgical experience, or histopathological examination. Even when registration accuracy is high, navigation cannot determine whether a microscopic tumor deposit remains at a resection margin. The reported registration accuracy in the present case was less than 0.8 mm, indicating close spatial correspondence between the preoperative imaging dataset and the operative field. Nevertheless, this numerical accuracy should not be equated with oncological accuracy. The adequacy of tumor resection ultimately depends on appropriate preoperative planning, intraoperative assessment, the macroscopic examination of the operative field and specimen, and definitive histopathological evaluation of the surgical margins.^{27-29,34,35}

Endoscopic assistance provided an additional means of assessing regions that were difficult to visualize through the primary operative exposure. In the present case, endoscopic inspection was particularly useful in the posterior maxillary region and around the orbital floor. Endoscopic techniques have been incorporated into selected maxillary and sinonasal procedures because they may provide a different viewing angle and improve visualization of anatomically concealed surfaces.^{23-26,30,33,35} These advantages are relevant when conventional direct visualization is limited by the geometry of the surgical field.

The role of endoscopy in the present case should nevertheless be viewed as complementary rather than independently oncological. The available literature supports the selective use of endoscopic assistance according to tumor location, extent, access, and the anatomy of the structures involved, but it does not establish that endoscopy by itself improves local

control or survival in maxillary ameloblastoma.^{23-25,30,33,35} Its principal value in this setting is the ability to inspect areas that may otherwise be difficult to assess and to provide additional visual information during and after resection.

Navigation and endoscopy therefore provide different types of information. Navigation offers a spatial relationship between the surgical instruments and the preoperative three-dimensional anatomical model, whereas endoscopy provides direct visualization of the actual operative surface.²⁷⁻³⁵ The combination may be particularly useful when tumor growth has distorted normal landmarks and when critical structures lie immediately adjacent to the planned osteotomy or resection planes. In this context, the two technologies should not be considered interchangeable. Rather, they address different limitations of complex maxillary surgery and can be used together when clinically justified.

Another important aspect of the present case was immediate reconstruction. Extensive maxillary resection can produce a complex three-dimensional defect involving the facial skeleton, orbital support, maxillary sinus, alveolar region, and the separation between the oral and sinonasal cavities. Such defects may affect facial contour, orbital support, mastication, speech, swallowing, and subsequent dental rehabilitation.^{9-11,18} Consequently, reconstruction should be considered as part of the initial surgical plan rather than as a separate procedure performed only after the tumor has been removed.

The reconstructive requirements of a maxillectomy defect vary according to its location and extent. Classification systems for midface defects emphasize the importance of restoring both structural support and the functional separation of anatomical compartments.^{11,18} In extensive defects, skeletal reconstruction may be necessary to restore facial projection and orbital support, while soft-tissue reconstruction is required to provide stable coverage and separation of the oral and sinonasal spaces.⁹⁻¹¹

Titanium mesh offers several practical advantages in this setting. Its rigidity allows restoration of the three-dimensional skeletal framework, while its relatively low weight and adaptability make it suitable for reconstruction of complex orbital and midfacial contours. Titanium mesh has been used extensively in orbital and midface reconstruction, including computer-assisted fabrication of individualized meshes for defects created by extensive maxillectomy.^{15-17,34} In the present case, a pre-contoured three-dimensional titanium mesh was used to reconstruct the resected maxillary and orbital region and to restore the structural contour of the midface.

The use of titanium mesh, however, does not by itself

guarantee a successful reconstruction. Stable soft-tissue coverage is essential, particularly when the reconstructed defect communicates with the oral cavity or sinonasal tract. Exposure of titanium to the oral or sinonasal environment may increase the risk of contamination, soft-tissue breakdown, infection, and subsequent reconstructive procedures.^{15–17,34} For this reason, the biological environment surrounding the implant is an important consideration when titanium mesh is used in extensive maxillary reconstruction.

The pedicled buccal fat pad (BFP) was selected in the present case as a local vascularized soft-tissue flap. The BFP has several characteristics that make it suitable for intraoral reconstruction, including its close anatomical location, relatively rich vascular supply, mobility, and ability to epithelialize after intraoral placement. It has been successfully used for reconstruction of oral, maxillary, palatal, and oroantral defects.^{19–22,36} In addition, the BFP can be harvested without creating a distant donor-site defect and can provide a relatively straightforward method of obtaining vascularized tissue for coverage of a complex intraoral wound.

In the present case, the pedicled BFP was mobilized and positioned over the reconstructed area to provide vascularized soft-tissue coverage of the titanium mesh. Complete intraoral epithelialization was observed within approximately four weeks, and no clinically evident titanium mesh exposure was identified during the 12-month follow-up. These findings support the technical feasibility of using a pedicled BFP for soft-tissue coverage in this particular reconstructive setting. They should not, however, be interpreted as evidence that BFP is superior to other vascularized reconstructive options.

The combination of titanium mesh and BFP is conceptually attractive because the two components address different reconstructive requirements. The titanium mesh provides the mechanical framework and maintains the desired skeletal contour, whereas the BFP provides vascularized biological coverage of the reconstructed field. Previous clinical reports have described the use of BFP together with titanium mesh or other reconstructive materials for maxillary defects, supporting the feasibility of combining rigid skeletal reconstruction with vascularized local soft-tissue coverage.^{19–22,36–38}

This distinction between structural and biological reconstruction is particularly relevant in extensive maxillary defects. A rigid implant may restore the contour of the facial skeleton but remains dependent on adequate soft-tissue coverage. Conversely, a soft-tissue flap may provide reliable closure without

restoring the lost skeletal architecture. Combining the two approaches allows each component to address a different part of the reconstructive problem. In the present case, the titanium mesh was used to restore the skeletal framework, while the BFP was used to establish a vascularized tissue layer over the reconstruction.

The reconstructive strategy also had functional implications. Restoration of the maxillary contour and orbital support contributes to facial symmetry and structural stability, while reliable soft-tissue closure helps maintain separation between the oral and sinonasal compartments. In the present patient, the postoperative facial contour was satisfactory, and mastication, swallowing, and speech remained preserved during the reported 12-month follow-up. These clinical findings suggest that the reconstruction achieved the principal immediate structural and functional objectives in this individual patient.

The main value of the present report does not lie in the introduction of a new individual surgical technology. Computer-assisted navigation, endoscopic assistance, titanium mesh reconstruction, and pedicled BFP reconstruction have all previously been described in the maxillofacial literature.^{15–17,19–21,23–38}

Rather, the clinical interest of the present case is the coordinated use of these established techniques in the treatment of a single extensive maxillary ameloblastoma.

The treatment pathway combined preoperative three-dimensional planning with navigation-guided resection, endoscopic inspection, immediate skeletal reconstruction, and vascularized soft-tissue coverage. Each component addressed a different part of the clinical problem. Preoperative imaging established the anatomical extent of the lesion and helped define the anticipated defect. Navigation provided intraoperative spatial orientation. Endoscopy allowed direct inspection of selected concealed areas. Titanium mesh restored the skeletal framework, while the BFP provided vascularized coverage. The overall strategy therefore represents an integrated approach to a complex maxillary defect rather than reliance on any single technology.^{27–35}

This integrated approach is consistent with the broader development of contemporary maxillofacial surgery toward image-guided planning and greater anatomical precision. Computer-assisted technologies have become increasingly useful in complex cranio-maxillofacial procedures, particularly when conventional anatomical landmarks are altered or when reconstruction requires accurate restoration of three-dimensional contours.^{27–29,31,32,34} At the same time, the use of these technologies should remain clinically driven. Digital planning and navigation are most useful when they improve the

surgeon's ability to understand and manage a difficult anatomical problem rather than being used simply because the technology is available.

The literature should also be interpreted with caution when considering the potential advantages of navigation and endoscopic assistance. Although navigation can improve intraoperative orientation and facilitate transfer of preoperative planning to the surgical field, current evidence does not demonstrate that navigation independently improves oncological survival or local tumor control.^{27–29,34} Similarly, endoscopic assistance can improve visualization in selected regions, but its usefulness depends on the location and extent of the tumor and on the surgical access required.^{23–25,30,33,35} The fundamental oncological principle remains unchanged: the tumor must be removed according to an appropriate surgical plan, and the adequacy of the margins must ultimately be determined by histopathological examination.

The present case also emphasizes the importance of planning reconstruction before resection begins. In an extensive maxillary lesion, the dimensions and location of the expected defect can be anticipated from the preoperative imaging, allowing the reconstructive strategy to be incorporated into the surgical plan from the beginning. In this case, the anticipated skeletal defect was considered during three-dimensional planning, allowing a pre-contoured titanium mesh to be prepared for immediate reconstruction. The BFP was then used to provide vascularized coverage of the reconstructed region. This coordination reduced the separation between the ablative and reconstructive stages of treatment and allowed reconstruction to be performed immediately after tumor removal.

An additional advantage of this approach is that the surgeon can evaluate the reconstruction in relation to the original three-dimensional anatomy rather than treating the defect simply as a two-dimensional surgical wound. Restoration of the orbital floor and maxillary contour requires attention to the spatial relationship between the orbit, maxillary sinus, nasal cavity, and facial skeleton. The use of preoperative three-dimensional planning and a pre-contoured mesh is therefore particularly relevant in extensive defects in which small deviations in contour may affect facial symmetry or orbital support.^{11,15–17,34}

Several limitations of the present report should be acknowledged. First, this is a single clinical case, and the favorable postoperative findings cannot be generalized to all patients with giant or extensive maxillary ameloblastoma. Ameloblastoma is biologically heterogeneous, and the extent of disease, histological characteristics, surgical margins, and

anatomical involvement may differ considerably between patients.^{1–8,39,40}

Second, the literature component of the manuscript was designed as a narrative review rather than a systematic review. The discussion therefore provides a clinically oriented synthesis of relevant literature but should not be interpreted as an exhaustive quantitative evaluation of all available evidence. Third, the present case does not establish the comparative superiority of navigation, endoscopic assistance, titanium mesh, or BFP reconstruction over alternative techniques. The favorable result demonstrates feasibility in this patient, not superiority.

Fourth, the follow-up period of 12 months is relatively short for assessing the long-term oncological behavior of ameloblastoma. Long-term clinical and radiological surveillance remains necessary because recurrence may occur after apparently successful treatment, particularly in extensive lesions.^{4–9,39,40} Fifth, standardized patient-reported outcome measures and formal comparative functional assessments were not incorporated into the present case. Although mastication, swallowing, speech, and facial appearance were clinically satisfactory, these observations cannot replace validated outcome instruments.

Finally, the reported absence of recurrence at 12 months should not be presented as evidence of long-term oncological control. The appropriate interpretation is that no clinically evident local recurrence was identified during the available follow-up period. Longer surveillance is required before any conclusion regarding durable local control can be made.

Overall, the present case supports the technical feasibility of combining navigation-guided resection, endoscopic visualization, titanium mesh reconstruction, and pedicled BFP coverage in selected patients with extensive maxillary ameloblastoma. The approach should be regarded as an illustrative integrated surgical strategy in which established technologies and reconstructive principles are coordinated according to the individual anatomical requirements of the patient. It should not be interpreted as a demonstrated superior treatment modality or as evidence of improved oncological survival.

5. CLINICAL RELEVANCE

The present case illustrates an integrated surgical and reconstructive strategy for an extensive maxillary ameloblastoma in which oncological resection and reconstruction were planned as parts of the same treatment pathway. The approach incorporated five complementary components:

1. **Three-dimensional preoperative planning** to define the extent of the tumor, anticipated resection planes, relationship to the orbit and maxillary sinus, and the expected reconstructive defect.
2. **Intraoperative computer-assisted navigation** to provide three-dimensional spatial orientation during osteotomy and tumor resection, particularly in areas where normal anatomical landmarks were altered by tumor expansion.
3. **Endoscopic visualization** to facilitate direct inspection of anatomically restricted regions, including the posterior maxillary area and orbital floor, that were difficult to evaluate through the main operative exposure.
4. **Pre-contoured titanium mesh reconstruction** to restore the three-dimensional skeletal framework of the resected maxilla and adjacent orbital region.
5. **Pedicled buccal fat pad coverage** to provide vascularized soft-tissue coverage of the reconstructed area and contribute to separation of the oral cavity from the deeper reconstructed spaces.

Each component had a distinct role. Navigation provided spatial orientation based on the preoperative three-dimensional dataset, whereas endoscopy provided direct visualization of the operative anatomy. The titanium mesh addressed the structural component of reconstruction, while the BFP provided vascularized biological coverage. The combination was therefore based on the complementary functions of the individual techniques rather than on the assumption that any single technology could solve all aspects of the surgical problem.

This distinction is clinically important. Extensive maxillary defects often involve both loss of skeletal support and loss of soft-tissue separation. Reconstruction with a rigid material alone may leave the implant dependent on inadequate soft-tissue coverage, whereas soft-tissue reconstruction without restoration of the skeletal framework may not adequately restore facial contour or orbital support.^{11,15–18,34} The combination of titanium mesh and a vascularized BFP offers a practical way of addressing these two components simultaneously in appropriately selected cases.^{19–22,36–38}

The present case also highlights the potential usefulness of combining navigation with endoscopic inspection. These technologies provide different forms of intraoperative information and can therefore complement rather than replace one another. Navigation assists with spatial orientation, while

endoscopy allows direct inspection of selected areas that may not be readily visible through the primary surgical field. 23–35

Importantly, the present case should be interpreted as an illustrative clinical application rather than evidence of treatment superiority or improved oncological survival. The principal objective remains complete and appropriately planned tumor removal, with definitive assessment of the resection margins by histopathological examination. Navigation, endoscopy, and digital planning should therefore be regarded as adjuncts that may assist the surgeon in achieving the planned procedure rather than as substitutes for sound oncological judgment.

The clinical relevance of this strategy lies primarily in the coordination of ablative and reconstructive planning. This may be particularly useful in extensive lesions involving the maxillary sinus, orbital floor, nasal cavity, or other anatomically complex regions where the surgical defect cannot be considered separately from the reconstruction that follows. The favorable structural and functional outcome observed in the present patient demonstrates that this integrated concept can be implemented successfully in an individual case.

Further evaluation in larger patient cohorts is necessary to determine whether the combination provides reproducible advantages in surgical accuracy, functional recovery, complication rates, quality of life, and long-term reconstructive stability.

6. CONCLUSIONS

Management of extensive maxillary ameloblastoma requires close coordination between oncological resection, three-dimensional anatomical orientation, and immediate reconstruction. In the present case, computer-assisted navigation was used to support intraoperative orientation during resection of an extensive maxillary ameloblastoma involving the maxillary sinus and orbital floor. Endoscopic visualization provided additional inspection of anatomically restricted areas that were difficult to evaluate through the primary operative field.

Immediate reconstruction with a pre-contoured titanium mesh restored the three-dimensional skeletal framework of the maxilla and involved orbital region, while a pedicled buccal fat pad flap provided vascularized soft-tissue coverage of the reconstructive field. At 12 months, the patient demonstrated satisfactory facial symmetry, preserved mastication, swallowing, and speech, complete intraoral epithelialization of the BFP, no clinically evident local recurrence, and no titanium mesh exposure or clinically apparent infection.

The principal novelty of this report is not the introduction

of a new surgical device or technique. Rather, it lies in the integrated application of established image-guided, endoscopic, ablative, and reconstructive techniques within a single treatment pathway for an extensive maxillary ameloblastoma. The case demonstrates how these complementary methods can be coordinated to address the anatomical, oncological, functional, and reconstructive requirements of a large maxillary defect.

The favorable postoperative result supports the technical feasibility of this integrated strategy in the present patient. However, the findings should not be interpreted as evidence of superiority over conventional surgical or reconstructive approaches, nor as evidence that navigation or endoscopic assistance improves long-term oncological control.

Because this report represents a single case with 12 months of follow-up, further clinical experience is required. Larger case series, comparative studies, standardized functional and patient-reported outcome measures, and longer-term oncological surveillance will be necessary to determine the reproducibility, safety, functional value, and long-term reconstructive and oncological outcomes of this approach

DECLARATIONS

Ethics Approval

Institutional ethical approval for publication of this clinical case should be reported according to the requirements of the participating institution and the target journal.

Patient Consent

Written informed consent for publication of the clinical information and associated clinical and radiological images should be explicitly documented.

Conflict of Interest

The authors declare no conflict of interest related to this manuscript.

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REVIEW ARTICLE

CONTEMPORARY CONCEPTS IN THE MANAGEMENT OF CLEFT LIP IN CHILDREN: CURRENT SURGICAL PRINCIPLES, MULTIDISCIPLINARY CARE, AND EMERGING DIGITAL TECHNOLOGIES-A NARRATIVE REVIEW

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Abstract

Background: Cleft lip represents one of the most prevalent congenital craniofacial anomalies, affecting approximately 1 in 700 live births worldwide. Over recent decades, management has shifted from isolated surgical repair toward comprehensive, multidisciplinary, and increasingly individualized treatment strategies. Despite major advances in surgical techniques, presurgical interventions, and digital technologies, substantial variability persists regarding optimal timing, operative approaches, and long-term therapeutic pathways.

Objective: This narrative review aims to critically evaluate contemporary concepts in pediatric cleft lip management, including embryological and genetic considerations, classification systems, diagnostic approaches, surgical techniques, presurgical orthopedic interventions, multidisciplinary rehabilitation, and emerging technologies that may facilitate personalized treatment planning.

Methods: A comprehensive literature search was conducted in PubMed, Scopus, Web of Science, and Google Scholar databases. Publications including systematic reviews, meta-analyses, clinical practice guidelines, randomized clinical trials, prospective cohort studies, and high-quality observational studies. Foundational publications that established major surgical principles and classification systems were additionally considered. The identified evidence was critically synthesized to provide an updated overview of current clinical concepts and future directions in cleft lip management.

Results: Current evidence demonstrates that successful cleft lip management depends on coordinated multidisciplinary care integrating surgical expertise, orthodontic guidance, pediatric dentistry, speech and hearing assessment, genetic evaluation, and psychosocial support. Contemporary cheiloplasty techniques, including rotation-advancement, anatomical subunit repair, and their modifications, provide predictable restoration of lip form and function when performed within structured treatment protocols. Presurgical nasoalveolar molding may improve anatomical alignment and facilitate primary repair, although indications and long-term benefits remain debated.

Recent developments in three-dimensional imaging, virtual surgical planning, digital simulation, and artificial intelligence-assisted facial analysis have introduced new opportunities for objective assessment, surgical precision, and individualized outcome prediction.

Conclusions: The management of cleft lip in children has evolved into a precision-based, multidisciplinary approach combining refined surgical principles with advanced diagnostic and digital technologies. While current strategies have substantially improved facial aesthetics, oral function, and quality of life, persistent heterogeneity in treatment protocols highlights the need for standardized outcome measures, prospective multicenter investigations, and evidence-based algorithms to optimize long-term care.

Keywords: cleft lip; pediatric craniofacial surgery; cheiloplasty; multidisciplinary treatment; nasoalveolar molding; virtual surgical planning; three-dimensional imaging

1. INTRODUCTION

Cleft lip with or without cleft palate (CL/P) is among the most common congenital craniofacial anomalies

and remains an important global health concern because of its long-term anatomical, functional, psychosocial, and developmental consequences. Although the most apparent manifestation is disruption of the upper lip, the condition may also affect feeding, speech and language

development, dental eruption, maxillofacial growth, nasal function, hearing, facial appearance, and psychosocial well-being. Consequently, contemporary cleft care has progressively shifted from isolated surgical closure of the lip defect toward coordinated, longitudinal, multidisciplinary management extending from infancy through adolescence and, when necessary, adulthood.^{1,3,25,26}

The prevalence of CL/P varies substantially between populations and geographic regions, reflecting differences in genetic background, environmental exposures, maternal characteristics, ascertainment, and access to specialized healthcare. Its etiology is considered multifactorial, involving interactions between genetic susceptibility and environmental factors rather than a single causative mechanism.^{1–6} Genetic studies have identified multiple susceptibility loci associated with craniofacial development, epithelial adhesion, neural crest cell biology, and tissue morphogenesis, while epidemiological research has demonstrated contributions from maternal and environmental factors.^{2–5}

Normal development of the upper lip requires coordinated growth, migration, and fusion of the facial prominences during early embryogenesis. Disturbance of these processes can result in a broad spectrum of phenotypes, ranging from subtle incomplete vermilion defects to complete unilateral or bilateral clefts extending through the alveolus and associated with nasal deformity.⁶ Phenotypic variability is influenced by the extent of tissue deficiency, alveolar and palatal involvement, nasal skeletal and soft-tissue abnormalities, and associated syndromic or nonsyndromic conditions.^{2,3,6}

Genetic investigations have substantially expanded the understanding of cleft pathogenesis. Genome-wide association studies and candidate-gene investigations support the concept that nonsyndromic cleft lip represents a genetically heterogeneous developmental disorder.^{4,5} Environmental and maternal factors may modify genetic susceptibility, with maternal smoking, diabetes, nutritional disturbances, obesity, alcohol exposure, and selected medications investigated as potential risk factors, although the strength and consistency of individual associations vary among studies.^{2,3,6} Increasing attention has also been directed toward epigenetic regulation and gene–environment interactions as potential mechanisms contributing to phenotypic variability.

Accurate clinical classification is essential for communication between cleft team members,

documentation of anatomical severity, treatment planning, and comparison of outcomes. The classification system introduced by Kernahan and Stark provided a simplified anatomical framework for describing cleft lip and palate, while subsequent modifications, including the symbolic “striped Y” system, improved its clinical applicability.^{7–9} Nevertheless, contemporary assessment increasingly recognizes that simple categorical classification may not adequately describe the three-dimensional anatomical variation observed among individual patients. The degree of lip deficiency, vermilion discontinuity, nasal asymmetry, alveolar involvement, and associated skeletal abnormalities must therefore be considered during individualized treatment planning.

The clinical consequences of CL/P extend beyond the primary anatomical defect. Infants may experience difficulties with feeding and nutrition, while later developmental stages may be complicated by dental abnormalities, altered maxillary growth, speech and language problems, hearing impairment, and psychosocial difficulties.^{1,2,25,26} These multiple needs explain why modern cleft management is increasingly organized around multidisciplinary teams rather than individual surgical intervention. Coordinated care permits repeated assessment of facial growth, speech, hearing, dental development, facial appearance, psychosocial adaptation, and quality of life throughout childhood.^{25,26}

Surgical repair remains the principal reconstructive intervention for cleft lip. The objectives of primary cheiloplasty extend beyond simple closure and include restoration of orbicularis oris continuity, appropriate vertical lip height, Cupid's bow symmetry, vermilion continuity, philtral architecture, nasal base position, and harmonious facial proportions. Historically established approaches include the Millard rotation-advancement technique, the Tennison-Randall triangular-flap method, modified rotation-advancement techniques, and the anatomical subunit approach developed by Fisher.^{15–19,32,36} Current surgical practice increasingly emphasizes individualized selection of the operative design according to cleft severity, tissue availability, nasal deformity, anatomical landmarks, surgeon experience, and anticipated growth rather than assuming that one technique is universally superior.

The anatomical subunit concept has been particularly influential in contemporary unilateral cleft lip repair because it seeks to position postoperative scars along recognizable facial anatomical boundaries while restoring the relationships between the philtral column, Cupid's bow, vermilion, and nasal base.^{16,32}

Comparative investigations indicate that both Fisher-based and modified Millard techniques can provide satisfactory outcomes, although differences may occur in vermilion symmetry and scar characteristics. Thus, surgical technique should be considered as one component of a broader reconstructive strategy.

Timing of primary cleft lip repair remains another important component of treatment planning. The procedure is commonly undertaken during infancy to restore lip function and anatomy, improve facial symmetry, facilitate feeding and psychosocial adaptation, and establish a favorable anatomical foundation for subsequent craniofacial development.^{23,35} However, optimal timing may vary according to the patient's general health, cleft severity, nutritional status, associated anomalies, institutional protocols, and availability of multidisciplinary care.

Presurgical infant orthopedic interventions represent another important component of contemporary cleft management. Nasoalveolar molding (NAM) was developed to modify cleft anatomy before primary repair by approximating the alveolar segments, reducing cleft width, improving nasal symmetry, and facilitating surgical closure.^{10–14} Although NAM has become established in many specialized cleft programs, its long-term effectiveness remains debated.

Available evidence demonstrates heterogeneity regarding long-term nasolabial aesthetics, dentoalveolar development, midfacial growth, treatment burden, and other clinically important outcomes. More recent evidence suggests that NAM may reduce cleft width in selected patients, whereas the certainty of evidence for long-term aesthetic and functional benefits remains limited. Therefore, NAM should be considered within an individualized multidisciplinary treatment pathway rather than as a universally mandatory intervention.

Primary nasal management has also become increasingly integrated with cleft lip repair. In unilateral and bilateral clefts, nasal deformity is closely related to abnormal positioning of the alar cartilage, nasal base, columella, and surrounding soft tissues.^{20–22,33,37}

Contemporary approaches increasingly recognize the lip and nasal components as a coordinated anatomical unit, with the objective of restoring facial relationships and improving symmetry while potentially reducing secondary deformities.

Assessment of treatment outcomes has consequently evolved from predominantly subjective clinical judgment toward standardized multidimensional evaluation. Nasolabial appearance, lip symmetry, scar quality, nasal morphology, dental and skeletal development, speech, hearing, and patient-reported quality of life may all contribute to the overall assessment of treatment success.^{24–26,37–40} Standardized outcome systems and three-dimensional measurements have become increasingly important because they permit more reproducible comparisons between surgical techniques and treatment centers, particularly in the context of substantial intercenter variation in cleft treatment outcomes.^{25,39,40}

Three-dimensional imaging has introduced additional opportunities for quantitative evaluation of craniofacial morphology. Conventional two-dimensional photographs remain useful for routine clinical assessment, but three-dimensional surface imaging permits measurement of facial asymmetry, nasal projection, lip dimensions, soft-tissue relationships, and postoperative morphological changes.^{27,28} These technologies may improve documentation of growth, treatment outcomes, preoperative planning, and postoperative follow-up.

The expansion of digital workflows has further increased opportunities for individualized cleft care. Three-dimensional facial imaging can be combined with digital morphometric analysis, virtual surgical planning, computer-aided design and manufacturing (CAD/CAM), and three-dimensional printing to create patient-specific treatment simulations and customized devices.^{27–31} Such technologies may facilitate anatomical assessment, multidisciplinary communication, and quantitative comparison between planned and achieved surgical outcomes. Digital approaches are particularly promising for longitudinal monitoring of facial morphology during growth.

Artificial intelligence (AI) represents a newer development within this digital transformation. AI-assisted image analysis and automated landmark detection may facilitate objective characterization of craniofacial morphology and identify patterns that are difficult to assess consistently using conventional examination.³⁰ However, AI should currently be regarded primarily as a decision-support technology rather than a replacement for clinical expertise. Its implementation in cleft care requires sufficiently large and representative datasets, external validation, transparent algorithms, standardized imaging protocols, and careful assessment of bias and reproducibility. Prospective studies are therefore required to establish its clinical value.

Despite major advances in surgical reconstruction, presurgical orthopedics, multidisciplinary care, and digital assessment, important areas of uncertainty remain.

These include the optimal timing and technical design of primary repair, the comparative effectiveness of different cheiloplasty techniques, the indications and long-term benefits of NAM, strategies for prevention and correction of secondary nasal deformity, and the development of standardized outcome measures.^{33–}

^{35,38–41} Contemporary evidence also demonstrates persistent variation among cleft centers, suggesting that treatment outcomes may depend on institutional protocols, surgical experience, patient characteristics, and access to comprehensive multidisciplinary services.

Accordingly, contemporary cleft lip management should be regarded as a longitudinal and individualized process rather than a single surgical event. The integration of anatomical assessment, refined cheiloplasty techniques, presurgical orthopedic interventions, multidisciplinary rehabilitation, standardized outcome evaluation, and emerging digital technologies provides an increasingly comprehensive framework for pediatric cleft care. The present narrative review therefore aims to critically synthesize current concepts in the management of cleft lip in children, with particular emphasis on embryology and genetics, classification, surgical reconstruction, presurgical orthopedic management, multidisciplinary care, three-dimensional and digital technologies, artificial intelligence-assisted assessment, and future directions toward more precise and patient-specific craniofacial treatment.

1. MATERIALS AND METHODS

1.1 Study Design and Literature Review Approach

The present article was designed as a narrative review to provide an updated and comprehensive analysis of contemporary concepts in the management of cleft lip in children. The review focused on the evolution of treatment strategies, including primary surgical reconstruction, presurgical orthopedic interventions, multidisciplinary care, three-dimensional assessment, digital treatment planning, and emerging artificial intelligence-based technologies.

A narrative review methodology was selected because cleft lip management encompasses a broad range of clinical and scientific domains, including embryology,

genetics, classification, surgical reconstruction, nasoalveolar molding, craniofacial growth, functional rehabilitation, aesthetic assessment, quality of life, and digital technologies. The available literature includes historical surgical descriptions, observational studies, comparative clinical investigations, systematic reviews, and multidisciplinary outcome studies. Consequently, narrative synthesis allows these heterogeneous sources to be considered within a common clinical framework rather than restricting the analysis to studies with directly comparable designs or outcomes.^{1–6,10–14,23–35}

No systematic review protocol was registered, and no quantitative meta-analysis was performed. The purpose of the present review was to synthesize and critically interpret the available literature concerning contemporary clinical principles and emerging developments in pediatric cleft lip management.

1.2. Literature Search Strategy

A comprehensive literature search was conducted using PubMed/MEDLINE, Scopus, Web of Science, and Google Scholar. Publications published between January 2015 and June 2026 were prioritized to identify recent developments in cleft lip management. In addition, selected earlier publications were included when they represented important contributions to the development of cleft classification, surgical techniques, presurgical orthopedic treatment, outcome assessment, and fundamental principles of cleft care.^{7–19,23–25}

The search strategy combined controlled vocabulary and free-text terms related to cleft lip, cleft lip and palate, pediatric craniofacial surgery, primary cheiloplasty, surgical repair, nasoalveolar molding, multidisciplinary care, three-dimensional imaging, digital treatment planning, and artificial intelligence.

The principal search terms included:

“cleft lip”; “cleft lip and palate”; “orofacial cleft”; “children”; “pediatric craniofacial surgery”; “cheiloplasty”; “primary cleft lip repair”; “Millard technique”; “Fisher anatomical subunit repair”; “Tennison-Randall repair”; “Mohler modification”; “nasoalveolar molding”; “NAM”; “multidisciplinary cleft care”; “three-dimensional imaging”; “virtual surgical planning”; “CAD/CAM”; “three-dimensional printing”; “artificial intelligence”; “facial analysis”; “speech outcomes”; “facial growth”; and “quality of life”.

Additional publications were identified by manually screening the reference lists of relevant reviews and major

clinical investigations. Particular attention was given to studies addressing surgical outcomes, nasolabial appearance, presurgical nasoalveolar molding, long-term treatment outcomes, three-dimensional facial assessment, and quality-of-life measures.^{10–14,24–31,38–40}

1.3 Literature Selection and Eligibility Considerations

Literature was selected according to its clinical relevance, scientific contribution, and applicability to contemporary cleft lip management. Priority was given to systematic reviews, clinical investigations, comparative surgical studies, longitudinal cohort studies, multicenter studies, and publications describing standardized outcome assessment. The reviewed literature covered the principal domains of pediatric cleft lip management, including:

- 1.1.1 embryology, epidemiology, genetics, and environmental risk factors;^{1–6}
- 1.1.2 classification and anatomical assessment of cleft lip and palate;^{7–9}
- 1.1.3 primary cleft lip repair and surgical technique selection;^{15–23,32–33,36,37,41}
- 1.1.4 presurgical nasoalveolar molding and related orthopedic approaches;^{10–14}
- 1.1.5 nasolabial and aesthetic outcome assessment;^{24,25,37–40}
- 1.1.6 multidisciplinary treatment and long-term outcomes;^{23,25,26}
- 1.1.7 three-dimensional facial imaging and digital assessment;^{27,28,38}
- 1.1.8 computer-assisted and digital treatment planning;^{29–31}
- 1.1.9 and emerging applications of artificial intelligence in craniofacial diagnosis and treatment planning.³⁰

Studies dealing exclusively with isolated cleft palate without clinically relevant information concerning cleft lip were not considered central to the present review. Duplicate publications, conference abstracts without sufficient methodological information, and non-scientific sources were also excluded. When multiple publications addressed similar clinical questions, greater emphasis was placed on studies with stronger study designs, larger patient cohorts, longitudinal follow-up, objective outcome assessment, or standardized evaluation methods.

1.4 Data Extraction and Narrative Synthesis

Information from the selected publications was reviewed and organized according to the principal clinical domains of cleft lip management. Extracted information included publication characteristics, patient populations, treatment approaches, surgical techniques, timing of intervention, presurgical interventions, outcome assessment methods, aesthetic and functional outcomes, complications, long-term findings, and reported limitations.

Particular attention was given to evidence concerning the anatomical principles of primary cheiloplasty, including restoration of lip symmetry, orbicularis oris continuity, philtral anatomy, vermilion alignment, and correction of associated nasal deformity.^{15–23,32–33,36,37,41}

Evidence concerning presurgical nasoalveolar molding was evaluated with particular consideration of its proposed effects on preoperative anatomical alignment and nasal symmetry, as well as the continuing uncertainty regarding its long-term influence on definitive facial growth and treatment outcomes.^{10–14}

For multidisciplinary care, the synthesis considered evidence addressing treatment outcomes, nasolabial appearance, craniofacial development, patient and parent satisfaction, and quality of life.^{24–26}

Recent literature concerning three-dimensional imaging, digital workflows, and artificial intelligence was reviewed to assess their potential contribution to objective facial analysis, treatment planning, surgical simulation, and individualized outcome assessment.^{27–31,38} Because the included literature demonstrated substantial heterogeneity in patient populations, treatment protocols, surgical techniques, outcome measures, and follow-up duration, the findings were synthesized qualitatively rather than quantitatively. The narrative synthesis was therefore used to identify areas of consistent evidence, areas of controversy, emerging technologies, and remaining research gaps.

1.5 Interpretation of Evidence

As this study was designed as a narrative review, a formal methodological quality assessment and quantitative risk-of-bias analysis were not performed. Nevertheless, the interpretation of the literature considered differences in study design, sample size, follow-up duration, outcome measurement, and methodological rigor. Greater weight was given to longitudinal and multicenter investigations, systematic reviews, comparative studies, and studies using standardized or objective outcome assessment. For example, standardized assessment of nasolabial

appearance has been described using structured rating methods, while multicenter studies such as the Eurocleft investigations have demonstrated substantial intercenter variation in treatment protocols and outcomes.^{24,25} Evidence derived from retrospective investigations, individual institutional series, or expert-based recommendations was interpreted within the limitations inherent to those study designs.

2 RESULTS

2.4 Epidemiology and Etiological Factors of Cleft Lip

Cleft lip with or without cleft palate (CL/P) remains one of the most common congenital craniofacial anomalies worldwide and represents a complex developmental disorder characterized by considerable variation in clinical presentation, genetic background, and associated functional consequences. The reviewed literature indicates that cleft lip should not be considered a single pathological entity but rather a

heterogeneous group of craniofacial developmental disorders resulting from disturbances in facial morphogenesis during early embryonic life. Current evidence supports a multifactorial model in which genetic susceptibility interacts with environmental influences during critical periods of craniofacial development, leading to variable manifestations ranging from minor incomplete defects to complete unilateral or bilateral clefts involving the lip, alveolus, and associated nasal structures.^{1–6} Epidemiological investigations have demonstrated significant geographic and population-based differences in the prevalence of cleft lip. The overall incidence of cleft lip with or without cleft palate is generally estimated at approximately 1 per 700 live births; however, reported frequencies vary substantially according to ethnic background, geographical region, socioeconomic conditions, and environmental exposures. Higher prevalence rates have traditionally been described among Asian and Native American populations, whereas lower rates have been observed among populations of African ancestry. These variations support the contribution of both genetic diversity and environmental modifiers to the development of orofacial clefts.^{1,5,6} Representative epidemiological and etiological studies are summarized in Table 1.

Table 1. Representative Studies Evaluating Epidemiology and Etiological Factors of Cleft Lip

Study / Source	Study Focus	Principal Findings	Clinical / Etiological Relevance
Genetic association studies	Genetic susceptibility to CL/P	Multiple susceptibility loci and genes contribute to craniofacial development	Supports multifactorial and genetically heterogeneous etiology
IRF6 investigations	IRF6 and cleft susceptibility	IRF6 is strongly associated with syndromic and nonsyndromic clefting	Important for epithelial differentiation and craniofacial development
Genome-wide association studies	Common genetic variants	Associations involving IRF6, MSX1, PAX7, BMP4, VAX1, TP63 and 8q24	Demonstrates involvement of multiple developmental pathways
Epidemiological studies	Population and geographic variation	Prevalence varies according to ancestry, geography and environmental exposure	Supports genetic and environmental contributions
Maternal and environmental studies	Potential modifiable risk factors	Smoking, diabetes, obesity, nutritional disturbances, alcohol and selected medications have been investigated	Suggests interaction between environmental exposure and genetic susceptibility
Epigenetic studies	Gene regulation and environmental interaction	DNA methylation and microRNA mechanisms may modify craniofacial development	Provides emerging mechanistic and preventive perspectives
Syndromic cleft studies	Associated congenital abnormalities	Clefting may occur as part of broader developmental syndromes	Supports genetic assessment and multidisciplinary management

The distribution pattern of cleft lip also demonstrates considerable clinical variability. Unilateral clefts occur more frequently than bilateral defects, with left-sided involvement representing the most common unilateral presentation. The severity of the deformity depends on the extent of failure of fusion between the maxillary and medial nasal prominences and may involve isolated lip discontinuity or extend posteriorly through the alveolar ridge and palate. This phenotypic variability has important implications for surgical planning, functional rehabilitation, and long-term outcome assessment.^{1,6}

Advances in molecular genetics have substantially changed the understanding of cleft lip etiology. Contemporary evidence indicates that nonsyndromic cleft lip represents the majority of cases and results from the combined effects of multiple genetic variants interacting with environmental factors rather than from a single causative mutation. Genome-wide association studies and candidate gene analyses have identified several susceptibility loci involved in craniofacial development, epithelial differentiation, cell migration, and tissue remodeling pathways. Among the most consistently reported genetic contributors, IRF6 (interferon regulatory factor 6) represents one of the strongest susceptibility genes associated with both syndromic and nonsyndromic forms of cleft lip. IRF6 plays a critical role in epithelial differentiation and periderm development, processes essential for normal fusion of facial structures during embryogenesis.^{2–4}

Other genetic factors implicated in cleft lip susceptibility include MSX1, PAX7, BMP4, VAX1, TP63, and chromosomal regions such as 8q24, which have been identified through genome-wide association studies and molecular investigations. These findings have demonstrated that cleft lip development involves multiple biological pathways regulating neural crest cell migration, epithelial adhesion, extracellular matrix formation, and craniofacial patterning. Rather than representing isolated genetic abnormalities, cleft lip is now recognized as a complex developmental condition influenced by the interaction of multiple genetic variants with external factors.^{2–4}

Environmental and maternal factors represent another important component of cleft lip pathogenesis. Multiple epidemiological studies have identified maternal smoking, alcohol consumption, diabetes mellitus, obesity, nutritional deficiencies, particularly inadequate folate intake, and exposure to certain teratogenic medications as potential risk factors. However, the strength of these associations varies considerably among populations, suggesting that environmental influences may modify cleft risk differently depending on individual genetic susceptibility and population-specific characteristics.^{2,3,6}

Recent research has expanded the concept of cleft lip development through investigation of epigenetic mechanisms. Alterations in DNA methylation patterns, microRNA regulation, and other mechanisms controlling gene expression have been proposed as potential pathways through which environmental exposures influence embryonic craniofacial development. Although the clinical application of epigenetic findings remains limited, these discoveries provide new perspectives regarding disease mechanisms, early risk assessment, and future preventive strategies.^{2,3}

An important distinction in clinical evaluation is the differentiation between syndromic and nonsyndromic cleft lip. Syndromic forms occur as part of broader developmental disorders and may involve multiple organ systems, requiring detailed clinical assessment and genetic evaluation. More than 500 syndromes have been reported in association with orofacial clefts, with Van der Woude syndrome, commonly associated with mutations affecting IRF6, representing one of the best-characterized examples. Recognition of syndromic features is essential because it influences genetic counseling, treatment planning, and long-term patient management.^{3,6}

Overall, current evidence demonstrates that cleft lip results from a complex interaction between embryological processes, genetic susceptibility, and environmental influences. Understanding these mechanisms has clinical relevance beyond etiological classification, as it contributes to improved prenatal counseling, individualized risk assessment, multidisciplinary treatment planning, and the development of future precision-based approaches in craniofacial care.^{1–6}

2.5 Classification and Clinical Assessment of Cleft Lip

Accurate classification of cleft lip remains a fundamental component of contemporary cleft care because it provides the basis for diagnosis, communication among multidisciplinary specialists, treatment planning, surgical decision-making, and evaluation of clinical outcomes. The reviewed literature demonstrates that cleft lip represents a highly variable anatomical condition, and therefore classification systems have progressively evolved from simple descriptions of the location and extent of the defect toward more comprehensive approaches incorporating anatomical severity, functional impairment, associated anomalies, and objective three-dimensional morphological analysis.^{6–9} Historically, classification systems were primarily based on embryological concepts and anatomical relationships between the cleft defect and the incisive foramen. The classification proposed by Kernahan and Stark introduced a simplified anatomical framework distinguishing involvement of the primary and secondary palate and became one of the most widely recognized systems in cleft surgery.⁷

This concept was further developed through the “striped Y” diagram introduced by Kernahan, which provided a practical visual method for recording the location and extent of cleft involvement.⁸

The modified striped Y classification proposed by Elsahy further refined this approach by improving documentation of

anatomical variations and complex cleft patterns.⁹ A summary of the principal classification systems and contemporary clinical assessment approaches is presented in Table 2.

Table 2. Classification Systems and Clinical Assessment Approaches in Cleft Lip

Classification / Assessment Approach	Main Characteristics	Clinical Application	Main Advantages	Main Limitations
Kernahan and Stark classification ⁷	Embryologically based classification distinguishing primary and secondary palate involvement	Basic anatomical classification and multidisciplinary communication	Simple and historically well established	Limited description of detailed three-dimensional soft-tissue and nasal abnormalities
Kernahan “Striped Y” classification ⁸	Symbolic Y-shaped diagram representing anatomical extent	Documentation and visual communication	Easy to record and clinically practical	May not adequately represent complex anatomical variations
Modified “Striped Y” classification ^{8,9}	Expanded symbolic representation of cleft patterns	Classification of complex cleft configurations	Improves anatomical documentation	Primarily descriptive; limited quantitative assessment
Unilateral cleft lip classification ^{1,6}	Incomplete or complete involvement with possible alveolar and palatal extension	Surgical planning and assessment of asymmetry	Clinically relevant for operative planning	Does not fully quantify nasal, soft-tissue or skeletal abnormalities
Bilateral cleft lip classification ^{1,6}	Assessment of prolabium, columella, premaxilla, alveolus and nasal deformity	Planning primary lip and nasal reconstruction	Recognizes greater anatomical complexity	Phenotypic variability may exceed simple categories
Clinical anatomical assessment ⁶	Lip height, Cupid’s bow, philtral columns, vermilion, orbicularis oris, nasal base, alar position, columella and alveolar segments	Diagnosis, surgical planning and postoperative assessment	Patient-specific and directly treatment relevant	Examiner-dependent and potentially subjective
Syndromic and nonsyndromic assessment ^{3,6}	Identification of associated congenital abnormalities	Genetic evaluation, counseling and multidisciplinary planning	Identifies patients requiring broader assessment	Requires multidisciplinary expertise
Prenatal two-dimensional ultrasonography ⁶	Prenatal visualization of facial structures	Prenatal diagnosis and parental counseling	Widely available and non-invasive	Limited three-dimensional visualization
Three-dimensional prenatal imaging ⁶	Three-dimensional visualization of fetal facial structures	Prenatal characterization and counseling	Improved visualization of facial anatomy	Availability and image quality vary
Three-dimensional stereophotogrammetry ^{27,28}	Radiation-free three-dimensional surface imaging	Facial symmetry, lip/nasal morphology and longitudinal outcomes	Objective and reproducible	Requires specialized equipment and standardized acquisition
Digital morphometric analysis ²⁷⁻³⁰	Quantitative facial landmarks, distances, angles and surface morphology	Objective severity and treatment assessment	Reduces observer dependence	Dependent on image quality and landmark reliability
Virtual surgical planning and CAD/CAM ²⁹	Three-dimensional imaging integrated with computer-assisted planning and digital modeling	Preoperative simulation and customized devices	Improves visualization and multidisciplinary communication	Requires specialized software and expertise
Artificial intelligence-assisted assessment ³⁰	Automated landmark detection, morphology analysis and pattern recognition	Decision support, classification and outcome assessment	Potential for rapid standardized analysis	Requires large representative datasets and external validation

Although these traditional classification systems remain clinically useful, contemporary cleft management requires a more detailed description of the deformity. Modern evaluation considers not only the presence or absence of a cleft but also its laterality, completeness, alveolar involvement, nasal deformity, soft tissue deficiency, muscle discontinuity, and associated craniofacial abnormalities. This approach is particularly important because two patients with apparently similar cleft types may demonstrate substantially different anatomical challenges requiring individualized surgical strategies.^{6–9}

From a clinical perspective, cleft lip is generally categorized according to laterality and severity. Unilateral clefts represent the most common form and result from incomplete fusion between the maxillary and medial nasal prominences on one side. Depending on severity, unilateral clefts may be incomplete, involving only the lip structures, or complete, extending through the alveolus and frequently associated with cleft palate. Bilateral clefts demonstrate greater anatomical complexity because of disruption of the central prolabial segment, altered columellar development, nasal deformity, and possible premaxillary displacement.^{1,6}

Clinical assessment begins immediately after birth and requires systematic evaluation of both the cleft deformity and the overall health status of the infant. Initial examination should include assessment of feeding ability, airway function, associated congenital anomalies, nutritional status, and the presence of syndromic characteristics. A detailed facial examination should document the morphology of the upper lip, including Cupid's bow configuration, philtral column development, vermilion continuity, lip height, orbicularis oris muscle continuity, nasal base symmetry, alar position, columellar length, and alveolar segment relationship. These anatomical characteristics directly influence surgical planning and expected postoperative outcomes.^{1,6}

The identification of associated anomalies represents an essential component of cleft evaluation. Children with orofacial clefts may present with additional congenital abnormalities affecting multiple organ systems, particularly in syndromic cases. Therefore, comprehensive assessment, including genetic evaluation when indicated, is necessary to differentiate isolated cleft lip from conditions requiring broader medical management.^{3,6}

Advances in prenatal diagnosis have significantly influenced contemporary cleft care pathways. Traditional two-dimensional ultrasonography has been progressively supplemented by three-dimensional fetal imaging techniques, allowing improved visualization of facial structures and more accurate prenatal characterization of cleft severity. Early diagnosis facilitates parental counseling, psychological preparation, delivery planning, and timely referral to specialized multidisciplinary cleft teams.⁶

Three-dimensional imaging technologies have further transformed the evaluation of cleft lip by enabling objective and reproducible assessment of facial morphology. Three-dimensional stereophotogrammetry provides accurate measurements of facial symmetry, lip contour, nasal morphology, and postoperative changes without radiation exposure. Compared with conventional two-dimensional photography, three-dimensional analysis reduces observer dependency and allows quantitative evaluation of subtle anatomical differences that may not be detectable through routine clinical assessment.^{27,28}

The application of digital workflows has expanded beyond diagnostic assessment toward comprehensive treatment planning. Three-dimensional imaging data can be integrated with computer-assisted planning systems to simulate surgical procedures, evaluate anatomical relationships, and monitor postoperative changes over time. In cleft orthodontics and craniofacial rehabilitation, digital models and CAD/CAM approaches have increasingly supplemented traditional impressions and manual laboratory procedures, improving communication among surgeons, orthodontists, and dental specialists.²⁹ Artificial intelligence-assisted facial analysis represents an emerging development in cleft classification and outcome prediction. Machine-learning algorithms have demonstrated potential for automated facial landmark detection, severity classification, and quantitative analysis of craniofacial morphology. Although artificial intelligence systems currently function primarily as supportive tools rather than replacements for specialist evaluation, they may contribute to improved standardization, objective assessment, and personalized treatment planning in future cleft care models.³⁰ Overall, the evolution of cleft lip classification reflects a transition from descriptive anatomical systems toward integrated diagnostic approaches combining clinical examination, genetic assessment, digital imaging, and quantitative facial analysis. Such comprehensive evaluation allows more accurate characterization of individual deformities and supports personalized treatment strategies aimed at optimizing both functional recovery and aesthetic outcomes.^{6–9,27–30}

2.6 Contemporary Surgical Management of Cleft Lip

Primary cheiloplasty remains the cornerstone of cleft lip management, with the main objectives of restoring anatomical continuity, re-establishing functional orbicularis oris muscle activity, improving facial symmetry, and achieving an aesthetically acceptable upper lip contour. Contemporary cleft lip surgery has evolved substantially from simple closure of the visible defect toward anatomical reconstruction based on restoration of lip subunits, precise muscle repair, reconstruction of philtral anatomy, accurate vermilion alignment, and preservation of long-term facial growth potential. The principal contemporary surgical techniques and their reconstructive concepts are illustrated in Figure 1.

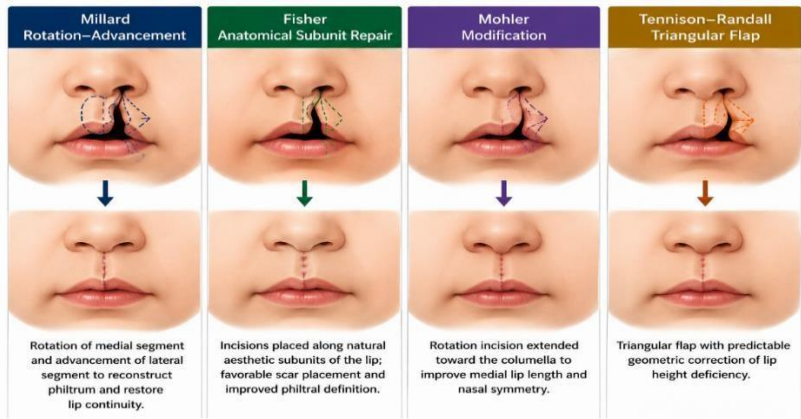


Figure 1. Contemporary Surgical Techniques for Cleft Lip Repair.

Comparison of the principal surgical techniques used for unilateral cleft lip repair, including the Millard rotation–advancement technique, Fisher anatomical subunit repair, Mohler modification, and Tennison–Randall triangular flap technique. Although these procedures differ in incision design and tissue rearrangement principles, all aim to restore orbicularis oris muscle continuity, reconstruct the philtral column, achieve symmetrical Cupid’s bow and vermilion alignment, and minimize scar deformity.^{15–19} Several surgical techniques have been developed during the last decades, with the Millard rotation–advancement technique, Fisher anatomical subunit repair, Mohler modification, and Tennison–Randall triangular flap technique representing the most commonly reported approaches in contemporary cleft lip surgery. The principal characteristics, surgical principles, advantages, and limitations of these techniques are summarized in Table 3.^{15–19}

Table 3. Comparison of Principal Primary Cleft Lip Repair Techniques

Technique	Key Surgical Principle	Main Advantages	Potential Limitations / Considerations
Millard rotation-advancement	Rotation of the medial lip segment with advancement of the lateral segment	Flexible design; permits adjustment of lip height and Cupid’s bow; widely used	Scar orientation and vermilion symmetry may vary; technically demanding in severe clefts
Tennison-Randall triangular flap	Triangular lateral lip flap interdigitated with the medial segment	Predictable lengthening and geometric planning	Can create less anatomically aligned scars and requires accurate flap design
Mohler modification	Modified rotation-advancement with extended back-cut and refinement of rotation	Facilitates medial segment rotation and lip height correction	Outcome depends on precise design and tissue availability
Fisher anatomical subunit repair	Repair based on anatomical subunits with scar placement along natural boundaries	Anatomical reconstruction and potentially favorable scar camouflage	Requires detailed anatomical planning and experience
Modified rotation-advancement techniques	Adaptations of established rotation-advancement principles	Allows individualized correction according to cleft morphology	Technique-specific variations complicate direct comparison

Although these techniques differ in their design principles, the fundamental objectives remain consistent: restoration of normal lip anatomy, reconstruction of muscular continuity, preservation of facial landmarks, improvement of vermilion symmetry, and reduction of postoperative scar visibility.^{15–19} The Millard rotation–advancement technique remains one of the most widely performed approaches for unilateral cleft lip repair because of its versatility and adaptability to different cleft morphologies. The basic principle involves rotation of the medial lip segment downward to restore vertical lip height and advancement of the lateral segment to close the remaining defect.

This approach allows reconstruction of the philtral column, Cupid's bow, and vermilion border while maintaining natural anatomical relationships.^{15,36} Clinical experience accumulated over several decades has demonstrated favorable functional and aesthetic outcomes following Millard repair. However, limitations have also been described, including possible vermilion irregularity, scar asymmetry, and residual distortion in selected cases. These limitations have contributed to the development of alternative techniques focusing on more precise anatomical reconstruction and improved aesthetic predictability.^{15,36}

The Fisher anatomical subunit repair introduced a different reconstructive philosophy by emphasizing the aesthetic subunits of the upper lip. Rather than relying primarily on geometric tissue rearrangement, this technique places incisions according to natural anatomical boundaries, particularly the philtral column and facial subunit junctions. The aim is to achieve improved scar camouflage, restoration of philtral definition, and more predictable vermilion reconstruction.¹⁶ Comparative studies evaluating Fisher and modified Millard repairs have demonstrated that both techniques can achieve satisfactory clinical outcomes. Available evidence does not support universal superiority of one approach over another; instead, differences are mainly observed in specific aesthetic parameters, including scar appearance, vermilion contour, and lip symmetry. These findings emphasize that successful cleft lip repair depends primarily on accurate anatomical reconstruction, surgeon experience, appropriate patient selection, and long-term multidisciplinary follow-up rather than the selection of a single operative method.^{32,34} The Mohler modification represents an important refinement of the rotation–advancement concept. By extending the rotation incision toward the columellar region, this modification aims to improve medial lip length, enhance philtral reconstruction, and achieve better balance between the repaired lip and adjacent nasal structures.^{17,37}

Although favorable results have been reported with the Mohler approach, outcomes remain influenced by cleft severity, tissue characteristics, and surgical technique. Comparative evidence suggests that differences between Mohler, Fisher, and other rotation–advancement modifications are generally related to selected aesthetic characteristics rather than overall functional success.^{17,37}

The Tennison–Randall triangular flap technique represents one of the historically important approaches in unilateral cleft lip repair. The technique uses a triangular flap from the lateral lip segment to correct vertical deficiency and improve alignment of the vermilion border. Its predictable geometric principles contributed significantly to the evolution of modern cleft lip reconstruction.^{18,19} Despite its historical importance, contemporary practice has increasingly shifted toward anatomical subunit-based approaches because of greater emphasis on scar placement, restoration of natural facial landmarks, and long-term aesthetic outcomes. Nevertheless, the principles introduced by Tennison and Randall remain relevant and continue to influence current surgical concepts.^{18,19} The major anatomical objectives of modern cleft lip reconstruction are summarized in Figure 2.

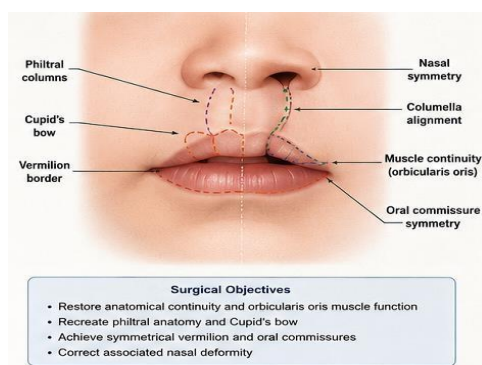


Figure 2. Key Anatomical Goals in Cleft Lip Repair.

Illustration of the principal anatomical objectives of primary cleft lip reconstruction. Modern repair focuses on restoration of the philtral columns, Cupid's bow, vermilion continuity, orbicularis oris muscle integrity, oral commissure symmetry, and balanced soft tissue relationships to optimize functional and aesthetic outcomes.^{16,36}

Objective evaluation methods have significantly influenced the assessment of surgical outcomes after cleft lip repair. Traditional assessment based on clinical photographs and expert opinion has progressively been complemented by standardized anthropometric measurements, validated aesthetic scoring systems, three-dimensional facial analysis, scar evaluation, and patient-reported outcome measures.^{24,38–40}

Three-dimensional imaging technologies have introduced new possibilities for quantitative assessment of postoperative facial morphology. These methods allow objective evaluation of lip symmetry, facial proportions, and soft tissue changes during growth. Compared with conventional two-dimensional photography, three-dimensional stereophotogrammetry provides improved reproducibility and reduces observer-related variability.^{27,28,38} The historical evolution of cleft lip surgery and contemporary approaches to outcome evaluation are summarized in Figures 3 and 4.

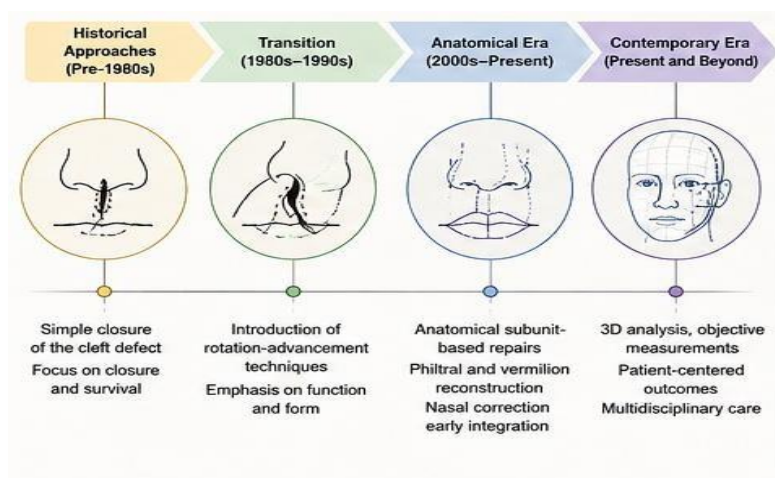


Figure 3. Evolution of Cleft Lip Surgical Approaches.

Overview of the evolution of cleft lip surgery from simple defect closure toward anatomical reconstruction, muscle-based repair, aesthetic subunit restoration, and multidisciplinary patient-centered care. Contemporary management emphasizes restoration of normal anatomy, functional rehabilitation, and long-term evaluation of outcomes.^{15,16,38}

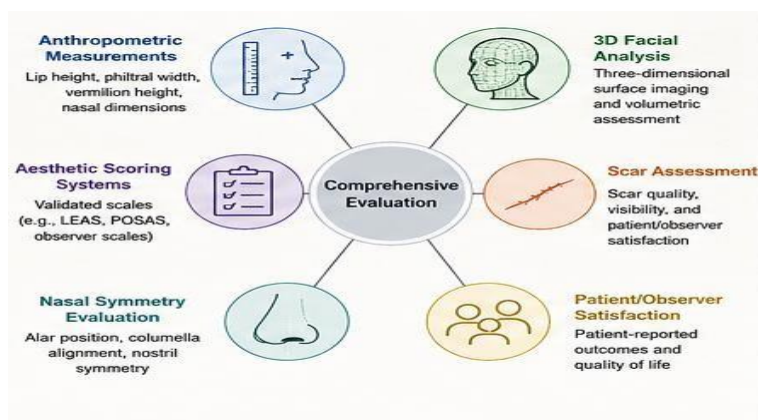


Figure 4. Methods for Evaluation of Surgical Outcomes.

Overall, current evidence indicates that no single surgical technique demonstrates universal superiority for all patients. Successful cleft lip reconstruction depends on individualized surgical planning, accurate anatomical restoration, preservation of functional structures, surgeon expertise, standardized outcome evaluation, and coordinated long-term multidisciplinary care.^{16, 32, 34, 36, 38–40} The overall evidence synthesized in this review is summarized in Figure 5.

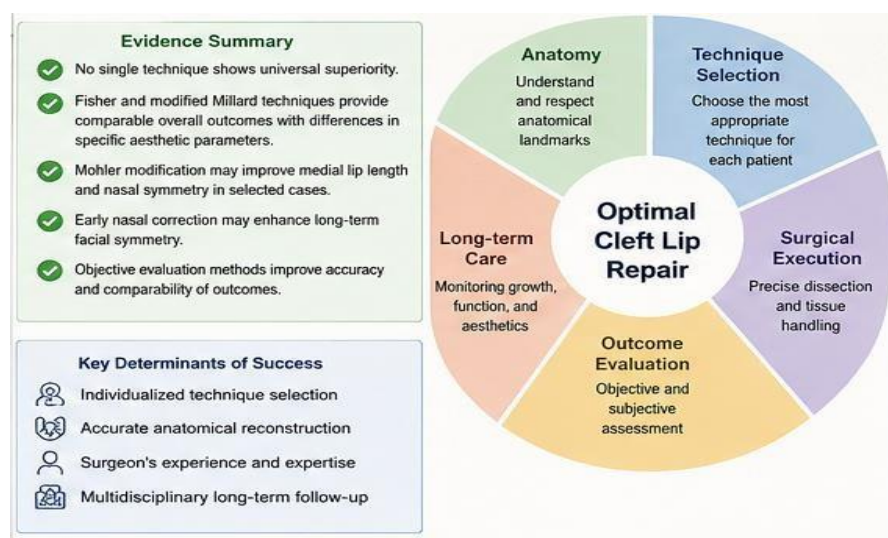


Figure 5. Evidence Summary and Key Determinants of Successful Cleft Lip Repair.

Summary of the main determinants influencing outcomes after cleft lip reconstruction. Current evidence indicates that successful results are primarily associated with individualized treatment planning, anatomical precision, surgical expertise, objective postoperative assessment, and long-term multidisciplinary follow-up rather than with a single universally superior technique.^{16,32,36,38_40}

2.7 Presurgical Orthopedic Management: Nasoalveolar Molding (NAM)

Presurgical nasoalveolar molding (NAM) has become an important component of contemporary multidisciplinary management of infants born with cleft lip and palate. Unlike surgical repair, which restores anatomical continuity after birth, NAM represents a preparatory orthopedic intervention designed to optimize the cleft anatomy before primary cheiloplasty. The principal objectives of NAM include reduction of the alveolar gap, improvement of maxillary segment alignment, approximation of cleft margins, molding of the displaced nasal cartilage, and reduction of soft tissue tension during primary surgical repair.^{10–14}

The reviewed literature demonstrates that NAM is particularly valuable in infants with wide unilateral clefts and bilateral cleft deformities, where significant alveolar separation, nasal asymmetry, and distortion of the surrounding soft tissues may complicate primary reconstruction. By improving the preoperative anatomical conditions, NAM may facilitate surgical closure, enhance nasal symmetry, and contribute to more favorable early aesthetic outcomes.^{10,12}

The concept of NAM was introduced by Grayson and colleagues as an extension of traditional presurgical orthopedic treatment. The technique combines intraoral alveolar molding with controlled nasal cartilage shaping through a nasal stent system, allowing simultaneous modification of the alveolar segments, nasal framework, and surrounding soft tissues during the neonatal period. This approach was based on the recognition that neonatal cartilage demonstrates increased plasticity, allowing controlled molding before surgical intervention.¹⁰

Subsequent clinical studies have evaluated the anatomical effects of NAM and demonstrated improvements in preoperative cleft width, alveolar alignment, and nasal symmetry. Maull et al. investigated the long-term influence of NAM on three-dimensional nasal morphology in unilateral cleft patients and reported favorable changes in nasal shape and symmetry following treatment.¹¹ Similarly, Barillas et al. demonstrated improved long-term nasal symmetry in unilateral cleft lip and palate patients treated with NAM compared with conventional surgical management without presurgical molding.¹²

The influence of NAM on nasal development has also been investigated through longitudinal studies. Liou and colleagues evaluated progressive changes in nasal symmetry and growth following NAM therapy and reported that early molding may provide measurable improvements in nasal morphology during subsequent development.¹³ These findings support the concept that presurgical orthopedic intervention may contribute not only to immediate surgical preparation but also to improved long-term facial symmetry.

Despite its widespread clinical application, the effectiveness and long-term benefits of NAM remain subjects of ongoing discussion. Although improvements in early nasal and alveolar morphology are consistently reported, evidence regarding its influence on definitive facial growth, maxillary development, and long-term functional outcomes remains limited. Differences in treatment protocols, appliance design, duration of therapy, surgical techniques, and outcome assessment methods contribute to variability among published studies.¹⁴

Recent technological developments have introduced digital approaches to NAM therapy. Three-dimensional imaging, computer-assisted design, and CAD/CAM technologies have enabled more precise appliance fabrication and improved documentation of treatment progress. Digital workflows may reduce laboratory complexity and improve reproducibility. A recent systematic review and meta-analysis of randomized controlled trials further evaluated digitally versus conventionally fabricated NAM appliances, providing contemporary evidence regarding the effectiveness of digital approaches.³¹

An important limitation of NAM is that successful treatment requires experienced multidisciplinary teams and significant family involvement. The therapy typically requires frequent adjustments, prolonged treatment duration, financial resources, and consistent parental cooperation. Therefore, patient selection and family counseling remain essential components of successful NAM protocols.¹⁴

Overall, current evidence supports NAM as a valuable presurgical adjunct in infants with cleft lip and palate. Its primary benefit appears to be optimization of the preoperative anatomical environment by improving alveolar alignment and nasal morphology rather than replacing surgical reconstruction. The principal indications, anatomical effects, potential benefits, and limitations of presurgical nasoalveolar molding are summarized in Table 4.^{10–14, 31}

Table 4. Presurgical Nasoalveolar Molding: Indications, Effects, and Limitations

Domain	Description	Clinical Implication
Primary objective	Approximation of alveolar segments and reduction of cleft width before surgery	May facilitate primary lip repair
Nasal molding	Gradual modification of nasal cartilage and soft-tissue position	May improve preoperative nasal symmetry
Alveolar alignment	Reduction of the separation between alveolar segments	May simplify surgical closure
Timing	Initiated during early infancy and continued until primary repair	Requires early referral and regular follow-up
Potential benefits	Improved presurgical anatomy and reduced cleft width in selected patients	May facilitate surgical reconstruction
Long-term evidence	Evidence for durable aesthetic, dentoalveolar and midfacial benefits remains heterogeneous	Routine universal use is not supported by high-certainty evidence
Treatment burden	Requires repeated appliance adjustment, monitoring and caregiver participation	Access, compliance and socioeconomic factors may affect feasibility
Digital NAM	Digital scans and CAD/CAM approaches can assist appliance design	May improve customization and workflow efficiency

2.8 Primary Nasal Reconstruction During Cleft Lip Repair: Contemporary Concepts, Techniques, and Long-Term Outcomes

Nasal deformity represents one of the most complex and aesthetically significant components of cleft lip and remains a major determinant of long-term facial harmony. The nasal abnormalities associated with cleft lip are not limited to external appearance but reflect a three-dimensional disturbance involving cartilage, soft tissues, and underlying

skeletal structures. Typical characteristics include lateral displacement of the alar base, flattening and malposition of the lower lateral cartilage on the cleft side, shortening of the columella, deviation of the nasal tip, widened or asymmetric nostrils, and altered relationship between the nose, upper lip, and maxillary structures. The severity of nasal deformity is closely associated with cleft type, extent of tissue deficiency, and degree of disruption of normal anatomical relationships.

Historically, correction of cleft-associated nasal deformity was frequently postponed until adolescence, when facial growth was considered sufficiently complete. However, contemporary concepts of cleft care have progressively shifted toward early nasal reconstruction performed simultaneously with primary cheiloplasty. This change in philosophy is based on improved understanding of neonatal cartilage characteristics, the potential for early remodeling, and the recognition that untreated nasal cartilage displacement may contribute to persistent asymmetry during facial growth.^{20–}

²² Primary nasal reconstruction during cleft lip repair aims to restore the position and shape of the lower lateral cartilage, improve alar base symmetry, correct nasal floor deformity, and establish a more balanced nasal framework while preserving future growth potential. Modern approaches range from limited soft tissue repositioning and nasal molding techniques to more comprehensive primary rhinoplasty maneuvers involving cartilage repositioning, suspension techniques, and refinement of the nasal base. The principles of contemporary primary nasal reconstruction are illustrated in Figure 6.

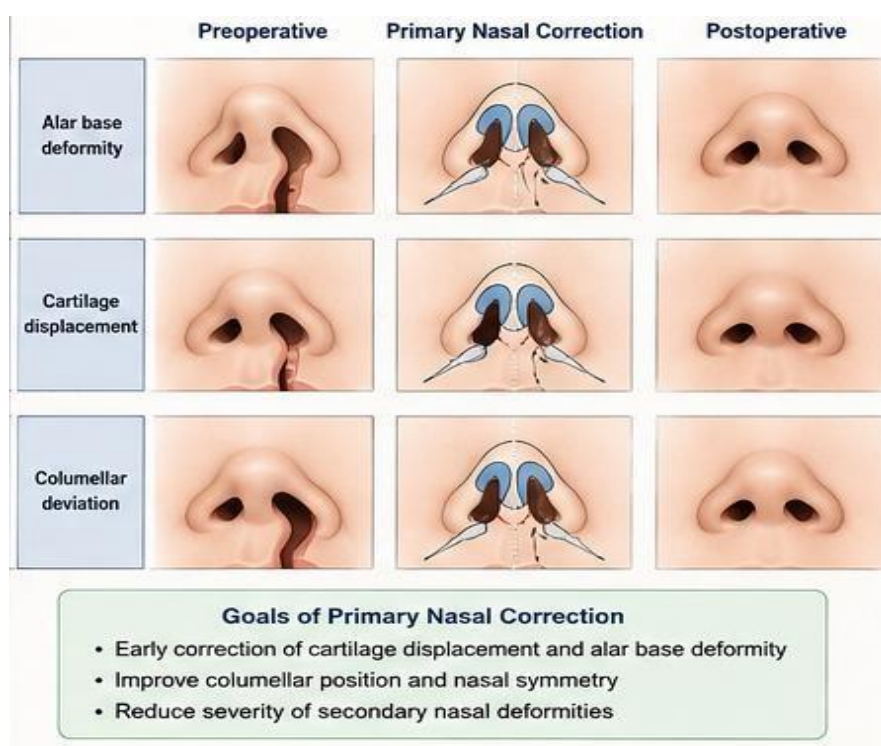


Figure 6. Principles of Primary Nasal Reconstruction During Cleft Lip Repair.

Illustration demonstrating the major components of primary nasal correction, including repositioning of the cleft-side lower lateral cartilage, correction of alar base displacement, restoration of columellar alignment, improvement of nostril symmetry, and integration of nasal reconstruction with primary cleft lip repair.

The concept of simultaneous nasal correction has been strongly influenced by the work of Salyer, McComb, Mulliken, and other pioneers who emphasized that correction of nasal deformity should be considered an integral component of primary cleft reconstruction rather than a separate secondary procedure. Early approaches demonstrated that careful manipulation of nasal soft tissues and cartilage could improve nasal appearance without compromising subsequent facial development. Contemporary protocols increasingly incorporate primary nasal correction as part of anatomical reconstruction of the cleft deformity, particularly in patients with significant nasal asymmetry or bilateral cleft involvement.^{33, 20–22}

The literature demonstrates that several principles are consistently associated with favorable outcomes. These include accurate repositioning of displaced cartilage structures, preservation of vascular supply, avoidance of excessive tissue tension, restoration of nasal base symmetry, and coordinated management of the lip–nose complex. Mulliken emphasized the importance of anatomical reconstruction of the nasal deformity during primary repair, particularly in bilateral cleft lip where columellar shortening, prolabial deficiency, and nasal tip distortion represent major reconstructive challenges.²⁰ Despite increasing acceptance of primary nasal correction, the optimal extent and timing of intervention remain debated. Some surgeons advocate limited primary correction to minimize potential interference with nasal growth, whereas others support more comprehensive early reconstruction based on evidence that neonatal cartilage demonstrates significant adaptability. Current evidence suggests that appropriately performed primary nasal correction can improve early and intermediate nasal symmetry without necessarily compromising subsequent growth, although long-term evidence remains heterogeneous.^{21, 22, 33}

A major advancement in the evaluation of cleft nasal outcomes has been the introduction of objective assessment methods. Traditional evaluation based on clinical photography and subjective expert grading has gradually been complemented by anthropometric measurements, three-dimensional stereophotogrammetry, and digital facial analysis. These approaches allow quantitative assessment of nasal width, nostril symmetry, alar position, columellar deviation, and changes occurring during growth. Three-dimensional evaluation has become increasingly important because cleft nasal deformity represents a complex spatial abnormality that cannot be fully characterized using two-dimensional measurements alone.^{27,28,38} The management of cleft nasal deformity should also be considered within the broader context of multidisciplinary rehabilitation. The relationship between the nose, upper lip, alveolus, and maxilla requires coordinated planning between cleft surgeons, orthodontists, pediatric dentists, and other specialists. Primary nasal reconstruction should therefore be individualized according to cleft morphology, associated deformities, patient age, and long-term functional and aesthetic goals.^{34, 35} Current evidence does not support a single universally superior technique for primary nasal reconstruction. Instead, successful outcomes appear to depend on anatomical understanding, appropriate surgical timing, preservation of nasal growth potential, surgeon experience, and standardized long-term evaluation. The principal contemporary approaches, anatomical objectives, potential benefits, and limitations of primary nasal management during cleft lip repair are summarized in Table 5.^{20, 22-33, 35, 38}

Table 5. Contemporary Approaches to Primary Nasal Management in Cleft Lip

Approach	Principal Objective	Potential Benefits	Important Considerations
Primary nasal correction	Correct alar, nasal base and soft-tissue asymmetry during primary cheiloplasty	Improved early facial symmetry and nasal contour	Requires careful preservation of growth potential
Alar cartilage repositioning	Reorient displaced alar cartilage	Improves nostril shape and alar symmetry	Technique must account for abnormal cartilage anatomy
Nasal base correction	Improve relationship between nasal floor, alar base and lip	May improve nasolabial symmetry	Overcorrection should be avoided
Columellar management	Address columellar shortening or deviation, particularly in bilateral clefts	May improve nasal projection and symmetry	More complex in severe bilateral deformity
Integrated lip–nose repair	Treat lip and nasal deformities as a coordinated anatomical unit	Provides comprehensive primary reconstruction	Requires individualized surgical planning
Three-dimensional assessment	Quantitative evaluation of nasal morphology before and after surgery	Improves objective outcome assessment	Requires standardized imaging protocols

2.9 Postoperative Outcomes, Complications, and Long-Term Results After Cleft Lip Repair

Evaluation of outcomes after cleft lip repair has progressively evolved from a simple assessment of wound healing and anatomical closure toward a multidimensional analysis incorporating functional recovery, facial aesthetics, psychosocial adaptation, and patient satisfaction. The reviewed literature emphasizes that the success of cleft lip reconstruction cannot be determined solely by the immediate postoperative appearance, because facial growth, nasal development, dental maturation, and psychosocial factors continue to influence treatment outcomes throughout childhood and adolescence.

The primary objectives of cleft lip repair include restoration of anatomical continuity, reconstruction of the orbicularis oris muscle, improvement of upper lip symmetry, preservation of facial growth potential, acceptable scar quality, and harmonious integration of the reconstructed lip and nose with the developing craniofacial structures. Contemporary outcome studies increasingly support the use of combined clinician-based assessments and patient-reported outcome measures because objective anatomical correction does not always correspond directly with patient satisfaction or perceived facial improvement.

Functional Outcomes After Primary Cleft Lip Repair

Functional restoration remains a fundamental objective of cleft lip reconstruction. Accurate reconstruction of the orbicularis oris muscle and restoration of muscular continuity contribute to improved lip competence, oral function, and facial animation. Modern anatomical repair techniques emphasize precise muscle alignment rather than simple closure of the mucocutaneous defect, resulting in improved functional integration of the reconstructed lip.

Although cleft lip has a less direct influence on speech development than cleft palate, alterations in lip morphology, maxillary development, and dental relationships may affect feeding efficiency, articulation patterns, and overall oral function. Therefore, long-term follow-up within specialized cleft teams remains essential to identify functional limitations and provide coordinated interventions when required.^{1, 35}

Aesthetic Outcomes and Objective Evaluation

Aesthetic assessment after cleft lip repair remains complex because facial appearance is influenced by multiple interacting factors, including surgical technique, scar maturation, nasal growth, maxillary development, and individual biological variability. Historically, evaluation relied primarily on subjective assessment of standardized clinical photographs. However, contemporary approaches increasingly incorporate validated scoring systems, anthropometric measurements, and three-dimensional facial analysis.

Common parameters used for postoperative evaluation include:

- Cupid's bow symmetry;
- philtral column reconstruction;
- vermilion border continuity;
- lip height and projection;
- scar quality and visibility;
- nasal base symmetry;
- nostril shape and position.

The Asher-McDade nasolabial aesthetic rating system has been widely used for standardized evaluation of cleft-related facial appearance and remains an important reference tool in clinical research.²⁴ More recent studies have demonstrated that three-dimensional stereophotogrammetry provides additional quantitative information regarding facial symmetry and postoperative morphological changes, reducing observer dependency and improving reproducibility.^{27, 38-40} Comparative studies evaluating different surgical approaches indicate that modern anatomical repair techniques generally achieve favorable aesthetic outcomes. However, available evidence suggests that differences between techniques are often smaller than the influence of surgeon experience, quality of anatomical reconstruction, postoperative management, and long-term facial growth patterns.^{32,34} The principal domains, assessment methods, and outcome measures used for evaluating patients after cleft lip repair are summarized in Table 6.^{24,27,38-40}

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Table 6. Multidimensional Assessment of Outcomes After Cleft Lip Repair

Outcome Domain	Representative Measures	Clinical Relevance
Lip symmetry	Cupid's bow symmetry, lip height, vermillion alignment	Assesses restoration of lip anatomy
Scar quality	Scar width, visibility, hypertrophy and contour	Important aesthetic and patient-centered outcome
Nasal morphology	Alar symmetry, nasal width, projection and nostril shape	Evaluates primary nasal reconstruction
Facial growth	Maxillary and midfacial development	Important for long-term craniofacial outcome
Dental development	Dental eruption, alignment and occlusion	Reflects dentoalveolar consequences of clefting and treatment
Speech	Articulation, resonance and velopharyngeal function when relevant	Assesses functional rehabilitation
Hearing	Audiological status and middle-ear function	Important because of associated otologic problems
Patient-reported outcomes	Satisfaction, appearance perception and quality of life	Captures outcomes not fully represented by clinical measurements
Three-dimensional morphometry	Landmark distances, angles, asymmetry indices and surface measurements	Provides objective and reproducible assessment

Postoperative Complications and Secondary Procedures

Despite significant advances in surgical techniques, postoperative complications and secondary deformities remain important considerations in cleft lip management. Reported complications include hypertrophic or widened scars, vermillion irregularities, residual lip asymmetry, whistle deformity, Cupid's bow distortion, and persistent nasal asymmetry.

The frequency and severity of secondary deformities depend on multiple factors, including cleft severity, surgical technique, timing of repair, tissue characteristics, and duration of follow-up. Secondary procedures may include scar revision, lip revision, secondary rhinoplasty, orthodontic treatment, and alveolar reconstruction when indicated.

Current evidence indicates that meticulous primary reconstruction based on restoration of anatomical subunits and functional muscle continuity reduces the severity of secondary deformities. Nevertheless, cleft patients require prolonged surveillance because craniofacial growth may reveal residual asymmetry or functional limitations that become clinically significant later in development.^{34,35}

Patient-Reported Outcomes and Quality of Life

Modern cleft care increasingly recognizes patient perception and psychosocial well-being as essential components of treatment success. Although surgical outcomes have traditionally been evaluated by clinicians, contemporary research highlights the importance of understanding how patients perceive facial appearance, function, and social integration.

2.10 Quality-of-life studies demonstrate that successful cleft treatment extends beyond anatomical reconstruction and includes improvement in confidence, communication, social participation, and psychological adaptation. Patient-reported outcome measures are therefore increasingly incorporated into clinical studies to provide a more comprehensive assessment of treatment effectiveness.²⁶ Overall, current evidence indicates that primary cleft lip repair performed within specialized multidisciplinary programs provides reliable improvement in facial appearance and function. However, long-term follow-up remains essential because growth-related changes, secondary deformities, and psychosocial factors continue to influence final outcomes throughout childhood and adolescence.

Multidisciplinary Management of Children with Cleft Lip

Contemporary management of children with cleft lip has evolved from isolated surgical correction toward a comprehensive, lifelong rehabilitation model based on multidisciplinary care. The reviewed literature consistently demonstrates that cleft lip represents a complex craniofacial condition involving anatomical reconstruction, facial growth, dental development, speech and hearing function, nutritional status, and psychosocial adaptation. Consequently, optimal outcomes cannot be achieved through surgery alone but require coordinated collaboration among specialists throughout childhood and adolescence.

The establishment of multidisciplinary cleft teams has substantially improved treatment consistency and long-term outcomes. Modern cleft programs integrate the expertise of cleft surgeons, orthodontists, pediatric dentists, speech-language pathologists, otolaryngologists, geneticists, psychologists, nurses, and imaging specialists. This coordinated approach allows individualized treatment planning according to cleft severity, associated anomalies, developmental stage, and patient-specific functional requirements.^{1,25,35}

Role of the Cleft Team in Early Childhood Management

The multidisciplinary pathway begins immediately after birth, when early assessment focuses on feeding ability, nutritional status, associated congenital anomalies, and parental counseling. Infants with cleft lip, particularly those with associated palatal involvement, may experience impaired oral seal and reduced feeding efficiency. Early intervention by pediatricians, specialized nurses, and feeding specialists helps establish adequate nutrition and supports normal growth during the preoperative period. Family-centered counseling represents an essential component of early cleft care. Parents require clear information regarding surgical timing, expected treatment stages, long-term prognosis, and the need for prolonged multidisciplinary follow-up. Evidence from international cleft programs indicates that effective communication between healthcare providers and families contributes to improved treatment adherence and psychosocial adaptation.^{25,26}

Coordination Between Surgical and Orthodontic Management

Close collaboration between cleft surgeons and orthodontists is fundamental for achieving stable functional and aesthetic outcomes. Orthodontic evaluation begins early, particularly in patients with alveolar involvement, maxillary segment displacement, or complex cleft morphology. Presurgical orthopedic interventions, including nasoalveolar molding (NAM), are integrated into many treatment protocols to optimize soft tissue and alveolar relationships before primary repair.^{10–14} During later stages of development, orthodontic treatment addresses dentofacial abnormalities associated with cleft formation, including maxillary deficiency, dental crowding, crossbite, tooth eruption disturbances, and preparation for alveolar bone grafting when indicated. The timing of orthodontic intervention must be coordinated with surgical procedures to achieve predictable long-term facial and occlusal outcomes.

Speech, Hearing, and Functional Rehabilitation

Although isolated cleft lip has a limited direct influence on speech compared with cleft palate, many children with combined cleft lip and palate experience speech-related difficulties due to velopharyngeal dysfunction, hearing impairment, and altered craniofacial development. Speech-language specialists play a critical role in early evaluation, monitoring of language development, and implementation of individualized rehabilitation strategies. Otolaryngological assessment is also an important component of long-term cleft care. Children with cleft conditions have an increased prevalence of middle ear dysfunction and conductive hearing loss related to impaired Eustachian tube function. Early identification and management of hearing abnormalities are essential for normal speech development, learning ability, and social integration.^{25,35}

Dental and Oral Health Management

Dental care represents another essential component of multidisciplinary cleft rehabilitation. Children with cleft lip frequently present with dental abnormalities, including missing or malformed teeth, delayed eruption, enamel defects, and malposition of permanent teeth, particularly adjacent to the cleft region.

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Pediatric dentists contribute to preventive care, oral hygiene education, management of dental disease, and coordination of treatment before orthodontic and surgical procedures. Maintaining optimal oral health is particularly important before alveolar reconstruction and orthodontic correction because dental infection and poor hygiene may negatively influence treatment outcomes.

Psychosocial Support and Patient-Centered Care

Contemporary cleft care increasingly recognizes psychosocial well-being as an important determinant of treatment success. Facial differences may influence self-esteem, social interaction, emotional development, and quality of life, particularly during school years and adolescence.

Psychological assessment and counseling have therefore become integrated components of specialized cleft programs. Patient-reported outcome measures demonstrate that successful rehabilitation involves not only restoration of facial anatomy but also improvement in confidence, social participation, and overall quality of life.²⁶

Future Perspectives in Integrated Cleft Care

Recent technological developments have further enhanced multidisciplinary collaboration. Three-dimensional facial imaging, digital treatment planning, computer-assisted surgical simulation, and artificial intelligence-based analysis provide new opportunities for objective diagnosis, individualized planning, and longitudinal assessment of treatment outcomes.²⁷⁻³⁰

The principal specialists involved in contemporary cleft care and their respective roles across the different stages of childhood and adolescent rehabilitation are summarized in Table 7.^{1,25,26,35}

Table 7. Multidisciplinary Components of Contemporary Cleft Care

Specialty / Professional	Principal Role	Timing / Focus
Cleft / plastic / maxillofacial surgeon	Primary lip and nasal repair; secondary reconstruction when indicated	Infancy through adolescence/adulthood as required
Orthodontist	Growth modification, dentoalveolar alignment and preparation for later treatment	Childhood through adolescence
Pediatric dentist	Dental prevention, caries control and eruption monitoring	Early childhood onward
Speech-language specialist	Speech and language assessment and therapy	Infancy/childhood and as clinically indicated
Otolaryngologist / audiologist	Hearing assessment, middle-ear disease and airway evaluation	Throughout childhood
Geneticist	Assessment of syndromic features, counseling and testing	At diagnosis and when indicated
Psychologist / mental health professional	Psychosocial assessment and support	Throughout development as needed
Nursing / feeding specialists	Feeding support, caregiver education and nutritional monitoring	Neonatal period and early infancy
Radiology / imaging specialists	Three-dimensional imaging and quantitative assessment	Preoperative planning and longitudinal follow-up

2.10 Digital Technologies and Artificial Intelligence in Cleft Lip Management

The integration of digital technologies into cleft lip management represents one of the most important developments in contemporary craniofacial care. Over the last decade, cleft treatment has progressively moved from conventional two-dimensional clinical evaluation toward individualized, three-dimensional, and data-driven approaches. The reviewed literature demonstrates that digital technologies have influenced multiple stages of cleft care, including diagnosis, anatomical assessment, presurgical planning, surgical simulation, orthodontic management, and postoperative outcome

evaluation. Unlike traditional photographic documentation, modern digital platforms allow objective quantification of facial morphology and provide reproducible measurements of complex three-dimensional structures. These innovations have improved communication among members of multidisciplinary cleft teams and have facilitated more individualized treatment planning according to the specific anatomical characteristics of each patient.

Three-Dimensional Facial Imaging and Morphometric Assessment

Three-dimensional (3D) facial imaging has become an increasingly valuable tool in the evaluation of children with cleft lip and associated craniofacial deformities. Conventional two-dimensional photography provides important clinical information; however, it is limited by differences in head position, lighting conditions, and observer interpretation. In contrast, three-dimensional stereophotogrammetry enables non-invasive acquisition of facial surface data and allows quantitative assessment of facial symmetry, lip morphology, nasal contour, soft tissue volume, and postoperative changes without exposure to radiation.

Heike et al. emphasized that three-dimensional imaging has significantly expanded the possibilities for craniofacial research and clinical monitoring by providing objective measurements of facial growth and treatment outcomes. This technology allows longitudinal evaluation of changes occurring during childhood development and facilitates comparison of different surgical strategies using standardized morphological parameters.²⁷

Comparative studies evaluating different three-dimensional surface imaging systems have demonstrated high accuracy and reproducibility for facial analysis. Tzou et al. reported that modern stereophotogrammetry systems provide reliable assessment of craniofacial soft tissues and represent a valuable alternative to conventional anthropometric evaluation.²⁸

In cleft lip management, 3D imaging enables assessment of parameters such as facial asymmetry, nasal deviation, nostril shape, lip height, vermilion contour, and differences between cleft and non-cleft sides. These measurements are particularly important because postoperative evaluation increasingly requires objective assessment rather than relying exclusively on subjective aesthetic judgment.

Three-dimensional models also improve communication within multidisciplinary teams. Surgeons, orthodontists, and families can visualize anatomical abnormalities, treatment objectives, and expected surgical outcomes using patient-specific digital representations. This approach contributes to more informed decision-making and improves coordination between different specialists involved in long-term cleft rehabilitation.

Virtual Surgical Planning and Computer-Assisted Treatment

Virtual surgical planning (VSP) has become an important component of modern craniofacial surgery and has gradually expanded into cleft care. Initially developed for complex maxillofacial reconstruction, VSP is now increasingly applied in patients requiring secondary correction, severe alveolar deformity management, and orthognathic procedures. Digital planning allows integration of clinical examination, three-dimensional facial imaging, and anatomical datasets to simulate surgical interventions before treatment. Surgeons can evaluate anatomical relationships, analyze tissue deficiencies, and plan individualized procedures based on patient-specific morphology. The use of computer-assisted workflows has also improved communication between specialists. Orthodontists, surgeons, and restorative teams can simultaneously evaluate digital models and coordinate treatment sequences, particularly in patients requiring multiple surgical and orthodontic interventions.

Digital orthodontic workflows and CAD/CAM technologies have introduced new possibilities for cleft and craniofacial treatment planning, appliance fabrication, and interdisciplinary collaboration.²⁹ These approaches may reduce dependence on conventional impressions and manual laboratory procedures while improving reproducibility and efficiency.

Three-Dimensional Printing and Customized Devices

Additive manufacturing technologies have further expanded the role of digital approaches in cleft care. Three-dimensional printing enables production of patient-specific anatomical models, surgical simulation tools, orthodontic appliances, and educational materials. In presurgical orthopedic management, digital workflows combining intraoral

scanning, computer-aided design, and three-dimensional printing have emerged as alternatives to conventional appliance fabrication techniques. These methods may reduce laboratory processing time, improve manufacturing accuracy, and increase patient comfort while maintaining comparable clinical effectiveness. Velickovic et al. evaluated digitally versus conventionally fabricated nasoalveolar molding appliances in a systematic review and meta-analysis of randomized controlled trials and provided contemporary evidence regarding the comparative effectiveness of these approaches.³¹ Although digital fabrication technologies remain under continuous development, current evidence suggests that they represent an important step toward personalized cleft care. Their integration with three-dimensional imaging and virtual planning may allow more predictable and patient-specific therapeutic strategies.

Artificial Intelligence Applications in Cleft Care

Artificial intelligence (AI) represents one of the most rapidly developing areas in craniofacial medicine. Current applications of AI in cleft lip management are primarily focused on automated facial analysis, anatomical landmark identification, severity classification, and prediction of treatment outcomes. Machine-learning and deep-learning algorithms have demonstrated the ability to analyze large numbers of facial images and identify morphological characteristics associated with craniofacial deformities. These technologies may reduce observer variability and provide standardized quantitative evaluation of facial structures. Harrison et al. reviewed emerging applications of artificial intelligence in pediatric craniofacial surgery and emphasized the potential role of AI-based systems in automated landmark detection, morphological analysis, classification, and individualized treatment planning.³⁰

In cleft care, AI-assisted analysis may support clinicians by providing objective measurements that complement traditional clinical assessment. Another promising application involves prediction of postoperative outcomes. By integrating preoperative facial morphology, three-dimensional imaging data, surgical parameters, and patient characteristics, machine-learning models may eventually assist in estimating expected postoperative appearance and selecting the most appropriate treatment strategy.

However, current evidence indicates that AI should be considered a decision-support technology rather than a replacement for clinical expertise. Several limitations remain, including insufficiently large datasets, differences between imaging systems, limited external validation, ethical concerns, and the need for integration into existing multidisciplinary workflows. Future clinical implementation will require prospective studies evaluating the accuracy, reliability, generalizability, and clinical relevance of AI-based systems before routine adoption in cleft care.

Future Perspectives of Digital Cleft Care

The future of cleft lip management is expected to involve increasingly integrated digital workflows combining three-dimensional imaging, artificial intelligence, virtual surgical planning, additive manufacturing, and personalized treatment strategies. Digital transformation has the potential to improve early diagnosis, optimize surgical planning, standardize postoperative assessment, and facilitate long-term monitoring of facial growth. Furthermore, integration of digital technologies into multidisciplinary cleft teams may enhance communication between specialists and improve patient-centered care. Nevertheless, digital technologies should be viewed as complementary tools that enhance established principles of cleft management rather than replace clinical judgment and surgical expertise. The success of future digital approaches will depend on validation through high-quality clinical studies, standardized outcome measurements, and effective integration into comprehensive multidisciplinary treatment pathways. Overall, current evidence supports the expanding role of digital technologies and artificial intelligence as important components of contemporary cleft lip management. These innovations provide opportunities for more accurate diagnosis, individualized surgical planning, and objective evaluation of long-term outcomes, while maintaining the fundamental principles of anatomical reconstruction and multidisciplinary rehabilitation. The principal digital technologies, artificial intelligence applications, clinical purposes, potential benefits, and current limitations are summarized in Table 8.^{27–31}

Table 8. Digital and Artificial Intelligence Applications in Contemporary Cleft Lip Management

Technology	Current / Potential Application	Potential Clinical Value	Key Limitations
Three-dimensional facial imaging	Surface capture and quantitative facial morphology	Objective assessment of symmetry and treatment outcomes	Equipment cost and standardized acquisition requirements
Digital morphometric analysis	Automated or semi-automated landmark and measurement analysis	Improved reproducibility and longitudinal comparison	Landmarking and protocol variability
Virtual surgical planning	Three-dimensional simulation of surgical changes	Improved preoperative planning and team communication	Requires specialized software and expertise
CAD/CAM	Digital design of patient-specific devices and models	Customized treatment and workflow efficiency	Technical and financial requirements
Three-dimensional printing	Production of anatomical models and customized devices	Facilitates planning, education and individualized care	Material, accuracy and workflow considerations
Artificial intelligence	Automated landmark detection, classification and pattern recognition	Potential decision support and standardized assessment	Requires large datasets, validation and bias assessment
AI-assisted outcome prediction	Prediction of postoperative morphology or treatment response	Potential for personalized treatment planning	Currently requires stronger prospective clinical validation
Digital longitudinal monitoring	Repeated three-dimensional assessment during growth	Quantitative monitoring of facial development	Requires standardized repeated imaging

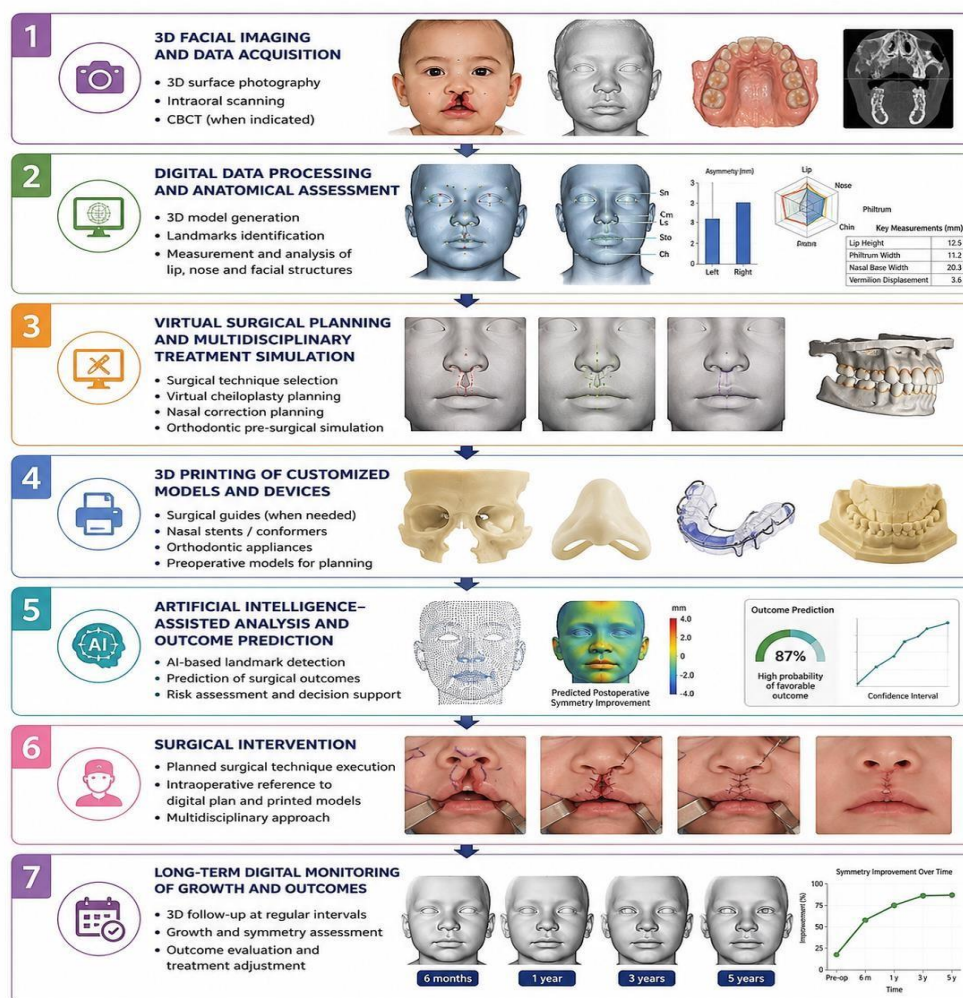


Figure 7. Digital Workflow in Contemporary Cleft Lip Management.

Representative Clinical Illustrations of Cleft Lip and Residual Deformities

Representative Clinical Illustrations of Cleft Lip and Residual Deformities

Representative clinical photographs complement the evidence synthesized in the preceding sections by demonstrating how anatomical differences in cleft morphology, lip deficiency, nasal asymmetry, and residual soft-tissue distortion may influence clinical assessment and reconstructive decision-making. In such patients, careful assessment of lip height, vermilion continuity, Cupid's bow, orbicularis oris muscle alignment, nasal symmetry, and the relationship between the lip and alveolar segments is essential for individualized treatment planning. Their management requires comprehensive assessment and individualized planning, with secondary lip revision, orthodontic treatment, nasal correction, or other reconstructive procedures considered according to the specific anatomical and functional deficits. These illustrations reinforce the principle that cleft lip treatment should not be regarded as a single operative procedure but rather as a longitudinal process involving primary reconstruction, nasal and orthodontic management, functional rehabilitation, objective outcome assessment, and, when required, secondary correction. The clinical photographs also support the increasing importance of standardized three-dimensional assessment, which may provide quantitative information regarding facial symmetry, lip morphology, nasal position, and growth-related changes that cannot be adequately captured by conventional two-dimensional clinical photography alone.



Figure 8. Preoperative clinical appearance of a child with cleft lip.

Figure 9. Postoperative clinical view two weeks after cleft lip repair.



Figure 10. Preoperative view showing a unilateral cleft lip involving the vermilion and philtrum.

Figure 11. Three-week postoperative view demonstrating satisfactory healing, well-adapted lip margins, and improved symmetry of the upper lip and philtrum.



Figure 12. Preoperative view showing a unilateral cleft lip involving the vermilion and philtrum.

Figure 13. Three-week postoperative view demonstrating satisfactory healing, well-adapted lip margins, and improved symmetry of the upper lip and philtrum.



Figure 14. Preoperative view showing a complete bilateral cleft of the upper lip involving the philtrum and vermillion. **Figure 15.** One-week postoperative view demonstrating early healing, well-approximated lip margins, and improved symmetry of the lip.



Figure 16. a,b. Preoperative clinical appearance of an adult woman with cleft upper-lip and nasal asymmetry



Figure 17.a,b Postoperative clinical view two weeks after surgical repair of the cleft

DISCUSSION

Cleft lip remains one of the most extensively investigated congenital craniofacial anomalies, yet achieving consistently predictable long-term functional and aesthetic outcomes continues to represent a significant clinical challenge. Advances in embryology, molecular genetics, surgical reconstruction, orthodontic management, and digital technologies have profoundly changed the philosophy of cleft care. The current concept has evolved from simple closure of an anatomical defect toward individualized reconstruction aimed at restoring facial harmony, preserving normal growth potential, optimizing function, and improving psychosocial well-being. Contemporary cleft management therefore represents a complex continuum of care rather than a single surgical event. The findings synthesized in the present narrative review demonstrate that, despite considerable progress, substantial variation remains in clinical protocols among cleft centers worldwide. Differences exist regarding timing of primary cheiloplasty, selection of surgical technique, extent of primary nasal correction, application of presurgical orthopedic therapy, methods of postoperative evaluation, and indications for secondary revision procedures. This variability the multifactorial nature of cleft deformities and the absence of a universally accepted treatment algorithm. Previous multicenter investigations have similarly emphasized that outcomes are influenced not only by the selected operative technique but also by surgeon experience, institutional protocols, multidisciplinary coordination, and duration of follow-up.²⁵

One of the most important developments in contemporary cleft surgery is the transition from procedure-based treatment toward anatomical and patient-specific reconstruction. Historically, successful cleft lip repair was primarily defined by closure of the cleft gap and acceptable early postoperative appearance. However, modern concepts emphasize restoration of normal facial anatomy through precise reconstruction of the orbicularis oris muscle, restoration of lip subunits, reconstruction of the philtral complex, preservation of Cupid's bow morphology, and correction of associated nasal deformity.^{15,16,36} This evolution reflects the broader transformation of craniofacial surgery from defect repair toward functional and aesthetic restoration based on detailed understanding of facial anatomy. The optimal surgical technique for unilateral cleft lip repair remains an ongoing subject of discussion. The comparison between rotation-advancement techniques, particularly the Millard approach, and anatomical subunit-based procedures such as Fisher repair illustrates the complexity of evaluating surgical superiority.^{15,16} Although Fisher's anatomical subunit repair has been associated with favorable scar placement, improved

philtral definition, and more predictable vermilion reconstruction in some studies, comparative investigations have also demonstrated that both Fisher and modified Millard techniques may provide satisfactory functional and aesthetic outcomes when performed by experienced surgeons.³² These observations suggest that future research should move beyond identifying a universally superior procedure and instead focus on determining which anatomical characteristics, surgical principles, and patient-related factors influence long-term outcomes.

The role of presurgical nasolabial molding (NAM) represents another important area of contemporary discussion. Available evidence indicates that NAM can improve preoperative anatomy by reducing alveolar segment displacement, decreasing soft tissue tension, and improving nasal symmetry before primary repair.^{10–13} Long-term studies have demonstrated improved nasal morphology in selected patients treated with NAM; however, its influence on definitive facial growth and long-term aesthetic outcomes remains incompletely established.^{12,14} Therefore, NAM should be regarded as an adjunctive component of multidisciplinary cleft management rather than a substitute for surgical reconstruction. Future prospective studies with standardized treatment protocols and long-term follow-up are required to better define patient groups most likely to benefit from NAM. Primary nasal reconstruction during cleft lip repair represents another important evolution in treatment philosophy. Historically, nasal deformity correction was frequently delayed because of concerns regarding potential effects on nasal growth. However, contemporary approaches increasingly support early anatomical repositioning of displaced nasal structures during primary cheiloplasty.^{20–22,33} Current evidence suggests that primary nasal correction may improve nasal symmetry and reduce the severity of residual deformity requiring later rhinoplasty. Nevertheless, interpretation of available studies remains limited by heterogeneity in surgical techniques, inconsistent outcome measures, and differences in follow-up duration. The wider implementation of standardized three-dimensional assessment methods may provide more reliable evidence regarding the long-term effectiveness of early nasal interventions.^{27,38}

A major advancement in contemporary cleft research is the incorporation of objective digital assessment technologies. Traditional evaluation methods based on clinical photography and subjective expert scoring remain valuable but are influenced by observer variability. Three-dimensional stereophotogrammetry and digital morphometric analysis provide quantitative evaluation of facial structures, allowing assessment of lip symmetry, nasal morphology, soft tissue changes, and growth-related alterations over time.^{27,28,38} These technologies have improved both clinical research methodology and multidisciplinary communication by enabling more precise comparison of treatment outcomes. The integration of artificial intelligence represents one of the most promising future directions in cleft care.

Current AI-based approaches have demonstrated potential for automated facial landmark detection, morphological classification, analysis of craniofacial abnormalities, and prediction of treatment outcomes.³⁰ The principal value of artificial intelligence is not replacement of surgical decision-making but enhancement of clinical analysis through objective data interpretation. Nevertheless, current applications remain at an early stage, and widespread clinical implementation requires validation through large multicenter datasets, external testing, standardized imaging protocols, and careful consideration of ethical and methodological limitations.

The present review contributes to the existing literature by integrating multiple aspects of contemporary cleft lip management within a unified clinical framework. Previous publications have frequently focused on specific components of treatment, including surgical techniques, NAM protocols, or digital technologies individually. In contrast, this review emphasizes the interconnected nature of modern cleft care by combining surgical reconstruction, orthodontic preparation, multidisciplinary rehabilitation, objective outcome assessment, and emerging digital innovations. This integrated perspective reflects the current transition toward personalized cleft management. Another important development in modern cleft care is the increasing recognition of patient-centered outcomes. Anatomical reconstruction alone does not fully define treatment success. Quality of life, psychosocial adaptation, satisfaction with facial appearance, and social confidence are increasingly considered essential outcome parameters.²⁶

The incorporation of patient-reported outcome measures provides valuable information regarding the real-world impact of treatment and highlights the importance of evaluating outcomes from both clinician and patient perspectives. Despite significant advances, several limitations remain within the current evidence base. Many available studies are retrospective, include heterogeneous patient populations, and apply different surgical protocols and outcome assessment methods. Variability in surgical timing, operator experience, follow-up periods, and reporting standards limits direct comparison between studies

Furthermore, much of the available evidence originates from highly specialized cleft centers, which may reduce generalizability to different healthcare systems and resource settings. The evidence concerning NAM also requires careful interpretation. Although numerous studies have reported improvement in preoperative alveolar and nasal relationships, the magnitude of these benefits varies according to treatment protocol, appliance design, patient characteristics, and the timing of surgical repair. The 2024 systematic review and critical appraisal by Dunworth et al. emphasized the continuing

limitations of the NAM evidence base.¹⁴ More recent evidence comparing digital and conventional NAM fabrication may help clarify whether technological modifications can improve reproducibility and efficiency without compromising clinical effectiveness.³¹

The growing use of digital imaging offers an opportunity to address some of the methodological limitations of historical cleft research. Three-dimensional stereophotogrammetry can provide reproducible measurements of facial morphology without ionizing radiation and can be repeated longitudinally during growth.^{27,28}

Such approaches may facilitate development of standardized outcome databases that allow more meaningful comparison between institutions and surgical techniques. Artificial intelligence may further enhance these developments by enabling automated extraction of quantitative facial parameters from large datasets. However, the clinical value of AI will depend on the quality and representativeness of the data used for model development. Differences in age, ethnicity, cleft phenotype, imaging equipment, surgical protocols, and follow-up duration may substantially influence algorithm performance. Consequently, future AI research should prioritize multicenter datasets, external validation, transparent reporting, and clinically meaningful endpoints rather than focusing exclusively on algorithmic accuracy. Future investigations should prioritize prospective multicenter studies using standardized outcome assessment protocols, including three-dimensional morphometric analysis, validated aesthetic scoring systems, and patient-reported outcome measures.^{24,38–40} The combination of artificial intelligence, digital workflow integration, three-dimensional planning, and personalized treatment strategies may further transform cleft management by enabling predictive and individualized treatment approaches.

CONCLUSION

In conclusion, contemporary cleft lip management has evolved from traditional surgical closure toward a comprehensive model based on individualized reconstruction, multidisciplinary collaboration, objective assessment, and technological innovation. Current evidence supports the importance of anatomical precision, early optimization of deformities, long-term monitoring, and patient-centered evaluation. The future of cleft rehabilitation will likely depend on successful integration of surgical expertise with digital technologies and artificial intelligence, creating more predictable and personalized treatment pathways for children affected by this complex craniofacial condition.

DECLARATIONS

Ethical Approval

Not applicable.

Competing Interests

The authors declare no conflict of interest.

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REVIEW ARTICLE

ADVANCES IN FACELIFT SURGERY: A SCOPING REVIEW OF SURGICAL TECHNIQUES, CLINICAL OUTCOMES, COMPLICATIONS, AND FUTURE PERSPECTIVES

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Abstract

Background:Facial aging is a multifactorial process characterized by skin laxity, soft tissue descent, volume loss, and weakening of the superficial musculoaponeurotic system (SMAS). Rhytidectomy (facelift surgery) remains the gold standard for the correction of moderate-to-severe facial aging. Over the past two decades, advances in surgical techniques—particularly SMAS-based procedures—have significantly improved aesthetic outcomes while maintaining facial harmony and reducing complications. Despite the growing number of published studies, a comprehensive synthesis of current evidence regarding facelift techniques, clinical outcomes, and postoperative complications is warranted.

Objective:This scoping review aimed to summarize and map the current evidence on facelift surgery, including surgical approaches, indications, contraindications, perioperative management, clinical outcomes, complications, and future directions in facial rejuvenation.

Methods:A scoping review methodology was designed following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) guidelines. Electronic databases including PubMed/MEDLINE, Scopus, Web of Science, and Embase were searched for English-language publications. Original clinical studies, systematic reviews, meta-analyses, and consensus statements evaluating facelift procedures were considered eligible. Data regarding patient characteristics, operative techniques, postoperative outcomes, complications, and long-term effectiveness were extracted and synthesized narratively.

Results:Current evidence indicates that SMAS-based facelift techniques provide superior and longer-lasting aesthetic outcomes compared with skin-only facelift procedures. Deep-plane and composite facelift approaches demonstrate enhanced correction of midface ptosis and nasolabial folds while preserving natural facial contours. Endoscopic techniques offer shorter recovery periods and reduced postoperative morbidity in carefully selected patients. The most frequently reported complications include hematoma, seroma, transient facial nerve dysfunction, infection, skin flap necrosis, hypertrophic scarring, and prolonged edema, whereas permanent functional deficits remain uncommon when surgery is performed by experienced surgeons. Long-term patient satisfaction is consistently high, with rejuvenation effects commonly maintained for 8–12 years.

Conclusions:Modern facelift surgery has evolved into a safe and highly effective procedure for facial rejuvenation through the restoration of both superficial and deep facial support structures. SMAS-based techniques currently represent the standard of care because they provide durable, natural-appearing outcomes with acceptable complication rates. Future research should focus on standardized outcome reporting, patient-reported quality-of-life measures, and the integration of regenerative medicine and minimally invasive technologies to further optimize surgical results.

Keywords: facelift; rhytidectomy; SMAS facelift; facial rejuvenation; deep-plane facelift; facial aging; plastic surgery; aesthetic surgery

1. INTRODUCTION

Facial aging is a complex and progressive biological process that involves structural, functional, and aesthetic changes affecting multiple anatomical layers of the face. Traditionally, facial aging was considered primarily a consequence of skin laxity; however, contemporary anatomical studies have demonstrated that aging involves progressive alterations of the skin, superficial musculoaponeurotic system (SMAS), retaining ligaments, facial fat compartments, muscles, and underlying skeletal structures. These combined changes contribute to soft tissue descent, loss of facial volume, deepening of facial folds, development of jowls, and deterioration of the cervicomental contour¹⁻⁴.

Understanding the multidimensional nature of facial aging has fundamentally changed the principles of surgical facial rejuvenation, shifting the focus from simple skin tightening toward restoration of facial anatomy and preservation of natural appearance. Rhytidectomy, commonly known as facelift surgery, remains the most effective surgical procedure for correcting moderate-to-severe age-related changes of the face and neck. Since the early descriptions of facelift techniques, surgical approaches have continuously evolved in response to improved anatomical knowledge and increasing patient expectations for natural and long-lasting outcomes. Early facelift procedures relied predominantly on skin excision and elevation, which could provide temporary improvement but were associated with increased skin tension, recurrence of laxity, and occasionally unnatural facial appearance. The introduction of deeper tissue manipulation represented a major advancement in facial rejuvenation surgery^{5, 6}.

A significant milestone in the evolution of facelift surgery was the anatomical recognition of the superficial musculoaponeurotic system (SMAS) as a key structural component of facial soft tissues. Improved understanding of facial layers and supporting structures demonstrated that deeper tissues could be safely mobilized and repositioned during surgery. The development of SMAS-based facelift techniques allowed redistribution of tension from the skin to deeper anatomical structures, contributing to improved durability and more harmonious aesthetic outcomes. Since then, multiple refinements, including SMAS plication, SMASectomy, extended SMAS facelift, high-SMAS approaches, and deep-plane facelift techniques, have been developed to address different patterns of facial aging and soft tissue descent³⁻⁶.

The deep-plane facelift further advanced the concept of anatomical repositioning by allowing mobilization of deeper facial tissues as a composite skin–SMAS unit and by incorporating controlled release of retaining ligaments. This approach improved correction of midface descent, nasolabial fold prominence, and lower facial laxity while reducing reliance on skin tension. Subsequent refinements of deep-plane and extended SMAS techniques have focused on achieving predictable rejuvenation, maintaining facial dynamics, and avoiding an overcorrected or operated appearance. Current evidence suggests that these advanced techniques can provide substantial improvement in appropriately selected patients; however, surgical planning should be individualized according to facial anatomy, degree of soft tissue ptosis, skin characteristics, and surgeon experience⁴⁻⁶.

Modern facelift surgery is increasingly based on the concept of comprehensive facial rejuvenation rather than isolated lifting. Aging-related volume loss and changes in facial fat compartments have encouraged the incorporation of adjunctive procedures, including autologous fat grafting, neck contouring, platysmaplasty, eyelid surgery, brow lifting, and skin resurfacing techniques. These combined approaches aim to restore youthful facial proportions while preserving individual characteristics and avoiding excessive correction⁷⁻⁹. The contemporary objective of facelift surgery is therefore not simply to tighten tissues but to recreate balanced anatomical relationships between facial structures.

Despite major improvements in surgical techniques, facelift surgery remains one of the most technically demanding procedures in aesthetic surgery. Successful outcomes require detailed knowledge of facial anatomy, careful patient selection, appropriate surgical planning, and meticulous postoperative management. Potential complications include hematoma, seroma, infection, skin flap necrosis, temporary or permanent facial nerve dysfunction, alopecia at incision sites, hypertrophic scarring, prolonged edema, and asymmetry¹⁰⁻¹². Although serious complications are uncommon in experienced hands, they remain clinically important because they may negatively affect patient satisfaction and quality of life.

Patient expectations have also changed significantly in recent years. Individuals seeking facial rejuvenation increasingly desire subtle, natural-looking improvements rather than dramatic changes. This shift has encouraged surgeons to develop techniques that preserve facial identity, minimize visible signs of surgery, and provide long-term but natural results. Patient-reported outcome

measures and quality-of-life assessments have become increasingly important tools for evaluating the effectiveness of facelift procedures beyond traditional surgeon-based aesthetic assessment^{13–16}.

Although numerous studies have investigated individual facelift techniques, variability remains regarding surgical terminology, outcome assessment methods, follow-up duration, and reporting of complications. The absence of standardized evaluation criteria makes direct comparison between different facelift approaches challenging. Therefore, a comprehensive mapping of current evidence is necessary to clarify the advantages, limitations, and clinical applications of modern facelift techniques¹⁷.

The objective of this scoping review is to systematically map the available literature on contemporary facelift surgery, including surgical approaches, anatomical principles, clinical indications, outcomes, complications, and future perspectives. By summarizing current evidence, this review aims to provide an updated overview of the evolution of facelift surgery and identify areas requiring further investigation to improve safety, reproducibility, and patient satisfaction.

2. MATERIALS AND METHODS

2.1. Study Design and Methodological Framework

This scoping review was conducted to map the existing evidence regarding contemporary facelift surgery techniques, anatomical principles, clinical outcomes, complications, and future perspectives in facial rejuvenation. The methodology was developed based on the framework originally proposed by Arksey and O'Malley and further enhanced by Levac et al. for conducting scoping reviews. The review was reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) guidelines to ensure methodological transparency, reproducibility, and standardized reporting^{18,19}.

A scoping review approach was selected because the available literature on facelift surgery includes a broad range of study designs, including anatomical investigations, technical reports, retrospective clinical studies, prospective studies, systematic reviews, and expert consensus articles. Unlike systematic reviews focused on narrowly defined clinical questions,

scoping reviews are particularly suitable for exploring heterogeneous evidence, identifying knowledge gaps, and describing the evolution of surgical techniques and concepts.

2.2. Review Question and Objectives

The primary research question was formulated as follows:

What is the current evidence regarding surgical techniques, clinical outcomes, complications, and future directions in modern facelift surgery?

The specific objectives were:

1. To identify and categorize contemporary facelift techniques, including SMAS facelift, extended SMAS facelift, deep-plane facelift, composite facelift, and minimally invasive approaches.
2. To evaluate reported clinical outcomes and long-term effectiveness of different surgical techniques.
3. To summarize commonly reported postoperative complications and safety considerations.
4. To identify current limitations in facelift research and areas requiring further investigation.

2.3. Search Strategy

A comprehensive literature search was conducted in PubMed/MEDLINE, Scopus, Web of Science Core Collection, and Embase databases to identify studies evaluating contemporary facelift surgery techniques and clinical outcomes.

The search strategy combined Medical Subject Headings (MeSH) terms and free-text keywords related to facelift surgery. The following key terms were used individually and in combination: “facelift,” “rhytidectomy,” “face lift,” “SMAS facelift,” “deep plane facelift,” “extended SMAS,” “facial rejuvenation,” “facelift outcomes,” and “facelift complications.” Boolean operators (AND/OR) were applied to optimize retrieval of relevant publications. Only studies published in English and involving adult human participants were included. Reference lists of relevant articles and previous reviews were additionally screened to identify studies not captured through electronic database searches.

2.4. Eligibility Criteria

Studies were considered eligible according to predefined inclusion and exclusion criteria.

Inclusion criteria:

- Original research articles evaluating facelift or rhytidectomy procedures;
- Anatomical studies related to facelift surgery;
- Clinical studies reporting surgical outcomes, patient satisfaction, or complications;
- Systematic reviews, narrative reviews, and expert consensus publications;
- Studies published in the English language;
- Publications involving adult human participants.

Exclusion criteria:

- Studies unrelated to surgical facial rejuvenation;
- Non-human studies;
- Conference abstracts without full-text availability;
- Publications without sufficient methodological information;
- Articles focusing exclusively on nonsurgical facial rejuvenation techniques, injectables, or cosmetic products.

2.5. Study Selection Process

After removal of duplicate records, titles and abstracts were screened independently for relevance according to the predefined eligibility criteria. Potentially relevant articles were subsequently assessed through full-text review.

The study selection process followed the PRISMA-ScR framework, documenting the number of identified, screened, included, and excluded studies. Disagreements regarding study eligibility were resolved through discussion and consensus.

2.6. Data Extraction and Charting

A standardized data extraction form was developed to collect relevant information from included studies. The following data were extracted:

- publication characteristics (author, year, country, study design);
- patient demographics and sample size;
- facelift technique performed;
- anatomical level of intervention;

- surgical indications;
- follow-up duration;
- reported aesthetic outcomes;
- patient satisfaction measures;
- postoperative complications;
- limitations and recommendations for future research.

Data extraction was performed in a structured manner to allow comparison between different surgical approaches and identify trends in modern facelift practice.

2.7. Data Synthesis

Due to the expected heterogeneity of included studies, a quantitative meta-analysis was not planned. Instead, extracted data were synthesized using a narrative approach.

The findings were organized into major thematic categories:

1. Evolution of facelift techniques;
2. Anatomical principles of SMAS-based procedures;
3. Clinical effectiveness and durability of outcomes;
4. Safety profile and complications;
5. Emerging technologies and future directions.

This approach allowed comprehensive mapping of current evidence while highlighting areas where further high-quality research is required.

2.8. Ethical Considerations

As this study involved analysis of previously published literature and did not include direct involvement of human participants or identifiable patient data, ethical approval was not required.

3.1. Literature Search Results

The systematic search process identified a total of 198 records from electronic databases and additional reference screening. Database searching retrieved 186 publications, including 62 records from PubMed/MEDLINE, 54 from Scopus, 41 from Web of Science, and 29 from Embase. An additional 12 records were identified through manual screening of reference lists from relevant reviews and key publications. After removal of duplicate records, 142 unique publications remained for title and abstract screening.

During the screening phase, 67 records were excluded because they did not address surgical facelift procedures, involved non-human studies, were not published in English, represented conference abstracts only, or lacked sufficient clinical information.

A total of 75 full-text articles were assessed for eligibility. Thirty articles were excluded after full-text evaluation because they did not specifically investigate facelift techniques, focused exclusively on nonsurgical facial rejuvenation, lacked clinical outcome data, or represented overlapping patient

cohorts. Finally, 45 studies met the predefined inclusion criteria and were included in the qualitative synthesis of this scoping review. The included evidence consisted of anatomical investigations, technical descriptions, clinical outcome studies, systematic reviews, and expert consensus publications. The selected studies provided comprehensive information regarding the evolution of facelift techniques, anatomical principles, surgical approaches, clinical outcomes, and postoperative complications.

The complete study identification, screening, eligibility assessment, and inclusion process is presented in the PRISMA-ScR flow diagram (Figure 1).

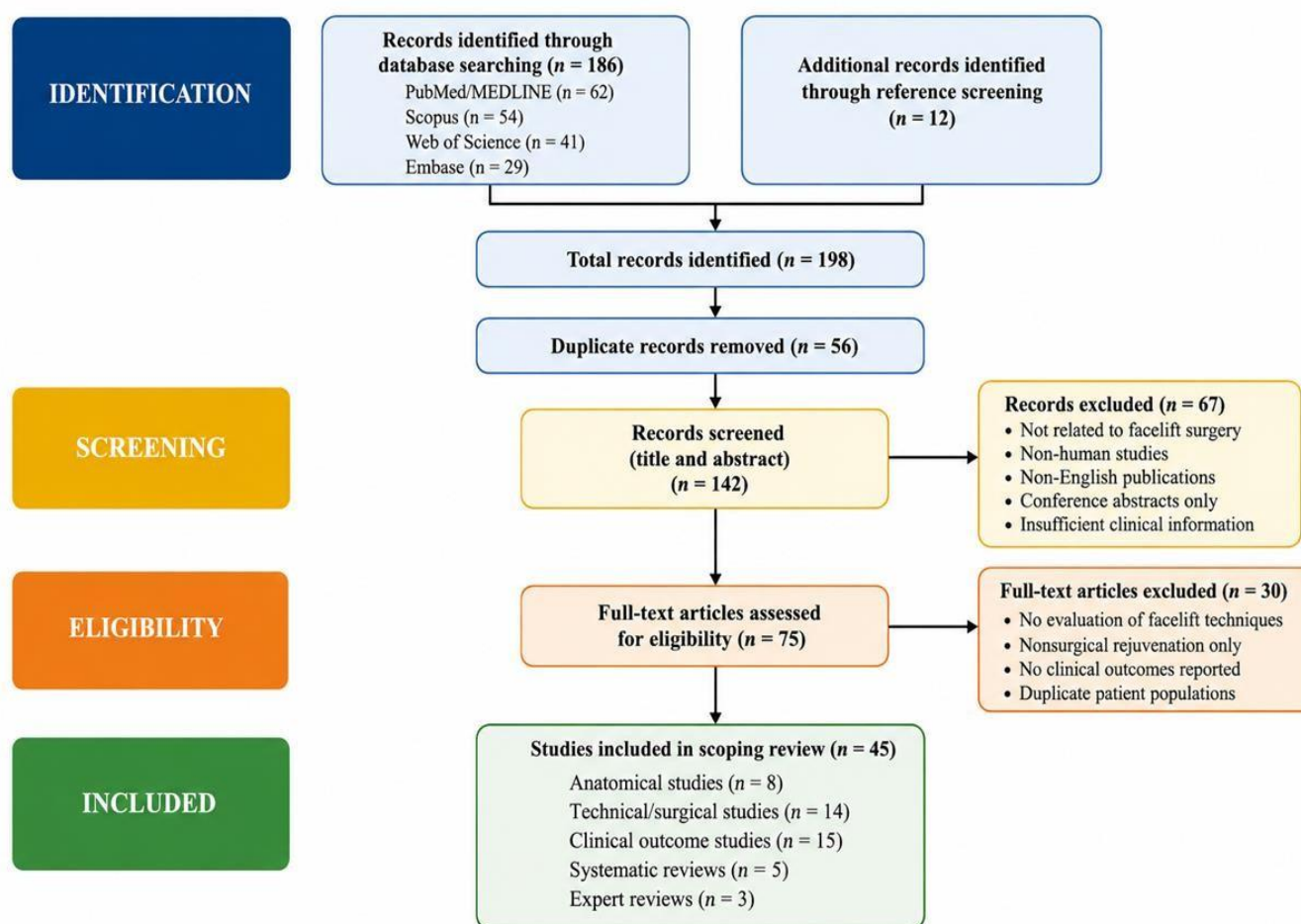


Figure 1. PRISMA-ScR flow diagram illustrating the study identification, screening, eligibility assessment, and inclusion process of studies included in the scoping review.

3.2. Evolution of Facelift Techniques

Facelift surgery has undergone remarkable evolution over the past century, progressing from procedures aimed solely at correcting superficial skin laxity to sophisticated operations that restore the three-dimensional architecture of the aging face. Each successive generation of facelift techniques has been developed to overcome the limitations of previous approaches, resulting in improved aesthetic outcomes, greater longevity, and more natural facial rejuvenation⁵.

The earliest facelift procedures, performed during the first half of the twentieth century, were based almost exclusively

on subcutaneous skin undermining followed by excision of redundant skin. These operations successfully reduced visible wrinkles and skin redundancy but failed to correct age-related descent of the deeper facial soft tissues. Because tissue support depended primarily on skin closure, excessive wound tension frequently resulted in widened scars, distortion of the hairline and earlobe, prolonged postoperative edema, and relatively short-lived aesthetic improvement. These limitations stimulated the development of techniques capable of addressing the structural causes of facial aging rather than merely its superficial manifestations ^{20–22}.

The major milestones in the evolution of facelift techniques, from early skin-only procedures to contemporary multimodal approaches, are summarized in Table 1.

Table 1. Milestones in the Evolution of Facelift Techniques

Technique	Period of Introduction	Key Innovation	Principal Clinical Benefit	Main Limitation
Skin-only facelift	Early 20th century	Skin excision and redraping	Improved correction of superficial skin laxity	High skin tension and limited longevity
Subcutaneous facelift	Mid-20th century	Wider skin undermining and redraping	Improved facial contour correction	Limited correction of deep tissue descent
SMAS facelift	Late 1970s	Repositioning of the superficial musculoaponeurotic system	More natural facial contour and reduced tension on skin closure	Increased technical complexity
SMAS modifications (plication/SMASectomy)	1980s–1990s	Different methods of SMAS manipulation and reinforcement	Greater adaptability according to patient anatomy	Variable long-term outcomes depending on technique
Extended SMAS facelift	1990s	Wider mobilization of SMAS and facial soft tissues	Enhanced correction of lower facial and cervical aging	Longer operative time and greater technical demands
Deep-plane facelift	1990s–present	Composite mobilization of skin and deeper facial tissues	Improved midface rejuvenation, jawline definition, and durable outcomes	Technically demanding procedure requiring advanced anatomical expertise
Contemporary multimodal facelift	2000s–present	Combination of lifting procedures with volume restoration and regenerative approaches	Comprehensive and individualized facial rejuvenation	Requires careful patient selection and advanced surgical expertise

A major turning point occurred following the description of the superficial musculoaponeurotic system (SMAS), which fundamentally changed the philosophy of facial rejuvenation. Instead of relying solely on skin tightening, surgeons increasingly focused on repositioning the deeper soft tissues responsible for facial contour and structural support. This conceptual shift enabled more effective correction of facial ptosis while reducing tension on skin closure, thereby improving scar quality and producing more natural postoperative results. SMAS surgery rapidly became the foundation of modern rhytidectomy and remains one of the most influential innovations in aesthetic facial surgery ^{3,6}.

Subsequent refinements led to the development of several SMAS-based techniques designed to balance surgical effectiveness with procedural complexity. SMAS plication provided a relatively conservative approach by reinforcing the fascial layer without extensive dissection, whereas SMASectomy involved partial excision of the SMAS to achieve stronger tissue repositioning. Extended SMAS procedures further increased the degree of tissue mobilization, allowing improved correction of lower facial and cervical aging. These modifications expanded the surgical armamentarium and enabled procedure selection according to the severity of aging changes and individual patient characteristics ^{3,20,23}.

The introduction of deep-plane facelift techniques represented another important stage in the evolution of facial rejuvenation surgery. Unlike conventional SMAS procedures, deep-plane surgery allows simultaneous mobilization of the skin and underlying soft tissues as a unified flap, facilitating more effective repositioning of descended facial structures. Clinical experience has demonstrated improved restoration of midfacial contour, enhanced definition of the jawline, and durable rejuvenation in appropriately selected patients. As surgical expertise and anatomical knowledge have advanced, deep-plane facelift has become increasingly recognized as an important approach for comprehensive facial rejuvenation ^{4,6,23}.

Contemporary facelift surgery has moved beyond reliance on a single standardized technique. Current practice emphasizes individualized treatment planning based on patient-specific aging patterns and frequently combines traditional lifting procedures with complementary interventions such as structural fat grafting, neck contouring, laser resurfacing, and regenerative therapies. These multimodal strategies aim not only to reposition descended tissues but also to restore facial volume, improve skin quality, and optimize long-term aesthetic outcomes. Consequently, modern facelift surgery has evolved into a personalized reconstructive and aesthetic procedure that integrates multiple techniques to achieve harmonious, natural-looking facial rejuvenation ^{4,7-9}.

3.3. Surgical Approaches and Anatomical Considerations

Successful facelift surgery requires a detailed understanding of facial anatomy and age-related structural changes. Modern facelift techniques are no longer limited to skin tightening alone; they are based on the correction of multiple anatomical layers, including the skin, superficial musculoaponeurotic system (SMAS), retaining ligaments, facial fat compartments, and deeper soft tissues. Selection of the appropriate surgical approach depends on the patient's anatomical characteristics, degree of tissue descent, skin condition, and aesthetic goals.

3.3.1. The Superficial Musculoaponeurotic System (SMAS)

The superficial musculoaponeurotic system (SMAS) is a fibromuscular layer located between the superficial facial fat and the underlying facial muscles. Anatomically, it represents a continuous connective tissue network that connects the facial muscles of expression with the overlying dermis through numerous fibrous attachments. This anatomical relationship explains why changes in the SMAS directly influence facial contour and soft tissue position ^{3,6}. Functionally, the SMAS plays an important role in facial movement by transmitting muscular contractions to the skin. With aging, progressive weakening, stretching, and downward displacement of the SMAS contribute to soft tissue descent, loss of facial definition, development of jowls, and accentuation of nasolabial and marionette folds ³.

The recognition of the SMAS as a key anatomical structure significantly changed facelift surgery. Traditional skin-only facelifts provided limited durability because excessive tension was transferred to the skin. Modern SMAS-based techniques aim to reposition and stabilize deeper facial tissues, allowing more harmonious and durable rejuvenation. Different SMAS approaches, including SMAS plication, SMASectomy, SMAS flap elevation, extended SMAS procedures, and deep-plane techniques, are selected according to individual anatomical characteristics and the degree of soft tissue descent ^{6,23}.

3.3.2. Facial Retaining Ligaments

Facial retaining ligaments are specialized fibrous structures that connect the superficial soft tissues of the face with deeper anatomical structures, including the periosteum, deep fascia, and underlying muscles. These ligamentous structures provide essential support by maintaining facial contour and stabilizing the position of soft tissues. With aging, progressive changes in ligamentous support, soft tissue volume, and surrounding anatomical compartments contribute

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to downward displacement of facial tissues, loss of facial definition, and the development of characteristic signs of facial aging such as midface descent, jowling, and cervical laxity ^{2,3}. The zygomatic retaining ligament is an important midface support structure located near the zygomatic eminence.

It stabilizes the malar soft tissues and contributes to maintenance of cheek projection. Age-related descent of tissues supported by this ligament may result in flattening of the midface, accentuation of the nasolabial fold, and formation of tear trough deformity. A detailed understanding of the zygomatic ligament anatomy is essential during facelift surgery because controlled release can improve mobilization and repositioning of descended tissues ^{3,4}.

The masseteric retaining ligament represents a major lateral facial fixation structure associated with the anterior border of the masseter muscle. It connects superficial facial tissues with deeper structures and may restrict tissue mobility during facelift procedures. Selective release of this ligament during deep-plane and extended deep-plane techniques allows greater advancement of the facial flap and improves correction of lower facial aging changes ⁴.

The mandibular retaining ligament contributes to the anatomical transition between the cheek and mandibular regions. Age-related weakening and descent of tissues in this area are associated with the development of jowls and loss of mandibular contour. Proper management of this region is therefore important for achieving improved jawline definition during lower facelift procedures ^{1,4}.

Cervical retaining structures provide support for the soft tissues of the neck and influence the appearance of the cervicomental angle. Their management, together with platysma modification and neck contouring techniques, plays an important role in restoring harmony between the lower face and neck during comprehensive facelift procedures ^{4,6}. Release of retaining ligaments has become an important principle of advanced facelift techniques. Because these structures act as anatomical fixation points, controlled ligament release permits greater tissue mobilization, facilitates anatomical repositioning, and reduces excessive tension on the skin envelope. This concept represents a fundamental component of deep-plane and extended deep-plane facelift approaches aimed at restoring natural facial relationships rather than simply tightening superficial tissues ^{4,6}.

3.3.3. Facial Fat Compartments

Facial fat is not a single continuous layer but is organized into distinct superficial and deep compartments with specific anatomical and functional roles. Understanding the distribution and age-related changes of these fat compartments is essential for achieving balanced and natural facial rejuvenation ².

Superficial fat compartments

Superficial fat compartments are located between the skin and the SMAS and contribute to facial softness, contour, and surface smoothness. During aging, these compartments may undergo volume reduction, redistribution, and gravitational descent, leading to irregularities of the facial contour, loss of youthful fullness, and accentuation of facial folds ^{1,2}.

Deep fat compartments

Deep facial fat compartments are located beneath the SMAS and serve as important structural components supporting midfacial volume and projection. Age-related changes in these compartments, including deflation and descent, contribute to flattening of the malar region, deepening of nasolabial folds, and alteration of facial proportions. Modern facelift techniques increasingly consider restoration and repositioning of deep facial volume as an essential component of rejuvenation ^{2,3}.

Malar fat pad

The malar fat pad represents a key midface structure responsible for cheek projection and youthful facial contour. Inferior displacement of the malar fat pad is one of the characteristic manifestations of facial aging and contributes to the development of nasolabial folds, midface flattening, and tear trough deformity. Surgical correction requires careful consideration of the relationship between fat compartments, retaining ligaments, and the SMAS layer ^{2,3}.

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Aging changes in facial fat

Facial aging involves complex alterations in adipose tissue, including both volume loss and redistribution. Current anatomical concepts indicate that aging is not explained by simple global fat atrophy; rather, different compartments may demonstrate variable patterns of deflation, hypertrophy, and downward displacement. Consequently, modern facelift procedures frequently incorporate both repositioning of descended tissues and selective volume restoration using techniques such as structural fat grafting to achieve harmonious and natural outcomes ⁷⁻⁹.

3.3.4. Facial Nerve and Vascular Considerations

Preservation of neural and vascular structures represents one of the fundamental principles of safe facelift surgery. Because modern facelift techniques involve manipulation of multiple anatomical planes, detailed knowledge of facial nerve pathways, vascular networks, and tissue planes is essential for minimizing complications while achieving effective rejuvenation ^{3,10}.

Temporal branch of the facial nerve

The temporal branch of the facial nerve is particularly vulnerable during surgical dissection in the temporal region and near the zygomatic arch. Injury to this branch may result in weakness of the frontal muscle, impaired eyebrow elevation, and facial asymmetry. Safe dissection requires careful identification of anatomical planes and avoidance of unnecessary trauma in high-risk areas during SMAS and deep-plane procedures ^{3,4,12}.

Marginal mandibular branch of the facial nerve

The marginal mandibular branch innervates muscles responsible for lower lip depression and movement. Due to its anatomical course near the inferior border of the mandible, this nerve may be exposed to injury during lower facelift and cervical dissection. Preservation of this structure is essential to maintain lower facial symmetry and avoid functional impairment ^{10,12}.

Great auricular nerve

The great auricular nerve provides sensory innervation to the lower ear and adjacent periauricular skin. It is susceptible to injury during dissection along the sternocleidomastoid region, particularly during neck rejuvenation procedures. Damage may lead to postoperative numbness, altered sensation, or discomfort in the auricular area ¹⁰.

Vascular preservation

Adequate vascular preservation is critical for maintaining skin flap viability and reducing the risk of complications such as ischemia, delayed healing, and skin necrosis. Modern facelift techniques emphasize preservation of vascular connections and careful handling of tissue planes to maintain blood supply during flap elevation and repositioning. Appropriate surgical planning and meticulous technique remain essential factors in reducing vascular complications ^{10,11}.

3.3.5. Selection of the Surgical Plane

The selection of the appropriate surgical plane is one of the most important steps in facelift planning because each anatomical approach provides different advantages regarding tissue mobilization, correction of aging changes, technical complexity, and potential risks. Modern facelift surgery is based on individualized selection of the surgical plane according to the patient's facial anatomy, degree of soft tissue descent, skin quality, and aesthetic objectives rather than the application of a single universal technique ^{5,6}.

Subcutaneous Facelift

The subcutaneous facelift involves elevation of the skin flap above the SMAS layer. Historically, this approach represented the foundation of early facelift procedures and remains technically less complex compared with deeper

techniques. It may provide satisfactory improvement in patients with limited skin laxity; however, because deeper supporting structures are not directly addressed, correction of significant soft tissue descent is limited. In addition, excessive dependence on skin tension may reduce long-term durability and increase the risk of unnatural tightening effects ⁵.

SMAS Facelift

SMAS-based facelift procedures represent a major advancement in facial rejuvenation by addressing the deeper fascial support system. Manipulation of the SMAS allows redistribution of tension away from the skin and enables more stable repositioning of facial tissues. Different modifications, including SMAS plication, SMASectomy, and SMAS flap techniques, provide improved correction of lower facial laxity and mandibular contour changes while maintaining natural facial expression ^{6,20,23}.

Sub-SMAS Facelift

Sub-SMAS dissection involves surgical manipulation beneath the SMAS layer, allowing greater access to deeper facial structures and increased tissue mobilization. Although this approach provides enhanced correction of advanced aging changes, it requires extensive knowledge of facial anatomy because of the closer relationship with important facial nerve branches. Careful identification of anatomical planes is essential to reduce the risk of nerve injury ⁶.

Deep-Plane Facelift

The deep-plane facelift represents an evolution of anatomical facelift surgery in which the skin, SMAS, and deeper soft tissues are mobilized as a composite unit. Controlled release of retaining ligaments allows greater repositioning of descended midface and lower facial tissues with reduced reliance on skin tension. This approach may provide improved correction of midface ptosis, nasolabial folds, jawline definition, and cervical aging changes in appropriately selected patients ^{4,6}.

Composite-Plane Facelift

The composite-plane facelift preserves the anatomical continuity between the skin, SMAS, and underlying soft tissues by elevating them as a unified flap. This concept allows simultaneous repositioning of multiple facial layers and may be particularly beneficial for patients requiring comprehensive correction of midface, lower face, and neck aging. The technique emphasizes restoration of facial harmony rather than isolated tissue elevation ⁴.

Anatomical Indications for Plane Selection

The ideal surgical plane should be selected according to individual anatomical characteristics, including the severity of soft tissue ptosis, midface volume deficiency, skin elasticity, facial morphology, previous facelift procedures, and patient expectations. Contemporary practice increasingly favors a personalized approach in which the surgical plane is adapted to the specific pattern of facial aging rather than applying the same technique to all patients ⁴⁻⁶.

The key anatomical structures involved in facelift surgery and their functional relevance for surgical plane selection are summarized in Table 2.

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Table 2. Key Anatomical Structures and Their Role in Modern Facelift Surgery

Anatomical Structure	Main Function	Age-related Changes	Importance in Facelift Surgery
Superficial Musculoaponeurotic System (SMAS)	Provides connection between facial muscles and overlying skin; transmits facial movements	Weakening, elongation, and downward displacement leading to facial laxity	Main target layer for deep tissue repositioning and long-lasting facial rejuvenation
Zygomatic Retaining Ligament	Supports midface soft tissues and malar region	Inferior migration of cheek tissues and loss of midface projection	Release allows effective elevation of descended midface structures
Masseteric Retaining Ligament	Stabilizes lateral cheek tissues over the masseter muscle	Contributes to limitation of tissue mobility during aging	Controlled release improves lower face mobilization
Mandibular Retaining Ligament	Defines transition between cheek and mandibular region	Formation of jowls and loss of mandibular contour	Important for correction of lower facial aging
Cervical Retaining Ligaments	Support cervical soft tissues	Neck laxity and reduced cervicofacial definition	Important during neck lift and cervicofacial rejuvenation
Superficial Fat Compartments	Provide facial contour and smooth skin transition	Volume loss and redistribution	Require repositioning or volume restoration
Deep Facial Fat Compartments	Maintain midface volume and structural support	Atrophy and descent	Targeted correction improves midface rejuvenation
Facial Nerve Branches	Control facial expression muscles	Vulnerability during surgical dissection	Anatomical preservation prevents functional complications
Great Auricular Nerve	Provides sensation to ear and lateral neck	Risk during cervical dissection	Preservation reduces postoperative sensory disturbance
Facial Vasculature	Maintains tissue perfusion	Reduced vascular reserve with aging	Essential for flap survival and complication prevention

3.3.6. Patient-specific Anatomical Considerations

Facelift surgery requires individualized anatomical assessment because facial aging does not occur according to a uniform pattern. Variations in soft tissue descent, skin characteristics, facial proportions, skeletal structure, and previous procedures significantly influence both surgical planning and expected outcomes. Modern facelift surgery therefore emphasizes patient-specific strategies rather than applying a standardized technique to all individuals ^{1,3,4}.

Age

Age is an important factor affecting the extent and distribution of facial aging changes. Younger patients may primarily demonstrate early skin laxity or limited soft tissue descent and may benefit from less extensive procedures. In contrast, older patients frequently present with combined changes involving the skin, SMAS, retaining ligaments, facial fat compartments, and skeletal support, requiring correction of multiple anatomical layers ^{1,3}.

Skin Quality

Skin thickness, elasticity, collagen content, degree of photodamage, and regenerative capacity influence postoperative healing and aesthetic outcomes. Patients with better skin quality generally demonstrate more predictable results, whereas severe elastosis or significant sun damage may limit the degree of improvement achievable through surgical lifting alone. Appropriate evaluation of skin characteristics is therefore essential during preoperative planning ^{1,5}.

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Facial Morphology

Facial morphology plays a central role in selecting the appropriate facelift strategy. Skeletal structure, cheek projection, mandibular contour, facial width, and distribution of soft tissues determine the pattern of aging and the required degree of correction. The primary objective of modern facelift surgery is restoration of balanced facial relationships while preserving individual identity and avoiding an artificial appearance ^{3,4}.

Body Mass Index (BMI)

Body mass index and changes in body weight may influence facial volume distribution, skin behavior, and long-term stability of surgical results. Significant weight loss after facelift surgery may lead to recurrent volume deficiency and altered facial contour, whereas increased adiposity may affect tissue thickness and surgical planning. Stable body weight is therefore considered an important factor for maintaining long-term outcomes ^{7,8}.

Degree of Ptosis

The severity and anatomical location of soft tissue descent are critical determinants in selecting the surgical approach. Assessment should include midface descent, jowl formation, mandibular contour changes, and cervical laxity. Patients with limited ptosis may benefit from less extensive procedures, whereas advanced aging changes often require SMAS-based, deep-plane, or combined approaches to achieve adequate correction ^{4,6}.

Previous Surgery

Previous facelift procedures, filler treatments, thread lifting, or other facial interventions may significantly alter normal anatomical planes and increase surgical complexity. Revision facelift surgery requires careful evaluation of scar tissue, previous dissection planes, remaining tissue support, and vascular conditions to achieve safe and predictable results ^{4,10}. A comprehensive understanding of patient-specific anatomical characteristics allows surgeons to select the most appropriate surgical plane, optimize aesthetic outcomes, reduce complications, and achieve natural, durable facial rejuvenation. Increasing emphasis on individualized planning and patient-reported outcome assessment reflects the modern shift toward personalized facial aesthetic surgery ^{13–16}.

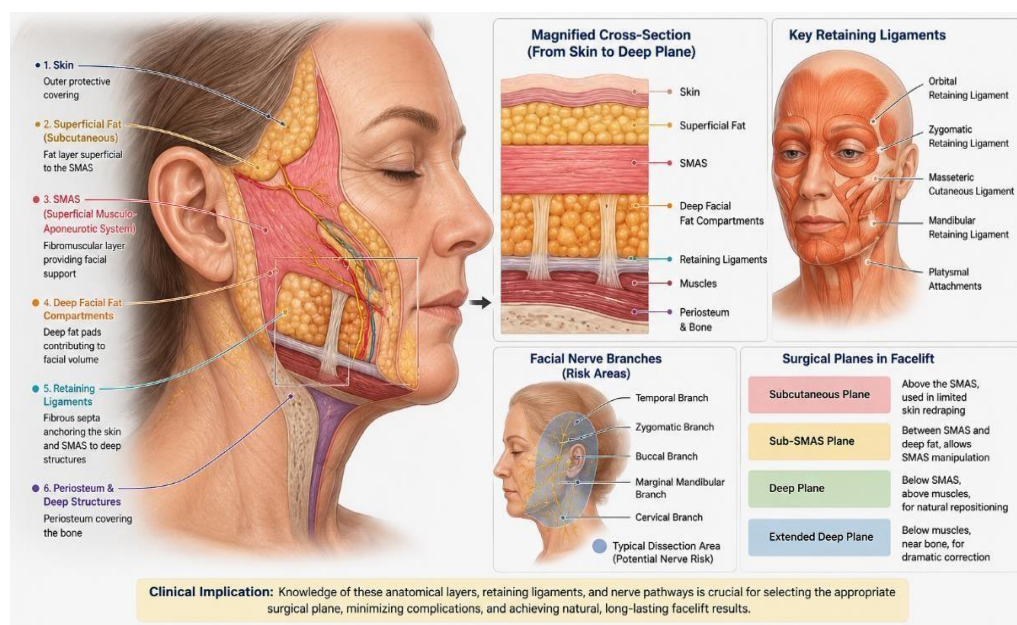


Figure 2. Anatomical layers and surgical planes involved in modern facelift procedures.

The illustration demonstrates the relationship between the skin, superficial fat, SMAS, deep facial fat compartments, retaining ligaments, and facial nerve structures, highlighting the anatomical basis of different facelift approaches.

3.4. Clinical Outcomes and Durability

The clinical success of facelift surgery should not be evaluated solely by the amount of tissue elevation achieved during surgery. Contemporary assessment focuses on restoration of harmonious facial proportions, preservation of natural facial expression, improvement of age-related deformities, and long-term patient satisfaction. Modern facelift procedures aim to correct multiple manifestations of facial aging, including skin laxity, soft tissue descent, volume redistribution, and loss of facial contour ⁴⁻⁶.

Published evidence demonstrates that facelift surgery provides consistent improvement in lower facial contour, jowl formation, midface descent, cervical definition, and overall facial rejuvenation. However, the magnitude and durability of improvement depend on several factors, including the selected surgical plane, patient anatomy, severity of aging changes, skin characteristics, and surgeon experience. Techniques that address deeper anatomical structures generally provide more comprehensive correction compared with procedures limited to skin excision and tightening ^{5,6}.

Traditional Subcutaneous Facelift

Traditional skin-only facelift techniques primarily address excess skin and superficial laxity. Although these procedures can produce visible short-term improvement, they do not directly correct descent of deeper facial structures. As a result, reliance on skin tension alone may limit long-term stability and may contribute to recurrent laxity or an unnatural appearance in some patients ⁵.

SMAS-based Facelift

SMAS-based techniques represent a major advancement in facial rejuvenation by addressing the deeper fascial support system. Redistribution of tension from the skin to the SMAS allows more stable repositioning of facial tissues and improves correction of lower facial aging, mandibular contour changes, and soft tissue laxity. These approaches have become a fundamental component of modern facelift surgery because they provide improved durability while maintaining natural facial movement ^{6,23}.

Deep-plane and Composite-plane Facelift

Deep-plane and composite-plane approaches further expand anatomical correction by allowing mobilization of the SMAS, facial fat compartments, and deeper soft tissues as a unified structure. Controlled release of retaining ligaments enables greater repositioning of descended midface and lower facial tissues with reduced skin tension. These techniques may provide enhanced correction of midface ptosis, nasolabial folds, jawline definition, and cervical aging changes in appropriately selected patients ⁴.

Role of Volume Restoration in Clinical Outcomes

Current concepts of facial rejuvenation recognize that aging involves both tissue descent and volume deficiency. Therefore, many facelift procedures are combined with structural fat grafting to restore facial fullness, improve contour transitions, and achieve more balanced results. Evidence suggests that combining lifting procedures with volume restoration may enhance overall aesthetic outcomes when performed according to individual anatomical requirements ⁷⁻⁹. The principal clinical outcomes, advantages, limitations, and expected durability of the major facelift techniques are summarized in Table 3.

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Table 3. Clinical Outcomes and Durability of Different Facelift Approaches

Surgical approach	Main anatomical target	Advantages	Limitations	Expected durability
Subcutaneous facelift	Skin and superficial laxity	Simpler technique, shorter operative time, suitable for mild aging changes	Limited correction of deep tissue descent; greater dependence on skin tension	Short- to medium-term
SMAS facelift	SMAS layer and lower facial soft tissues	Improved contour restoration, reduced skin tension, more natural facial appearance	Requires anatomical expertise and greater technical complexity	Long-term
Extended SMAS facelift	Extended SMAS and midface structures	Enhanced correction of midface and lower facial aging	More extensive dissection and longer operative time	Long-term
Deep-plane facelift	SMAS, retaining ligaments, deep facial tissues	Comprehensive rejuvenation, improved midface rejuvenation, jawline definition, and durable tissue repositioning	Technically demanding; requires advanced anatomical knowledge	Long-term
Composite-plane facelift	Skin–SMAS–deep tissue composite flap	Simultaneous repositioning of multiple tissue layers while preserving anatomical continuity	Increased operative complexity and prolonged learning curve	Long-term

Patient-reported Outcomes and Durability

Long-term success of facelift surgery is increasingly evaluated using validated patient-reported outcome measures rather than surgeon assessment alone. FACE-Q studies have demonstrated high levels of satisfaction following facelift procedures, particularly when outcomes are evaluated in terms of appearance, psychological well-being, and quality of life improvement^{13–16}.

The durability of facelift results varies among individuals and is influenced by age at surgery, genetic factors, lifestyle, sun exposure, smoking status, postoperative skincare, and continued facial aging. Although surgery does not stop the aging process, modern anatomical techniques can provide long-lasting rejuvenation while preserving facial identity and natural expression^{4–6}.

Patient Satisfaction and Functional Outcomes

Evaluation of facelift outcomes has progressively shifted from surgeon-based aesthetic assessment toward patient-reported measures that reflect personal satisfaction, confidence, and quality-of-life improvement. Contemporary evidence indicates that successful facelift surgery is associated not only with visible facial rejuvenation but also with improved psychological perception of facial appearance and overall well-being^{13–16}.

An important objective of modern facelift surgery is the preservation of facial identity and natural expression. Excessive skin tension, overcorrection, or inappropriate tissue repositioning may result in an unnatural appearance and reduced patient satisfaction. Therefore, optimal outcomes depend on achieving balanced restoration of facial anatomy while maintaining individual characteristics^{4,6}.

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Durability of Facelift Results

The longevity of facelift outcomes varies according to patient-related and procedure-related factors. Although surgery cannot prevent the biological aging process, anatomical repositioning of deeper facial structures may provide durable improvement compared with techniques limited to superficial skin tightening ⁴⁻⁶.

Long-term changes after facelift surgery continue to occur because of progressive skin aging, collagen degradation, alterations in facial volume, and gradual soft tissue descent. Factors influencing durability include patient age at surgery, genetic characteristics, skin quality, smoking status, sun exposure, postoperative care, weight stability, and surgical technique ^{1,4,5}.

Long-term evaluation of facelift outcomes requires a multidimensional assessment that integrates anatomical correction, facial harmony, preservation of expression, complication profile, and patient-reported satisfaction. The most successful procedures are those that achieve durable rejuvenation while maintaining natural facial characteristics and avoiding an overcorrected appearance. Therefore, modern facelift surgery should be considered successful not simply when tissues are elevated, but when balanced restoration of facial anatomy is achieved with stable and patient-perceived improvement over time ^{4-6,13-16}.

3.5. Complications and Safety Profile

Although facelift surgery has undergone substantial refinement through improved anatomical understanding, advanced surgical planes, and modern perioperative protocols, postoperative complications remain an important aspect of clinical decision-making. The safety profile of facelift procedures depends on multiple variables, including patient characteristics, surgical technique, extent of tissue dissection, preservation of vascular and neural structures, and surgeon experience. Large clinical analyses have emphasized that appropriate patient selection, risk assessment, and standardized perioperative management are essential components of improving facelift safety and reducing adverse outcomes ^{4,10,24}. Modern facelift surgery aims not only to achieve effective facial rejuvenation but also to minimize complications through careful anatomical planning, individualized selection of the surgical plane, meticulous hemostasis, and preservation of critical neurovascular structures. Contemporary safety strategies focus on balancing adequate tissue mobilization with preservation of vascular supply and functional anatomy ^{4,10,24}.

Early Postoperative Complications

Hematoma

Hematoma remains one of the most frequent and clinically significant early complications after facelift surgery. It usually develops during the immediate postoperative period and may present with progressive swelling, pain, increased flap tension, ecchymosis, or facial asymmetry. Because increased tissue pressure can compromise microcirculation, significant hematoma formation may threaten skin flap viability and increase the risk of delayed healing, skin necrosis, or need for surgical evacuation ^{10,11}.

Risk factors associated with hematoma formation include uncontrolled hypertension, inadequate intraoperative hemostasis, anticoagulant or antiplatelet medication use, smoking, and excessive physical activity during the early postoperative period. Prevention requires meticulous surgical technique, careful coagulation of bleeding vessels, appropriate perioperative blood pressure control, appropriate patient selection, and close postoperative monitoring. Recent evidence highlights the importance of systematic risk reduction protocols to decrease hematoma incidence and improve overall patient safety following rhytidectomy ^{10,11,24}.

3.3.3. Facial Fat Compartments

Facial fat is not organized as a single continuous layer but rather as a complex system of superficial and deep compartments that contribute to facial contour, volume distribution, and soft tissue support. The recognition of these anatomical units has significantly changed modern facelift surgery by demonstrating that facial aging involves selective volume loss, redistribution, and descent of specific fat compartments rather than uniform tissue atrophy ^{1,2}.

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Superficial fat compartments

Superficial facial fat is located between the skin and the superficial musculoaponeurotic system (SMAS) and plays an important role in facial smoothness and contour. Age-related changes within these compartments include volume reduction, thinning, and inferior displacement, which may contribute to irregular facial contours, loss of cheek fullness, and accentuation of facial folds. Understanding superficial fat behavior is essential during facelift surgery because excessive removal may result in an aged or hollow appearance, whereas preservation or selective repositioning can improve facial harmony ^{2,8}.

Deep fat compartments

Deep facial fat compartments are located beneath the SMAS and provide structural support for the midface. These compartments include the deep medial cheek fat, deep lateral cheek fat, and other supporting fat structures associated with midfacial projection. With aging, deep fat compartments undergo volume reduction and inferior migration, contributing to flattening of the malar region, increased nasolabial fold depth, and changes in facial proportions ^{1,3}.

Malar fat pad

The malar fat pad represents one of the most clinically important midface structures because it contributes significantly to cheek projection and youthful facial appearance. Descent of the malar fat compartment during aging contributes to midface ptosis, tear trough formation, and accentuation of the nasolabial fold. Modern facelift techniques, particularly SMAS-based and deep-plane approaches, aim not only to elevate soft tissues but also to restore the anatomical position of descended fat compartments ^{3,4}.

Aging changes in facial fat

Contemporary understanding of facial aging indicates that fat changes are characterized by both volume loss and redistribution. Different compartments may demonstrate simultaneous deflation, hypertrophy, and downward displacement. Therefore, modern rejuvenation strategies frequently combine anatomical repositioning of descended tissues with selective volume restoration using techniques such as structural fat grafting. This combined approach allows restoration of facial proportions while maintaining a natural appearance ⁷⁻⁹.

Nerve-Related Complications

Facial Nerve Injury

Facial nerve injury represents one of the most concerning complications following facelift surgery because it may lead to temporary or permanent functional impairment, facial asymmetry, and reduced patient satisfaction. The risk of nerve dysfunction depends mainly on the surgical plane, extent of dissection, and anatomical location of tissue manipulation. The temporal branch of the facial nerve is particularly vulnerable during temporal dissection, whereas the marginal mandibular branch requires careful protection during lower facial and cervical procedures. Most postoperative nerve disturbances are transient and are usually related to traction, edema, or neuropraxia. Permanent facial nerve dysfunction remains uncommon when surgery is performed with detailed anatomical knowledge and meticulous dissection techniques ^{12,25}.

Recent evidence indicates that nerve injuries after facelift surgery are rare, with most cases demonstrating spontaneous recovery during follow-up. However, prevention remains the primary goal, emphasizing the importance of anatomical plane selection and avoidance of unnecessary nerve manipulation ²⁵.

Sensory Disturbances

Temporary sensory changes are frequently observed after facelift surgery due to manipulation of superficial sensory nerves. The great auricular nerve is especially important during cervical dissection because injury may result in numbness, altered sensation, or hypersensitivity around the earlobe and lateral neck. In most patients, sensory

disturbances gradually improve over several months as nerve regeneration and adaptation occur. Careful preservation of sensory nerve pathways remains essential for reducing postoperative discomfort ^{12,25}.

Skin and Scar-Related Complications

Skin Flap Necrosis

Skin flap necrosis is an uncommon but serious complication caused by insufficient vascular perfusion of elevated facial tissues. Risk factors include excessive skin tension, aggressive flap thinning, smoking, vascular disease, previous surgery, and extensive undermining. Modern facelift techniques that preserve vascularity, reduce tension on the skin flap, and rely more on deeper tissue repositioning have contributed to improved safety profiles and reduced rates of flap compromise ^{10,24}.

Hypertrophic Scarring and Poor Scar Quality

Although facelift incisions are designed within natural skin folds and hair-bearing areas, scar quality remains an important factor influencing aesthetic satisfaction. Hypertrophic scarring, widened scars, or unfavorable scar appearance may occur due to individual healing characteristics, infection, increased wound tension, or inadequate postoperative care. Careful incision planning, reduction of skin tension, and appropriate postoperative scar management are important components of achieving optimal long-term results ^{10,26}.

Patient-related Risk Factors and Prevention Strategies

The occurrence and severity of facelift-related complications are influenced not only by surgical technique but also by individual patient characteristics and perioperative factors. Comprehensive preoperative evaluation is essential to identify conditions that may increase the risk of impaired wound healing, bleeding, infection, or suboptimal aesthetic outcomes. Important patient-related risk factors include active smoking, uncontrolled hypertension, diabetes mellitus, anticoagulant or antiplatelet therapy, significant fluctuations in body weight, previous facial surgery, and reduced skin quality associated with aging or environmental damage ^{10,24,26,28}.

Smoking remains one of the most significant modifiable risk factors because nicotine-induced vasoconstriction and impaired microcirculation may compromise skin flap viability and increase the risk of wound complications. Similarly, uncontrolled hypertension has been strongly associated with postoperative hematoma formation, emphasizing the importance of adequate perioperative blood pressure management ^{11,26,28}.

Previous facial procedures, including prior facelift surgery, filler injections, or energy-based treatments, may alter normal anatomical planes and increase surgical complexity. Therefore, detailed assessment of previous interventions and individualized surgical planning are necessary to minimize complications and optimize outcomes. Modern evidence-based approaches emphasize careful patient selection, optimization of medical conditions, meticulous surgical technique, and structured postoperative follow-up as essential components of facelift safety ^{27,29}.

The principal complications associated with facelift surgery, together with their typical timing, clinical significance, major risk factors, and recommended prevention strategies, are summarized in Table 4.

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Table 4. Complications Associated with Facelift Surgery: Incidence, Clinical Significance, and Prevention

Complication	Typical Timing	Clinical Significance	Main Risk Factors	Prevention Strategies
Hematoma	Early (first 24–48 hours)	Most important early complication; may compromise flap survival	Hypertension, anticoagulants, inadequate hemostasis, smoking	Careful hemostasis, blood pressure control, close monitoring
Edema and ecchymosis	Early postoperative period	Temporary swelling and bruising affecting recovery	Extensive dissection, individual healing response	Gentle tissue handling, postoperative care
Seroma	Early/intermediate	Fluid accumulation causing delayed healing	Lymphatic disruption, large dissection spaces	Preservation of lymphatics; aspiration when required
Infection	Early/intermediate	May impair wound healing and increase morbidity	Smoking, poor wound care, prolonged surgery	Sterile technique, early diagnosis, and appropriate treatment
Facial nerve injury	Early	Functional impairment and facial asymmetry	Incorrect dissection plane, excessive traction	Detailed anatomical knowledge and careful nerve preservation
Sensory nerve disturbance	Early/intermediate	Numbness or altered sensation	Great auricular nerve manipulation	Anatomical preservation and patient counseling
Skin flap necrosis	Early	Serious wound-healing complication	Smoking, excessive flap tension, vascular compromise	Preservation of blood supply and reduction of flap tension
Hypertrophic scarring	Late	Aesthetic dissatisfaction	Genetic predisposition, wound tension, infection	Optimal incision design and appropriate scar management
Facial asymmetry	Late	Compromised aesthetic outcome	Unequal tissue repositioning, healing variability	Accurate preoperative planning and individualized surgical technique

3.6. Emerging Trends in Facelift Surgery

Recent advances in facial rejuvenation have shifted the philosophy of facelift surgery from isolated tissue tightening toward a more comprehensive, anatomy-based approach. Modern concepts recognize facial aging as a multidimensional process involving progressive changes in skin quality, soft tissue descent, ligamentous laxity, fat redistribution, muscular alterations, and skeletal remodeling. Consequently, contemporary facelift procedures increasingly emphasize individualized treatment planning based on patient-specific anatomical characteristics rather than the application of a standardized surgical technique^{1,4,21}.

The current evolution of facelift surgery is characterized by integration of structural correction, volume restoration, and complementary rejuvenation procedures. These approaches aim to achieve balanced facial rejuvenation while preserving facial identity, natural expression, and long-term aesthetic stability^{7,9,27}.

Integration of Volume Restoration and the “Lift-and-Fill” Concept

One of the most important developments in modern facial rejuvenation is the recognition that facial aging involves not only gravitational descent of soft tissues but also progressive changes in facial volume distribution. Loss of fullness, particularly in the midface, temporal region, and periorbital area, contributes significantly to an aged appearance and cannot be completely corrected by lifting procedures alone ^{1,2}.

The “lift-and-fill” concept combines anatomical repositioning of descended tissues with restoration of age-related volume deficiency. Autologous fat grafting has become an important adjunctive technique because it allows correction of contour irregularities, restoration of soft tissue fullness, and improvement of facial harmony using a biologically compatible material ^{7,8}.

Compared with isolated lifting procedures, combined tissue repositioning and volume restoration strategies provide a more comprehensive approach by addressing both structural ptosis and facial deflation. Current evidence supports the integration of fat grafting with facelift surgery in selected patients to improve aesthetic balance and optimize rejuvenation outcomes ^{9,27}.

Combined Surgical and Minimally Invasive Approaches

Modern facial rejuvenation increasingly incorporates combined surgical and minimally invasive procedures to achieve comprehensive and harmonious aesthetic outcomes. Facelift surgery is frequently combined with complementary procedures such as cervical contouring, blepharoplasty, brow rejuvenation, laser resurfacing, and volume-enhancing treatments. These multimodal strategies allow simultaneous correction of different manifestations of facial aging, including tissue descent, volume depletion, and skin quality deterioration, while maintaining facial balance and natural appearance ^{7,27}.

Minimally invasive procedures, including neuromodulators, dermal fillers, energy-based skin tightening technologies, and biostimulatory treatments, are increasingly used as adjunctive methods for optimizing and maintaining facelift outcomes. Rather than replacing surgical rejuvenation, these techniques serve as complementary approaches that address superficial aging changes and contribute to long-term aesthetic maintenance ^{9,27}.

Regenerative and Biological Approaches

Regenerative medicine represents one of the emerging directions in contemporary facial rejuvenation. Current interest has shifted toward biological approaches aimed not only at restoring facial volume but also at improving tissue quality, vascularity, and dermal remodeling. Adipose-derived products, platelet-rich plasma (PRP), platelet-rich fibrin (PRF), and other biologically active materials have been investigated for their potential effects on collagen synthesis, angiogenesis, wound healing, and skin regeneration. These approaches may provide additional benefits when combined with surgical rejuvenation procedures by improving tissue quality and enhancing postoperative recovery ^{31,32}.

However, despite promising preliminary findings, the clinical application of regenerative techniques remains heterogeneous, with variations in preparation protocols, treatment parameters, and outcome assessment methods. Further well-designed clinical studies are required to establish standardized protocols and determine their long-term effectiveness in facial rejuvenation ^{27,31}.

Three-Dimensional Facial Analysis and Personalized Planning

Technological advances have introduced objective methods for facial assessment and surgical planning in modern facial rejuvenation. Three-dimensional (3D) imaging technologies allow quantitative evaluation of facial morphology, asymmetry, soft tissue distribution, and postoperative changes. Compared with conventional two-dimensional photography, 3D facial analysis provides more comprehensive information regarding volumetric changes and spatial relationships, improving patient consultation, surgical simulation, and individualized treatment planning. These technologies may enhance communication between surgeons and patients by providing a more precise representation of expected aesthetic outcomes ³³.

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Artificial Intelligence and Data-driven Facial Assessment

Artificial intelligence (AI) and machine-learning technologies are emerging as promising tools in aesthetic and reconstructive surgery. AI-based systems may assist in automated facial analysis, recognition of aging patterns, evaluation of facial symmetry, and objective assessment of postoperative results. Although clinical applications remain at an early stage, these technologies may contribute to more standardized assessment methods, improved surgical planning, and personalized decision-making in future facelift surgery ^{34,35}.

Personalized and Anatomy-Based Facelift Surgery

The future direction of facelift surgery is moving toward precision-based, anatomy-driven rejuvenation. Rather than selecting procedures solely according to chronological age, contemporary approaches increasingly consider individual anatomical characteristics, facial morphology, skin quality, volume distribution, skeletal structure, and patient expectations. Personalized surgical planning aims to achieve harmonious rejuvenation while preserving facial identity and avoiding excessive correction. The integration of objective facial analysis with anatomical principles may further improve predictability and long-term aesthetic outcomes ^{21,33}. Current emerging technologies and personalized strategies that are expected to shape the future of facelift surgery are summarized in Table 5.

Table 5. Emerging Trends and Future Directions in Facelift Surgery

Emerging Approach	Main Principle	Clinical Application	Potential Advantages	Current Limitations
Lift-and-fill facelift	Combination of tissue repositioning and volume restoration	Facelift combined with autologous fat grafting or volume correction	More balanced and natural facial rejuvenation	Long-term volume stability may vary
Autologous fat grafting	Restoration of lost facial volume using patient-derived adipose tissue	Midface, temples, periorbital region, and facial contour correction	Natural volume replacement and improved tissue quality	Variable graft survival
Combined facial rejuvenation procedures	Simultaneous treatment of multiple aging components	Facelift combined with neck lift, blepharoplasty, resurfacing, or injectables	Comprehensive aesthetic improvement	Increased procedural complexity
Minimally invasive maintenance strategies	Nonsurgical enhancement following facelift surgery	Dermal fillers, neuromodulators, and energy-based devices	Prolongation of aesthetic results with reduced downtime	Temporary effects requiring repeated treatments
Regenerative medicine approaches	Enhancement of tissue quality and healing capacity	PRP, PRF, and adipose-derived regenerative products	Potential improvement in skin quality and tissue regeneration	Limited standardization and variable level of clinical evidence
Three-dimensional facial analysis	Objective evaluation of facial morphology and aging changes	Preoperative planning and postoperative outcome assessment	Improved personalization and objective outcome measurement	Additional cost and technical requirements
Artificial intelligence-based assessment	Automated analysis of facial features and aging patterns	Surgical planning, decision support, and outcome evaluation	Increased objectivity, reproducibility, and personalized planning	Requires further validation and clinical integration
Personalized facelift planning	Anatomy-driven selection of surgical technique	Individualized treatment based on patient-specific anatomy	Preserves facial identity and improves patient satisfaction	Requires comprehensive preoperative assessment and advanced surgical expertise

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4. DISCUSSION

The evolution of facelift surgery reflects a fundamental transformation in the understanding of facial aging. Earlier procedures were primarily based on removal of excess skin and superficial tightening; however, contemporary concepts recognize facial aging as a complex three-dimensional process involving skeletal remodeling, redistribution of facial fat compartments, soft tissue descent, ligamentous changes, and alterations in skin quality ^{1,2,21}. Therefore, successful facial rejuvenation is no longer defined only by the amount of tissue elevation achieved, but rather by the ability to restore anatomical relationships, maintain facial identity, and achieve natural long-term outcomes.

Comparative Interpretation of Facelift Techniques

The available evidence demonstrates that facelift techniques have progressively evolved from skin-focused procedures toward anatomy-based approaches. Traditional skin-only facelifts may provide acceptable improvement in patients with mild skin laxity; however, their ability to correct deeper structural changes associated with facial aging remains limited ^{5,20,21}. The recognition of the superficial musculoaponeurotic system (SMAS) as a major supporting structure represented an important advancement because it allowed redistribution of tension away from the skin and improved correction of lower facial aging changes ^{6,23}.

SMAS-based procedures remain among the most widely used approaches because they provide reliable improvement of facial contour while maintaining favorable safety characteristics. Extended SMAS techniques further expanded this concept by allowing deeper mobilization and correction of midface descent through anatomical release of retaining structures ^{22,23}. Deep-plane and composite-plane techniques represent a continuation of this structural philosophy by treating multiple facial layers as an integrated unit, enabling more comprehensive repositioning of descended tissues ^{4,6}. However, current evidence does not support the concept that one facelift technique is universally superior. The choice of procedure should be based on individual anatomical characteristics, degree of tissue descent, skin quality, facial proportions, and patient expectations rather than chronological age alone ^{21,43,44}.

Modern facelift surgery therefore represents a personalized approach rather than a standardized operation.

Durability of Results and Factors Affecting Long-Term Outcomes

Long-term success after facelift surgery depends on both surgical correction and biological factors influencing facial aging. Procedures that address deeper anatomical structures generally demonstrate greater stability because they restore structural support rather than relying primarily on skin tension ^{6,23,38}. Nevertheless, facelift surgery does not interrupt the aging process, and progressive changes in skin elasticity, collagen metabolism, fat distribution, and skeletal morphology continue after surgery ^{1,2}.

The durability of facelift outcomes is influenced by multiple variables, including genetic predisposition, lifestyle factors, environmental exposure, smoking status, postoperative care, and maintenance treatments ^{10,27}. Therefore, the concept of a permanent facelift result should be replaced by the understanding of long-term rejuvenation through restoration of anatomical balance. The incorporation of adjunctive procedures, particularly volume restoration with autologous fat grafting, has further modified the concept of facial rejuvenation. Aging is associated not only with descent of tissues but also with progressive deflation and redistribution of facial fat compartments ^{2,8}. The combination of lifting and volume restoration may improve facial harmony by addressing both positional and volumetric changes ^{7,9,27}.

Patient Satisfaction and Individualized Treatment Planning

Modern evaluation of facelift outcomes increasingly emphasizes patient-reported measures rather than surgeon assessment alone. Instruments such as FACE-Q have demonstrated that successful facelift surgery is associated with improvements in satisfaction with facial appearance, psychological well-being, and quality of life ^{13–16}.

An important principle emerging from contemporary literature is that aesthetic success should not be measured only by visible tightening but by the preservation of facial expression and individual characteristics. Excessive correction may result in an unnatural appearance, whereas anatomical restoration aims to create a refreshed but recognizable facial appearance ^{21,43}.

Personalized planning has therefore become central to modern facelift practice. Patients with similar chronological ages may demonstrate substantially different patterns of volume loss, ligamentous laxity, skin changes, and skeletal remodeling. Individualized assessment allows selection of the most appropriate surgical strategy and reduces the risk of overcorrection ^{21,44}.

Safety Considerations and Current Limitations of Evidence

Although advances in surgical anatomy and perioperative management have improved the safety profile of facelift surgery, complications remain an important consideration. Hematoma, nerve injury, wound healing problems, infection, and scar-related complications continue to influence postoperative outcomes^{10,11,24,26,29}.

The available evidence indicates that complication rates are closely associated with patient selection, surgical technique, vascular preservation, and perioperative management. Smoking cessation, blood pressure control, optimization of medical conditions, and careful anatomical dissection remain essential strategies for reducing adverse events^{11,26,28}.

Despite extensive clinical experience, several limitations exist within the current evidence base. Many studies are retrospective, include heterogeneous patient populations, and use different outcome assessment methods, making direct comparison between facelift techniques difficult^{10,17,36,45}. Furthermore, objective measurement of aesthetic improvement remains challenging because traditional photography and subjective evaluation may not fully capture three-dimensional changes.

Future investigations should prioritize prospective multicenter studies, standardized outcome measures, longer follow-up periods, and objective assessment technologies to better define the comparative effectiveness of different facelift approaches^{36,45}.

Future Directions in Facelift Surgery

The future development of facelift surgery is expected to focus on precision, personalization, and integration of advanced technologies. Three-dimensional facial imaging has already demonstrated value in objective assessment of facial morphology, volume changes, surgical planning, and postoperative evaluation^{33,39,42}. Compared with conventional two-dimensional photography, three-dimensional systems provide more comprehensive information regarding spatial relationships and soft tissue changes.

Artificial intelligence and machine-learning technologies represent another emerging direction. AI-based systems may assist in facial analysis,

prediction of aging patterns, evaluation of symmetry, and development of individualized treatment plans^{34,35,40,41}. However, these technologies require further validation before routine clinical implementation.

Regenerative strategies, including adipose-derived products, platelet-based therapies, and biological approaches, may further influence the future of facial rejuvenation by targeting tissue quality, healing, and regeneration rather than only structural correction^{30–32}. Nevertheless, variations in preparation methods and treatment protocols highlight the need for high-quality clinical studies before widespread adoption.

Overall, the next generation of facelift surgery will likely combine advanced anatomical understanding, personalized surgical planning, digital assessment technologies, and regenerative concepts. The ultimate goal will remain achieving durable rejuvenation while preserving facial identity, natural movement, and patient satisfaction.

DECLARATIONS

Ethical Approval

Not applicable.

Competing Interests

The authors declare no conflict of interest.

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CASE REPORT

DIGITAL INNOVATION IN IMMEDIATE DENTURE DESIGN: A NEW ERA OF PATIENT-CENTERED CARE: A CLINICAL CASE REPORT

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Abstract

Background: Immediate complete dentures are frequently associated with reduced retention and stability because the prosthesis is fabricated before the post-extraction anatomy has stabilized. The resulting changes in the residual ridge and soft tissues may require early adjustment or replacement. These difficulties become particularly important when rapid prosthetic rehabilitation is required because of an impending systemic medical treatment.

Case Presentation: A 70-year-old woman presented with an ill-fitting maxillary immediate complete denture, inadequate retention, localized discomfort, and a symptomatic buccal exostosis. Following localized alveoloplasty, expedited prosthetic rehabilitation was required because the patient was scheduled to undergo breast cancer surgery followed by systemic chemotherapy. The conventional sequence of multiple clinical and laboratory appointments was therefore considered impractical.

Clinical Technique: The existing immediate denture was modified and used as a functional impression carrier. Underextended borders were corrected with sectional polyvinylsiloxane putty border molding, followed by a closed-mouth definitive impression with light-body polyvinylsiloxane. The resulting impression was digitized using a 3Shape E4 laboratory scanner. The mandibular dentition and interocclusal relationship were recorded with a 3Shape TRIOS 4 intraoral scanner. The prosthesis was digitally designed using the 3Shape Dental System and fabricated with a SprintRay Pro2 three-dimensional printer using dedicated denture-base and tooth resins.

Outcome: The resulting prosthesis demonstrated clinically satisfactory retention, stability, and tissue adaptation. The workflow reduced intermediate laboratory procedures and allowed rapid prosthetic rehabilitation within the patient's limited treatment window. At follow-up after two cycles of chemotherapy, the oral tissues appeared healthy, without clinical evidence of xerostomia or oral mucositis, and the patient reported satisfactory prosthesis use.

Conclusion: Using an existing immediate denture as a modified functional impression carrier can provide a practical connection between conventional prosthodontic principles and digital denture fabrication. This hybrid approach may be useful for selected patients in whom rapid prosthetic treatment is required and conventional laboratory timelines are difficult to accommodate.

Keywords: Immediate Complete Denture; Digital Denture; Hybrid Analog-Digital; Three-Dimensional Printing; Computer-Aided Design and Computer-Aided Manufacturing; Prosthodontics

INTRODUCTION

The fabrication of complete removable dentures traditionally involves a sequence of clinical and laboratory procedures, including preliminary impressions, custom tray fabrication, border molding, definitive impressions, jaw-relation records, tooth arrangement, and laboratory processing. These procedures remain clinically valuable because they

allow the clinician to evaluate tissue support, border extension, occlusion, and prosthesis adaptation at several stages of treatment. At the same time, the conventional workflow requires multiple appointments and laboratory procedures, and the cumulative nature of these steps may increase treatment time and the potential for procedural errors. The quality of the final prosthesis therefore depends not only on the materials used but also on the

accuracy and consistency of each clinical and laboratory stage ^{1,2}.

Impression making remains one of the most important stages of complete denture treatment. Adequate retention and stability depend on accurate recording of the denture-bearing tissues and appropriate functional extension of the peripheral borders. Polyvinylsiloxane impression materials have been widely used because of their dimensional stability, elastic recovery, detail reproduction, and resistance to permanent deformation ². Different border-molding approaches have been described, including sectional and single-stage techniques. Clinical studies have shown that silicone-based border molding can provide satisfactory recording of the functional vestibular anatomy when the material is appropriately manipulated and functional movements are incorporated into the procedure ^{3,4}.

The introduction of computer-aided design and computer-aided manufacturing has changed the way complete dentures can be planned and fabricated. Digital workflows permit clinical information to be converted into digital datasets that can be stored, modified, transferred electronically, and reused for future prosthetic treatment. Earlier clinical studies demonstrated that computer-aided design and computer-aided manufacturing dentures can provide favorable denture-base adaptation and retention compared with conventional fabrication methods ⁵⁻⁷. A systematic review and meta-analysis involving 73 studies further demonstrated that computer-aided design and computer-aided manufacturing complete dentures can reduce chairside time and overall treatment costs while providing clinically acceptable outcomes ⁸.

The development of additive manufacturing has expanded these possibilities further. Three-dimensional printing permits denture bases and prosthetic teeth to be produced directly from digital designs and offers advantages in manufacturing flexibility and digital reproducibility. Recent clinical evidence has demonstrated favorable intaglio surface trueness of three-dimensional printed denture bases, with printed bases showing greater surface trueness than conventional analog denture bases in one clinical investigation⁹. Nevertheless, three-dimensional printing should not be considered universally superior to conventional or milled fabrication. Differences in resin composition, printing parameters, post-processing, mechanical properties, color stability, and long-term clinical behavior remain important considerations ¹⁰. Systematic reviews published in recent years have provided a more balanced assessment of digital complete dentures. Thu et al.

identified substantial variation among digital clinical and laboratory protocols, emphasizing that the clinical steps used to acquire the initial records remain important determinants of the final result ¹¹. Similarly, Avelino et al. reported that digitally fabricated complete dentures generally demonstrated clinical performance comparable with or better than conventional dentures, although conventional printed dentures showed greater retention than conventional dentures in some analyses and patient-reported outcomes were not consistently different between manufacturing methods ¹².

Fouda et al. likewise found that digital workflows generally offered advantages in fabrication time and cost-effectiveness, but patient satisfaction and clinician-assessed denture quality were not consistently superior to conventional approaches ¹³.

Immediate complete dentures present a particular challenge because they are fabricated before extraction of the remaining natural teeth. The denture-bearing anatomy is therefore estimated rather than recorded after extraction and healing. Subsequent changes in the residual ridge and soft tissues may alter the relationship between the denture base and supporting tissues, leading to reduced retention, stability, and comfort. Digital techniques have recently been applied to immediate complete denture treatment, demonstrating that digital workflows can reduce some of the conventional laboratory stages and provide an efficient means of prosthesis fabrication ¹⁴.

The clinical problem becomes more complex when an existing immediate denture becomes significantly inaccurate during healing and the patient cannot reasonably undergo a conventional sequence of new impressions, cast fabrication, custom tray construction, and laboratory processing. In such situations, repeating the entire conventional procedure may require more time than the patient's medical circumstances allow. The existing prosthesis, however, may still contain useful information regarding tooth position, vertical dimension, occlusal relationships, and facial support.

The present case describes a hybrid approach in which the patient's existing immediate denture was not discarded. Instead, its deficient borders were corrected using polyvinylsiloxane putty, allowing the prosthesis to function as a patient-specific impression carrier. A definitive light-body polyvinylsiloxane impression was then obtained and digitized using a laboratory scanner. The opposing dentition and interocclusal relationship were recorded with an intraoral scanner, and the resulting datasets were incorporated into a computer-aided design workflow for three-dimensional printing.

The relevance of this approach is particularly apparent in patients who require rapid dental rehabilitation because of

impending systemic medical treatment. In the present case, the need for a functional prosthesis coincided with an imminent oncological treatment schedule. The hybrid technique permitted functional tissue recording using a conventional elastomeric material while avoiding several intermediate laboratory stages. At the same time, digital fabrication allowed the recorded anatomy to be transferred directly into the definitive prosthesis. Although previous reports have described fully digital immediate denture workflows¹⁴, the use of an existing, poorly fitting immediate denture as a modified functional impression carrier followed by laboratory digitization and additive manufacturing has received considerably less clinical attention. The present report therefore describes a practical hybrid protocol designed to preserve useful information from an existing prosthesis while adapting it to the patient's current anatomy.

CASE REPORT

A 70-year-old woman presented to the College of Dental Medicine at the Medical University of South Carolina with severe discomfort, localized pain, and poor retention of her maxillary immediate complete denture. The prosthesis had been inserted immediately after extraction of the remaining maxillary teeth in the oral surgery department of the same institution. During the subsequent healing period, however, the denture no longer adapted adequately to the changing maxillary anatomy.

Clinical examination demonstrated satisfactory healing of the extraction sites, except for a prominent buccal exostosis in the right maxillary posterior region corresponding to the areas of teeth #4, #5, and #6. The region showed localized erythema and tenderness (Figure 1).

The patient also had shallow buccal vestibules and a moderately flat palatal vault. The maxillary immediate denture exhibited inadequate adaptation and deficient peripheral extension. The mandibular arch was dentate and had been restored with full-coverage fixed crowns fabricated from different restorative materials (Figure 1).



Figure 1. Initial Intraoral clinical presentation.

Intraoral views demonstrating the poorly adapted maxillary immediate complete denture, localized buccal exostosis with associated erythema and tenderness in the right maxillary posterior region, shallow buccal vestibules, and the opposing mandibular dentition restored with full-coverage fixed crowns.

No additional intraoral lesions or clinically significant soft-tissue trauma were identified.

An oral and maxillofacial surgery consultation was obtained during the same visit. Because the buccal exostosis was symptomatic and interfered with the prosthesis, localized alveoloplasty was performed to remove the bony prominence.

Under ordinary circumstances, definitive prosthetic treatment would be postponed until appropriate healing of the surgical site had occurred. In this patient, however, the treatment plan was influenced by an urgent medical schedule. She had recently been diagnosed with breast cancer and was scheduled to undergo lumpectomy followed by systemic chemotherapy the following week. Providing a functional and comfortable prosthesis within the available treatment period was therefore considered an important component of her dental care.

Because of the ongoing medical treatment, the patient was unable to attend the routine 24-hour postoperative dental appointment. She subsequently returned after completing two cycles of chemotherapy. At that visit, she reported a favorable oncological response. Clinical examination demonstrated satisfactory healing of the alveolar and soft tissues. No clinical evidence of xerostomia, oral mucositis, or other chemotherapy-associated oral complications was observed.

Because the original immediate denture was poorly adapted and conventional prosthetic treatment could not be completed within the available timeframe, a hybrid analog-digital workflow was selected.

The existing denture was retained and modified rather than discarded. Its deficient peripheral borders were extended with high-viscosity polyvinylsiloxane putty, allowing the denture to function as a patient-specific impression carrier. A definitive light-body polyvinylsiloxane wash impression was subsequently obtained within the modified prosthesis. The resulting impression was digitized and used as the basis for computer-aided denture design and additive manufacturing.

MATERIALS AND METHODS

The digital workflow combined conventional elastomeric impression procedures, laboratory scanning, intraoral scanning, computer-aided design, and additive manufacturing.

The modified maxillary impression was digitized with a 3Shape E4 desktop laboratory scanner (3Shape A/S, Copenhagen, Denmark). The opposing mandibular dentition and interocclusal relationship were recorded using a 3Shape TRIOS 4 intraoral scanner. The resulting digital datasets were processed using the 3Shape Dental System software.

The definitive prosthesis was fabricated using a SprintRay Pro2 three-dimensional printer (SprintRay Inc., Los Angeles, CA, USA). Apex Base resin in Original Pink was used for the denture base, and Apex Teeth resin in Shade A2 was used for the prosthetic teeth. The uncured flowable form of the Apex Base resin was also used as the bonding medium between the printed teeth and denture base before final polymerization.

The laboratory fabrication process required approximately 40 minutes for digital denture design, performed in collaboration with a dental student. Printing of the denture base required approximately 1 hour and 17 minutes, while printing of the tooth segments required approximately 25 minutes. Post-processing, assembly, bonding, and final polymerization required approximately 1 hour.

Clinical Border Correction and Definitive Impression

The peripheral borders of the existing immediate denture were first evaluated intraorally. Because the flanges were underextended, high-viscosity polyvinylsiloxane putty was added incrementally to the deficient areas (Figure 2). Border correction was performed in sections to permit controlled adaptation of the material to the patient's vestibular anatomy.

During border molding, the clinician manually manipulated the facial tissues while the patient performed functional movements to activate the surrounding musculature. Particular attention was given to the buccal vestibule and posterior palatal region to obtain adequate extension without overextension. Once the desired border contours had been established, excess polyvinylsiloxane that had extended onto the intaglio surface was removed with a laboratory blade. Approximately 2 mm of material was maintained as a continuous peripheral rim along the denture borders.

The modified denture was then prepared for the definitive impression. Polyvinylsiloxane tray adhesive was applied to the modified denture, followed by placement of low-viscosity light-body polyvinylsiloxane over the intaglio surface (Figure 2).



Figure 2. Clinical modification of the existing immediate denture and definitive impression procedure.

Sequential clinical views demonstrating sectional addition of high-viscosity polyvinylsiloxane putty to the deficient denture borders, functional border molding, trimming of excess material, and subsequent application of light-body polyvinylsiloxane for the definitive closed-mouth impression.

The resulting impression was digitized and used as the basis for computer-aided denture design and additive manufacturing. The definitive prosthesis was designed using the 3Shape Dental System and fabricated with a SprintRay Pro2 3D printer.

The denture was seated intraorally, and the patient was guided into the previously established vertical dimension of occlusion. Functional movements were repeated during polymerization of the impression material to refine the peripheral extension and record the dynamic relationship between the denture borders and surrounding soft tissues.

Digital Scanning, Denture Design, and Additive Manufacturing

After removal from the oral cavity, the definitive maxillary PVS impression was scanned using the 3Shape E4 laboratory scanner.

The digital acquisition process included scanning of the definitive maxillary impression, acquisition of the opposing mandibular dentition, and registration of the interocclusal relationship (Figure 3).

This generated the digital datasets required for computer-aided denture design.

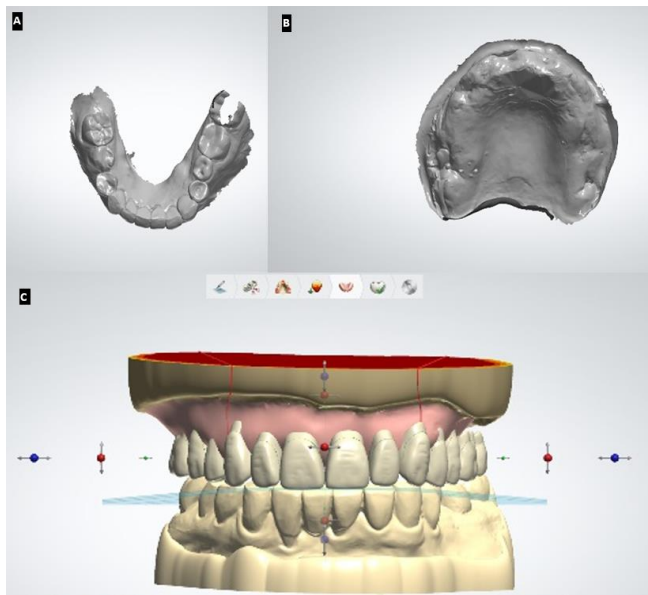


Figure 3. Digital acquisition and computer-aided denture design.

Digital workflow showing laboratory scanning of the definitive maxillary polyvinylsiloxane impression, intraoral scanning of the opposing mandibular dentition and interocclusal relationship, digital alignment of the maxillary and mandibular arches, and virtual design of the definitive complete denture.

The resulting datasets were imported into the 3Shape Dental System. The maxillary and mandibular digital models were aligned, and the maxillomandibular relationship was evaluated. The virtual denture was then designed with attention to the required denture-base thickness, peripheral contours, tooth position, and overall facial and occlusal form.

A lingualized occlusal scheme was selected, with a 15-degree cusp inclination. This arrangement was chosen to provide a stable occlusal relationship while limiting potentially destabilizing lateral forces. The prosthetic teeth were arranged digitally and incorporated into the final denture design before export to the printing software.

The denture base was printed horizontally using Apex Base resin, while the prosthetic teeth were printed separately using Apex Teeth resin.

Following printing, the denture base and tooth segments were cleaned, assembled, and bonded before final polymerization (Figure 4).



Figure 4. Additive manufacturing, assembly, and final prosthesis.

Three-dimensional printing of the denture base and prosthetic tooth segments, followed by positioning of the printed tooth segments within the denture base, application of uncured denture-base resin at the interfaces, final polymerization, and the completed definitive maxillary complete denture.

Before final polymerization, uncured flowable Apex Base resin was applied at the interfaces between the tooth segments and denture base. The assembled prosthesis was then subjected to the prescribed final thermal and ultraviolet-light polymerization procedure.

After completion of post-processing and inspection of the finished prosthesis, the denture was clinically evaluated and delivered to the patient (Figure 5).



Figure 5. Intraoral clinical appearance of the definitive prosthesis following completion of post-processing, final polymerization, and clinical delivery.

DISCUSSION

The present case demonstrates a practical method for combining conventional prosthodontic procedures with digital manufacturing when the usual treatment sequence cannot be completed within the available clinical timeframe. The important feature of this approach was not the replacement of conventional prosthodontic principles with digital technology. Rather, the existing immediate

denture was used as a starting point for recording the patient's current anatomy, after which the corrected impression was transferred into a digital workflow.

This distinction is clinically important. Digital fabrication does not eliminate the need for accurate tissue recording, functional border extension, appropriate maxillomandibular relationships, or careful clinical evaluation. These factors continue to determine the biological and mechanical performance of a complete denture^{1,2,7}.

Immediate dentures are inherently more difficult to manage than dentures fabricated after tissue healing because their intaglio surfaces are based on an anticipated post-extraction anatomy. Following extraction, the residual ridge and surrounding soft tissues undergo changes that may alter the relationship between the denture and supporting tissues. The resulting loss of retention and stability may require adjustment, relining, or replacement.

In the present patient, these anatomical changes were accompanied by a symptomatic buccal exostosis, shallow vestibular anatomy, and the need for surgical correction. The situation was further complicated by the patient's imminent breast cancer treatment. A conventional sequence of new impressions, cast fabrication, custom tray construction, definitive impression, and laboratory processing would have required additional time and appointments that were difficult to accommodate.

The modification of the existing prosthesis with polyvinylsiloxane provided a practical alternative. Polyvinylsiloxane has favorable dimensional stability, elastic recovery, detail reproduction, and resistance to distortion, making it suitable for recording complex intraoral anatomy². In this case, the material was used not simply as a conventional impression material but as a means of converting the existing denture into an individualized impression carrier.

The sectional approach was particularly useful because the original denture required correction in both the vertical and horizontal dimensions of the peripheral borders. Sectional border molding permitted the deficient regions to be addressed individually and allowed the clinician to assess the relationship between the material and the functional vestibular anatomy. Previous studies have demonstrated that silicone-based border molding can provide clinically acceptable functional extension^{3,4}. The use of a closed-mouth light-body polyvinylsiloxane impression further incorporated functional movements during impression making.

This was relevant in the present case because the final objective was not simply to reproduce the static tissue surface but to establish a clinically useful peripheral seal while maintaining the patient's established jaw relationship.

One of the main advantages of the described workflow was the ability to transfer the definitive anatomical record directly into a digital environment without fabrication of a conventional stone cast. The modified polyvinylsiloxane impression was scanned with a laboratory scanner, while the opposing dentition and interocclusal relationship were obtained with an intraoral scanner. This combination represents a useful hybrid approach because it assigns each technology to the part of the workflow for which it is most appropriate.

Direct intraoral scanning of completely edentulous tissues can be technically demanding because mobile mucosa, limited anatomical landmarks, saliva, and the absence of stable reference points may affect scanning accuracy. In the present case, the clinically established soft-tissue relationship was recorded conventionally and digitized afterward. This avoided the need to obtain the entire functional impression directly through intraoral scanning.

The digital workflow is supported by a growing body of evidence. Early studies demonstrated that computer-aided design and computer-aided manufacturing dentures can provide favorable adaptation and retention⁵⁻⁷. A larger systematic review and meta-analysis subsequently reported that computer-aided design and computer-aided manufacturing dentures can reduce chairside time and overall costs while providing acceptable clinical outcomes⁸.

More recent evidence provides a more nuanced interpretation. Faur et al. reported favorable intaglio surface trueness for three-dimensional printed denture bases, with a median deviation of 176.9 µm for the printed group compared with 342 µm for the analog group [9]. These findings support the potential of additive manufacturing to reproduce clinically relevant denture-base surfaces with considerable accuracy. However, such results should not be interpreted as evidence that every digital workflow will automatically produce a superior clinical prosthesis. The final accuracy depends on the quality of the initial impression or scan, data processing, design parameters, printing conditions, and post-processing.

Systematic reviews have also emphasized the heterogeneity of digital denture workflows. Thu et al. found considerable variation in the clinical and laboratory procedures used to fabricate digital complete dentures¹¹. This is particularly relevant to the present case because the workflow did not represent a completely digital

protocol. Instead, conventional functional impression making was intentionally retained and combined with digital scanning and additive manufacturing.

This hybrid approach may be more clinically realistic than attempting to convert every stage of complete denture fabrication into a digital procedure. The clinician remains responsible for establishing the correct tissue relationship and functional borders, while digital technology is used to improve efficiency in subsequent design and manufacturing stages.

The clinical evidence comparing digital and conventional dentures is also mixed. Avelino et al. found that digitally fabricated complete dentures demonstrated similar or better clinical performance overall, but conventional printed dentures showed greater retention than conventional dentures in one comparison, while patient satisfaction did not differ significantly according to the manufacturing method¹².

Fouda et al. similarly reported that digital workflows were generally associated with shorter fabrication times and better cost-effectiveness, but patient satisfaction and denture quality were not consistently superior¹³.

These findings are important when interpreting the present case. The clinical benefit was not that the digitally manufactured denture was necessarily superior to a conventional denture in every respect. Rather, digital manufacturing provided an efficient means of producing a prosthesis when the patient's medical circumstances made a conventional treatment sequence impractical.

A recent systematic review of patient satisfaction and oral health-related quality of life further supports this interpretation. Poker et al. compared digital and conventional complete dentures from both patient and clinician perspectives and found that digital dentures can provide favorable patient-centered outcomes, although the evidence does not establish universal superiority of digital treatment [16]. Thus, the principal advantage of digital technology in cases such as the present one may be its ability to make appropriate prosthetic treatment more accessible within a restricted timeframe.

The use of three-dimensional printing also requires careful consideration of material properties. Printed denture bases are produced layer by layer from photopolymerizable resins, and their final properties are influenced by printing orientation, layer thickness, resin composition, washing, and post-curing. Manufacturer-specific processing protocols should

therefore be followed carefully¹⁵.

Although printed dentures have demonstrated clinically acceptable outcomes, limitations remain. These include concerns regarding long-term mechanical behavior, surface characteristics, color stability, wear, and fracture resistance. Goodacre emphasized that three-dimensional printing has substantially expanded the possibilities of digital complete denture fabrication, but continued material development is required before all limitations of printed denture materials can be considered resolved¹⁰.

Recent evidence has reinforced the importance of these limitations. Sivaswamy et al. reported in a 2026 systematic review and meta-analysis that three-dimensional printed complete dentures generally demonstrated clinical outcomes comparable with conventional and milled dentures, although conventional dentures showed greater retention in some comparisons¹⁷. This supports the concept that three-dimensional printing is a clinically viable option, but not necessarily a universally superior manufacturing method.

Similarly, a 2026 systematic review by Smets et al. evaluated complications and post-insertion visits associated with three-dimensional printed dentures. The authors found that manufacturing technique could influence the type and frequency of complications and emphasized that digital fabrication does not eliminate the need for clinical follow-up¹⁸. This point is particularly relevant to immediate dentures, where anatomical changes after extraction can continue even after the definitive prosthesis has been delivered.

The present case also illustrates the value of digital archiving. Once the final prosthesis has been designed, the digital dataset can be retained for future modification or reproduction. This may be particularly valuable for patients who have difficulty attending multiple appointments or who may require replacement of a prosthesis because of fracture, loss, or changes in oral anatomy. Digital records can also facilitate communication between clinicians and dental laboratories.

The treatment time recorded in this case further illustrates the practical advantage of the workflow. Approximately 40 minutes were required for digital design, 1 hour and 17 minutes for denture-base printing, 25 minutes for tooth printing, and approximately 1 hour for post-processing and assembly. Although these times are specific to the equipment and materials used in this case and should not be generalized to all digital systems, they demonstrate that additive manufacturing can compress several laboratory stages into a relatively short period.

The clinical context was an important part of the treatment

decision. The patient had a narrow window between dental treatment and initiation of systemic cancer therapy. The objective was therefore not to circumvent appropriate healing or clinical evaluation but to provide a functional prosthesis within a medically determined timeframe. The subsequent follow-up after two cycles of chemotherapy demonstrated satisfactory healing and no clinically evident xerostomia or oral mucositis. Nevertheless, this individual observation cannot be interpreted as evidence that the described workflow reduces or prevents oral complications associated with cancer therapy.

Close communication between dental and medical teams remains essential when prosthetic treatment is provided to patients receiving systemic anticancer therapy. The timing of dental procedures, healing status, oral hygiene, mucosal condition, and potential treatment-related complications should all be considered before definitive prosthetic intervention.

Several limitations should be acknowledged. First, this is a single clinical case, and the outcome cannot establish superiority of the hybrid workflow over conventional or milled complete denture fabrication. Second, objective measurements of denture retention, three-dimensional intaglio trueness, occlusal accuracy, and dimensional stability were not performed. Third, the follow-up period described in this report was limited, and long-term evaluation of the printed materials was not possible. Fourth, the technique may not be appropriate when the existing denture has major deficiencies in tooth arrangement, vertical dimension, facial support, or occlusion.

The method is most likely to be useful when the existing immediate denture retains clinically useful information but has become inaccurate because of changes in the denture-bearing tissues. In such circumstances, the existing prosthesis can serve as a starting point rather than being discarded. However, when the original prosthesis is fundamentally inadequate, a new conventional or digital treatment plan may be more appropriate.

Future developments in digital complete denture therapy are likely to involve greater integration of clinical scanning, three-dimensional facial imaging, computer-aided design, additive manufacturing, and digital archiving. Automated design tools may eventually assist with tooth arrangement, occlusal analysis, denture-base design, and identification of anatomical landmarks. These technologies should remain under appropriate clinical supervision because automated systems cannot independently account for all biological and functional variables encountered in complete denture treatment.

The most useful future direction may therefore be the development of flexible hybrid workflows rather than complete replacement of conventional prosthodontic procedures. Conventional impression techniques remain valuable for recording mobile soft tissues and functional borders, whereas digital systems provide clear advantages in data storage, design modification, communication, and rapid manufacturing.

The present case illustrates this principle. The functional anatomy was established clinically using polyvinylsiloxane, transferred into the digital environment by laboratory scanning, combined with intraoral records of the opposing dentition, and subsequently used for computer-aided design and additive manufacturing. The resulting workflow preserved the clinical information required for successful prosthetic treatment while reducing unnecessary laboratory stages.

Future clinical research should evaluate this approach in larger patient populations and compare hybrid workflows directly with conventional and fully digital techniques. Such studies should include objective measurements of retention, stability, intaglio adaptation, occlusal accuracy, fabrication time, cost, number of appointments, patient satisfaction, oral health-related quality of life, and long-term material performance.

CONCLUSION

This clinical report presents a hybrid analog-digital approach for the management of an ill-fitting maxillary immediate complete denture in a patient with an urgent medical treatment schedule. The patient's existing prosthesis was modified with sectional polyvinylsiloxane border molding and used as a functional impression carrier. A definitive light-body polyvinylsiloxane impression was then digitized and transferred into a computer-aided design and additive manufacturing workflow.

The main clinical value of the technique was the preservation of useful information contained within the existing prosthesis while allowing the denture-bearing surface and peripheral borders to be adapted to the patient's changing post-extraction anatomy. This approach avoided several conventional laboratory stages and allowed the definitive prosthesis to be produced within a restricted treatment period.

The case also demonstrates that digital technology should complement rather than replace fundamental prosthodontic principles. Accurate impression making, functional border extension, adequate tissue support, appropriate maxillomandibular relationships, and careful clinical assessment remain essential regardless of the manufacturing method.

The favorable clinical outcome supports the feasibility of the described workflow, but it should not be interpreted as evidence of superiority over conventional or milled denture fabrication. The report represents a single clinical experience, and quantitative long-term measurements were not available. Further prospective clinical studies are required to establish the reproducibility, accuracy, cost-effectiveness, patient acceptability, and long-term clinical performance of this approach.

Overall, the hybrid analog-digital workflow may be a useful option for carefully selected patients who require rapid prosthetic rehabilitation. Its principal advantage is not the use of three-dimensional printing alone, but the integration of established clinical prosthodontic principles with digital technology to provide individualized treatment within a clinically realistic timeframe.

DECLARATIONS

Conflict of Interest

The author declare no conflict of interest.

Funding

No external funding was received for this study.

Ethical Approval

The study was conducted in accordance with the principles of the Declaration of Helsinki for research involving human subjects.

Informed Consent

Written informed consent was obtained from the patient for the clinical treatment and publication of this case report and the accompanying intraoral photographs.

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CASE REPORT

ORAL CANDIDIASIS ASSOCIATED WITH TRAUMATIC BRAIN INJURY: A CASE REPORT

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Abstract

Background: Oral candidiasis is a common opportunistic fungal infection that can develop when local or systemic factors disturb the normal balance of the oral microbiota. Patients with traumatic brain injury (TBI) may experience difficulties with oral hygiene because of impaired motor function, cognitive limitations, dysphagia, behavioral changes, or reduced ability to perform daily self-care. These problems may be accompanied by plaque accumulation and inadequate denture hygiene, creating conditions that favor Candida colonization and denture-associated oral disease. Oral health problems in patients with acquired brain injury have received considerably less attention than other consequences of neurological injury.¹⁻³

Case Presentation; A 43-year-old man with a history of severe traumatic brain injury presented for comprehensive dental rehabilitation. Clinical examination revealed poor oral hygiene, substantial plaque accumulation, continuous denture wearing, and traumatic lesions of the edentulous ridges. A tongue ring with visible plaque accumulation was also present. The oral mucosal findings were clinically compatible with oral candidiasis in the setting of several interacting local risk factors, including inadequate denture hygiene, continuous denture use, plaque accumulation, and limited capacity for independent oral care. Microbiological confirmation of Candida infection was not obtained.

Management consisted of antifungal therapy, improvement of oral and denture hygiene, removal of dentures during sleep, removal of the plaque-retentive tongue ring, and adjustment and smoothing of the denture surfaces. Follow-up demonstrated clinical resolution of the lesions consistent with candidiasis and improvement of the traumatic mucosal lesions.

Conclusion: This case illustrates that oral candidiasis in patients with traumatic brain injury should be considered within a multifactorial clinical context rather than attributed directly to the neurological injury itself. Functional limitations, inadequate oral hygiene, persistent denture use, plaque accumulation, and prosthesis-related factors may interact to create conditions favorable for Candida-associated disease. Comprehensive oral assessment, appropriate denture hygiene, individualized oral-care support, and correction of local traumatic factors are important components of management, particularly in patients who have limited capacity for independent oral self-care.

Keywords: traumatic brain injury; oral candidiasis; Candida; denture stomatitis; oral hygiene; dental plaque; denture hygiene; case report

Traumatic brain injury is a major neurological condition that can result in persistent motor, sensory, cognitive, behavioral, and functional impairments. Although these neurological consequences are well recognized, their effect on oral health is less frequently considered in routine clinical care. Patients with acquired brain injury may experience difficulties with oral hygiene, eating, swallowing, communication, and other activities required for maintaining oral health. A systematic review of oral health in patients with acquired brain injury found evidence of poorer oral health, increased tooth loss, greater plaque accumulation, and other oral-health problems in this population.¹

The relationship between brain injury and oral disease is likely to be indirect and multifactorial. Effective oral hygiene requires regular and coordinated toothbrushing, interdental cleaning, rinsing, and, in patients wearing removable prostheses, appropriate denture cleaning and handling. When motor, cognitive, or behavioral function is compromised, these activities may become difficult or may require assistance. In patients with traumatic brain injury, structured oral-hygiene interventions have been shown to reduce plaque accumulation, supporting the importance of individualized oral-care programs during rehabilitation.²

Dysphagia may represent an additional concern in patients with acquired brain injury. Difficulty swallowing can complicate routine oral care and may coexist with poor oral hygiene and oral microbial imbalance. Odgaard and Kothari reported an association between oral candidiasis and dysphagia in individuals with acquired brain injury, suggesting that oral fungal disease may be clinically relevant in this population.³

Plaque accumulation is important because dental and denture plaque provide a favorable environment for microbial adhesion and biofilm development. *Candida* species, particularly *Candida albicans*, are common members of the oral microbiota and may be present without producing clinical disease. Under favorable local conditions, however, *Candida* may increase in number, adhere to oral surfaces, and develop structured biofilms that contribute to clinical infection.⁴⁻⁶

Removable dentures are particularly relevant because their acrylic surfaces can support microbial adhesion and biofilm formation. *Candida* biofilms have been demonstrated directly on denture acrylic obtained from patients with denture stomatitis, supporting the concept that the prosthesis may function as a persistent microbial reservoir.⁷ Clinical studies have also demonstrated an association between denture hygiene, *Candida* colonization, and denture-related stomatitis.^{5,6}

Denture stomatitis is a common multifactorial condition among removable denture wearers. Poor oral hygiene, inadequate denture hygiene, continuous denture wearing, particularly overnight use, and *Candida*-containing biofilms have all been identified as important factors.^{8,9} Continuous denture use is clinically relevant because it prolongs contact between the prosthesis and the underlying mucosa and limits the opportunity for both prosthesis cleaning and mucosal recovery. Compagnoni et al. demonstrated a significant relationship between continuous denture wearing and *Candida* counts, supporting the importance of avoiding prolonged or nocturnal denture use when clinically appropriate.¹⁰

The presence of *Candida*, however, should not automatically be interpreted as evidence of active infection. *Candida* may colonize the oral cavity without causing clinical disease. Therefore, diagnosis should take into account the clinical appearance of the mucosa and the presence of relevant local and systemic predisposing factors.⁴⁻⁶ In cases in which microbiological testing has not been performed, the diagnosis should be described cautiously as clinically consistent with oral candidiasis rather than as a microbiologically confirmed infection.

Several local factors may contribute to *Candida* colonization and persistence, including poor oral hygiene, denture plaque, inadequate denture cleaning, prolonged denture wearing, mucosal irritation, and other plaque-retentive surfaces.^{5,6,8,9} In a patient with impaired ability to perform independent oral care, these factors may occur simultaneously and reinforce one another.

The clinical management of denture-associated candidiasis should therefore address both the oral mucosal disease and the prosthesis that may harbor *Candida*-containing biofilm. Antifungal treatment may be indicated according to the clinical presentation, but denture hygiene and prosthesis disinfection are also important. Current clinical guidance recommends denture disinfection together with appropriate antifungal therapy in patients with denture-related candidiasis.¹² Reviews of denture stomatitis similarly emphasize that treatment should address the denture biofilm and modifiable behavioral and prosthetic factors rather than relying exclusively on antifungal medication.^{8,9}

These considerations are particularly important in patients with neurological impairment. Individuals with traumatic brain injury may require individualized oral-care instructions, assistance from caregivers, and regular professional follow-up.² In this setting, the combination of impaired oral self-care, extensive plaque accumulation, removable denture use, and prolonged denture contact with the mucosa may create an environment favorable for *Candida*-associated disease. We present the case of a 43-year-old man with a history of severe traumatic brain injury who developed oral mucosal findings clinically consistent with oral candidiasis in the setting of

markedly compromised oral hygiene, continuous denture wearing, substantial plaque accumulation, and a plaque-retentive tongue ring. The case emphasizes the importance of recognizing and addressing modifiable local factors in patients with neurological impairment rather than attributing oral candidiasis directly to TBI.

2. CASE REPORT

A 43-year-old man presented to the dental clinic in 2025 for comprehensive oral rehabilitation. His medical history was significant for a motorcycle accident in 2019 that resulted in a left complex depressed comminuted skull fracture with an associated parietal epidural hematoma. The patient underwent craniotomy for evacuation of the intracranial hematoma and surgical elevation of the depressed skull fracture (Figure 1). His acute injuries were further complicated by traumatic subarachnoid hemorrhage, oropharyngeal dysphagia, acute blood loss anemia, multiple rib fractures, and pulmonary contusion.

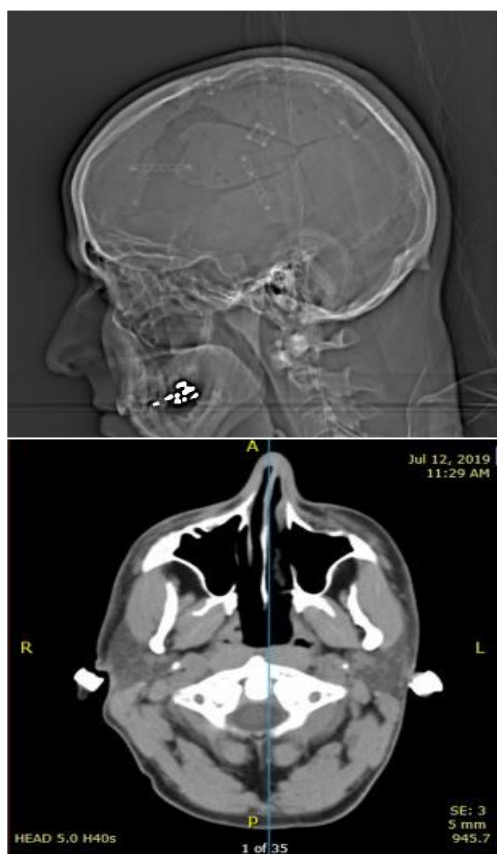


Figure 1. CT of head without contrast post-surgery showing multifocal comminuted left-sided calvarial fractures and postsurgical changes from left partial craniotomy with minimal residual subdural hematoma.

Several months after the traumatic event, the patient was diagnosed with a mood disorder secondary to

traumatic brain injury with loss of consciousness. Between 2020 and 2022, he required four psychiatric hospitalizations because of episodes of violent behavior and suicidal statements. Following the most recent hospitalization, his psychiatric condition remained clinically stable under prescribed psychotropic medication. At the time of dental presentation, no acute medical complications related to the previous traumatic brain injury were reported.

Upon comprehensive dental examination in 2025, all remaining teeth were considered to have a poor prognosis and were deemed non-restorable because of extensive carious destruction and/or advanced mobility (Figure 2). Because preservation of the remaining dentition was not considered feasible, full-mouth extraction was performed under sedation. Immediate maxillary and mandibular complete dentures were subsequently delivered. The immediate postoperative course was uneventful, and no surgical complications were documented.



Figure 2. Panoramic radiograph showing non-restorable teeth. The patient also has a tongue ring.

At a subsequent follow-up visit, clinical examination revealed yellowish crusting involving the lower lip and multiple small ulcerative lesions affecting the maxillary and mandibular edentulous ridges (Figure 3). The patient reported routinely wearing the dentures while sleeping. Clinical examination also identified a tongue ring with visible plaque accumulation.

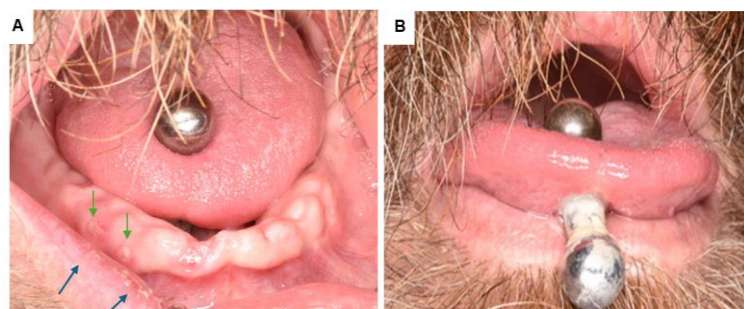


Figure 3. A. Intraoral examination reveals signs of oral candidiasis with yellowish crusting of the lower lip (blue arrows) and traumatic ulcers of the edentulous ridge (green arrows), and B. Tongue ring with plaque accumulation.

Given the appearance of the oral mucosal lesions and the presence of several local predisposing factors, including continuous denture wearing and inadequate denture hygiene,

the clinical working diagnosis was oral candidiasis associated with denture use, accompanied by traumatic ulceration of the edentulous ridges. Because no microbiological confirmation of *Candida* infection was obtained, the diagnosis was based on the clinical presentation and was not considered microbiologically confirmed.

Fluconazole 100 mg was prescribed for treatment of the clinically suspected oral candidiasis. The patient was instructed to remove both dentures during sleep and to improve daily denture hygiene. As an adjunctive measure, the dentures were immersed in a nystatin solution overnight for the first two nights. This intervention was used as part of the denture-hygiene management strategy in this individual case rather than as a universal treatment protocol.

The tongue ring was removed at the patient's request because of the substantial plaque accumulation observed around the appliance. In addition, the intaglio surfaces of both dentures were adjusted and smoothed to reduce local mechanical irritation and minimize further trauma to the edentulous ridges.

At follow-up after completion of antifungal treatment, the previously observed clinical findings consistent with oral candidiasis had resolved, and no persistent candidal lesions were evident on clinical examination. The traumatic ulcerations of the edentulous ridges also improved following adjustment of the denture surfaces and discontinuation of overnight denture wearing.

The clinical course supported the importance of addressing both the suspected fungal component and the local factors that may have contributed to the persistence of the lesions, particularly denture hygiene, continuous denture use, plaque accumulation, and mechanical irritation.

3. DISCUSSION

Oral candidiasis is a common fungal infection of the oral cavity, most often associated with *Candida albicans*.^{4,5} *Candida* species may also exist as part of the normal oral microbiota without producing clinical disease. Therefore, the presence of *Candida* does not by itself establish active infection. Clinical disease generally develops when local or systemic conditions disturb the balance between the microorganism and the host, promoting increased colonization, adhesion, and biofilm formation.⁴⁻⁶

The present case is clinically relevant because several predisposing factors were present simultaneously. The patient had a history of severe traumatic brain injury, impaired oral self-care, extensive plaque accumulation, continuous denture use, inadequate denture hygiene, and

a plaque-retentive tongue ring. These factors should not be considered independently. Rather, they formed a clinical environment in which oral hygiene was difficult to maintain and *Candida*-associated disease could develop.

The association between brain injury and oral-health problems has been described previously. Kothari et al., in a systematic review of oral health in patients with acquired brain injury, identified substantial oral-health problems in this population and emphasized the need for greater attention to oral hygiene and dental care.¹ Similarly, Zasler et al. demonstrated that an individualized oral-hygiene program could improve plaque control in patients following traumatic brain injury.² These findings support the importance of considering oral care as part of long-term rehabilitation rather than as a separate issue addressed only when dental disease becomes severe.

Dysphagia may further complicate oral health in patients with acquired brain injury. Odgaard and Kothari reported an association between oral candidiasis and dysphagia in this population.³ Although dysphagia alone cannot be considered a direct cause of candidiasis, it may occur together with other functional limitations that make oral hygiene more difficult. In the present patient, a history of oropharyngeal dysphagia was one component of a broader pattern of functional impairment.

The patient's extensive plaque accumulation is also important. Dental plaque and denture plaque can provide a suitable environment for *Candida* colonization and biofilm formation. Studies in denture wearers have demonstrated relationships between prosthetic hygiene, *Candida* carriage, and denture stomatitis.^{5,6} *Candida* biofilms have also been directly demonstrated on denture acrylic obtained from patients with denture stomatitis, indicating that the prosthesis can serve as a persistent reservoir for fungal biofilm.⁷

Denture use was another major factor in the present case. The patient reported wearing his dentures while sleeping. Continuous denture wearing has been associated with increased *Candida* counts, and Compagnoni et al. demonstrated a significant relationship between continuous denture use and *Candida*.¹⁰ The importance of nocturnal denture removal is also emphasized in contemporary reviews of denture stomatitis, which identify full-time denture wearing and inadequate prosthesis hygiene among the important modifiable factors associated with disease.^{8,9}

The clinical significance of the dentures in this patient was therefore not limited to their role as prosthetic replacements. The dentures also represented surfaces capable of accumulating plaque and supporting microbial biofilm. In a patient with limited capacity for independent oral hygiene, failure to remove and clean the prostheses regularly may allow this biofilm to persist for prolonged periods. The tongue ring was another notable finding. The appliance

had visible plaque accumulation and therefore represented an additional surface that could retain microorganisms. However, the present case does not provide microbiological evidence demonstrating *Candida* colonization of the tongue ring. It would therefore be inappropriate to describe the tongue ring as the cause of the candidiasis. Its role is better understood as a potential local, plaque-retentive factor within a much broader clinical context.

The distinction between colonization and infection is particularly important in this case. *Candida* may be present in the oral cavity without causing disease, and microbiological detection alone does not necessarily indicate clinically significant candidiasis.⁴⁻⁶ In the present patient, no culture or other microbiological testing was performed. Accordingly, the diagnosis was based on the clinical findings and their subsequent response to treatment and modification of local risk factors. The outcome should therefore be described as clinical resolution rather than microbiologically confirmed eradication of *Candida*. Management addressed both the suspected fungal disease and the local factors that could maintain the condition. Fluconazole was prescribed as antifungal therapy, while the patient was instructed to remove the dentures during sleep and improve denture hygiene. The dentures were also immersed in nystatin solution during the first two nights as an adjunctive denture-hygiene measure. Current Infectious Diseases Society of America guidance supports attention to denture disinfection in patients with denture-associated candidiasis in addition to appropriate antifungal treatment.¹²

The denture adjustment was also important because not all of the observed mucosal lesions were necessarily caused by candidiasis. The multiple ulcerative lesions along the edentulous ridges suggested a traumatic component related to mechanical irritation from the immediate dentures. The intaglio surfaces were therefore adjusted and smoothed to reduce local trauma. This distinction is clinically important because antifungal therapy alone would not correct a traumatic prosthetic lesion. The improvement of the mucosal lesions after treatment and modification of the local factors supports the clinical management approach used in this individual case. Nevertheless, the absence of microbiological testing means that the specific *Candida* species cannot be identified and microbiological clearance cannot be demonstrated. The favorable response should therefore be interpreted cautiously.

This case also demonstrates that oral candidiasis in patients with TBI should not be viewed simply as a consequence of the neurological injury. Rather, the neurological injury may create functional and behavioral limitations that indirectly increase the risk of oral disease. In this patient, impaired oral self-care, plaque

accumulation, continuous denture use, inadequate denture hygiene, and mechanical irritation occurred together.

For patients with neurological impairment, preventive dental care should therefore include assessment of the individual's ability to perform oral hygiene independently, evaluation of denture hygiene practices, monitoring of mucosal health, and consideration of caregiver assistance when necessary. Individualized oral-hygiene programs have demonstrated benefit in patients following TBI, supporting their incorporation into long-term rehabilitation.²

The present case further emphasizes that treatment of denture-associated candidiasis should not rely exclusively on antifungal medication. Cleaning and disinfection of the prosthesis, removal of dentures during sleep when appropriate, correction of traumatic denture surfaces, and regular professional follow-up are important parts of long-term management.^{8, 9, 12}

Finally, this case highlights the need for careful clinical interpretation when several oral lesions occur simultaneously. The patient had findings compatible with oral candidiasis as well as traumatic ulcerations. Recognizing the possibility of more than one process is important because treatment must address each contributing factor. In this patient, improvement occurred after both antifungal therapy and correction of the local prosthetic and hygiene-related factors.

4. CONCLUSION

This case illustrates the multifactorial nature of oral candidiasis in a patient with a history of traumatic brain injury. The patient developed oral mucosal findings clinically consistent with candidiasis in the presence of impaired oral self-care, extensive plaque accumulation, inadequate denture hygiene, continuous denture wearing, and a plaque-retentive tongue ring. Traumatic brain injury should not be considered a direct cause of oral candidiasis. Instead, its functional consequences may indirectly increase susceptibility to oral disease by making effective oral and prosthetic hygiene more difficult. In patients with neurological impairment, these limitations may interact with denture use and other local factors to create conditions favorable for *Candida*-associated disease. Successful management requires attention to both the suspected fungal infection and the local factors that may promote persistence or recurrence. Antifungal therapy, regular denture cleaning, avoidance of overnight denture wearing when appropriate, correction of traumatic prosthetic surfaces, and individualized oral-hygiene support should be considered complementary components of care. For patients with TBI who have limited capacity for independent oral self-care, regular dental assessment and individualized preventive strategies may be particularly important. Early recognition of plaque accumulation, denture-related mucosal changes, and other local risk factors may help prevent progression to more extensive oral disease.

Ethical Approval

The study was conducted in accordance with the principles of the Declaration of Helsinki for research involving human subjects.

Consent

Written informed consent was obtained from the patient for publication of the case report and accompanying clinical images. All identifying information was removed or de-identified to protect patient confidentiality.

Conflict of Interest

The authors declare that they have no conflicts of interest.

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REVIEW ARTICLE

TEMPORARY ANCHORAGE DEVICES IN ORTHODONTICS: A SCOPING REVIEW OF CLINICAL APPLICATIONS, DIGITAL WORKFLOW, AND ARTIFICIAL INTELLIGENCE IN TREATMENT PLANNING

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Abstract

Background: Temporary anchorage devices (TADs) have transformed orthodontic treatment by providing reliable skeletal anchorage for complex tooth movements while reducing dependence on patient compliance. In recent years, advances in cone-beam computed tomography (CBCT), intraoral scanning, three-dimensional (3D) imaging, and artificial intelligence (AI) have introduced new possibilities for individualized TAD planning, improving insertion accuracy and biomechanical efficiency. Despite these developments, the available evidence remains scattered across different areas of orthodontic research.

Objective: This scoping review aimed to map the current evidence on the clinical applications of TADs, summarize factors influencing their success, and explore the emerging role of digital technologies and AI-assisted planning in optimizing orthodontic treatment.

Methods: A scoping review was conducted according to the PRISMA-ScR guidelines and JBI methodology. Electronic searches were performed in PubMed, Scopus, Web of Science, Embase, and Google Scholar for studies published between 2015 and 2026. Clinical studies, randomized trials, observational studies, systematic reviews, and relevant reports evaluating orthodontic TADs, digital workflows, or AI-assisted planning were included.

Results: The mapped evidence demonstrated that TADs provide predictable skeletal anchorage for space closure, molar distalization, intrusion, extrusion, open-bite correction, and management of complex malocclusions. Clinical success is influenced by anatomical site, cortical bone thickness, insertion technique, primary stability, loading protocol, and oral hygiene. Recent evidence indicates that AI-based image analysis, CBCT segmentation, automated anatomical landmark detection, and digital treatment planning may improve TAD positioning, reduce the risk of root injury, and support personalized biomechanical planning. However, clinical validation of AI-assisted systems remains limited.

Conclusions: Temporary anchorage devices remain an essential component of contemporary orthodontics, while digital technologies and artificial intelligence are expanding their clinical potential through more precise and individualized treatment planning. Future prospective studies should focus on validating AI-assisted planning systems and integrating them into routine orthodontic practice.

Keywords: temporary anchorage devices; orthodontic mini-implants; skeletal anchorage; artificial intelligence; digital orthodontics; Smartee S4 technology; CBCT; treatment planning.

INTRODUCTION

Orthodontic treatment has evolved considerably over the past decades, moving beyond simple correction of dental alignment toward a comprehensive approach focused on controlled tooth movement, skeletal relationships, and individualized biomechanical strategies. Among the factors determining treatment predictability, anchorage control remains one of the fundamental challenges in orthodontics. The ability to maintain stable anchorage while applying controlled orthodontic forces is essential for achieving predictable treatment outcomes, particularly in complex malocclusions requiring significant tooth movement¹.

Conventional anchorage methods, including extraoral appliances, transpalatal arches, and intermaxillary elastics, have contributed significantly to orthodontic treatment; however, their effectiveness may be limited by factors such as patient compliance, unwanted reciprocal tooth movement, and insufficient control during complex biomechanical procedures. These limitations have encouraged the development of alternative anchorage strategies capable of providing more reliable and predictable force control².

The introduction of temporary anchorage devices (TADs), including orthodontic mini-implants and miniscrews, has represented a major advancement in modern orthodontics by providing a reliable method of skeletal anchorage. Unlike conventional dental anchorage systems, TADs obtain support directly from the surrounding alveolar bone, allowing orthodontists to apply controlled forces without depending exclusively on adjacent teeth. This biomechanical concept has expanded the scope of orthodontic treatment and enabled predictable management of challenging clinical situations, including severe anchorage requirements, complex space closure, molar movement, and vertical control problems^{3,4}.

Clinical applications of TADs have progressively expanded and currently include anterior en-masse retraction, extraction space closure, molar distalization and mesialization, intrusion of anterior and posterior teeth, open-bite correction, and correction of asymmetric dental relationships. The clinical value of TAD-assisted mechanics extends beyond anchorage reinforcement, as these devices allow the application of forces from strategically selected anatomical locations, improving biomechanical efficiency and reducing undesirable dental effects. In selected cases, TAD-assisted approaches may also provide minimally invasive alternatives to more complex surgical procedures^{5,6}.

In clinical practice, skeletal anchorage can also be

complemented by aligner mechanics, such as the Smartee S4 technology. The S4 framework utilizes strategically configured power arms—rigid levers attached to teeth or aligner structures—and precise touch-and-aligner contact dynamics to direct force vectors closer to the center of resistance, thereby enhancing root torque and bodily tooth movement during complex treatment phases (Figure 1).



Figure 1. S4 intelligent power arm & TADs

Despite their widespread clinical adoption, the success and predictability of TAD treatment remain dependent on multiple biological, anatomical, and mechanical variables. Factors including insertion site, cortical bone thickness, bone quality, implant dimensions, insertion torque, loading protocol, soft tissue characteristics, and peri-implant inflammation may influence primary stability and long-term success. Anatomical limitations such as inadequate interradicular space, unfavorable root proximity, insufficient cortical support, and proximity to critical structures represent important challenges during placement. Therefore, accurate preoperative assessment and individualized treatment planning are essential components of successful TAD-assisted orthodontic therapy⁴⁻⁶.

Recent advances in digital orthodontics have provided new opportunities to improve the accuracy and predictability of TAD planning by enabling detailed assessment of patient-specific anatomy. Cone-beam computed tomography (CBCT), three-dimensional reconstruction, intraoral scanning, and computer-assisted treatment planning allow clinicians to evaluate dental roots, cortical bone morphology, and anatomical boundaries with greater precision than conventional two-dimensional imaging approaches. These technologies have contributed to a transition from experience-based placement toward a more systematic, anatomy-driven planning strategy⁷⁻⁹.

Artificial intelligence (AI) has recently emerged as a promising extension of digital orthodontic workflows. AI-based technologies have demonstrated potential applications in automated image interpretation, anatomical

structure segmentation, landmark detection, predictive modeling, and clinical decision-support systems. Within TAD-assisted orthodontics, AI may provide additional value by analyzing CBCT-derived anatomical information, identifying potential insertion corridors, evaluating root–bone relationships, and assisting clinicians in selecting implant positions that optimize biomechanical requirements while maintaining anatomical safety^{10–12}.

However, despite increasing interest in AI applications within orthodontics, the specific role of artificial intelligence in TAD planning remains at an early stage of clinical development. Current evidence is mainly focused on algorithm development, image analysis, segmentation techniques, and preliminary technical validation, whereas clinical implementation and patient-centered outcome evaluation remain limited. Furthermore, important challenges include the absence of standardized AI-assisted planning protocols, the need for external validation across diverse patient populations, potential limitations related to training dataset variability, and incomplete integration into routine orthodontic workflows. Future studies are required to determine whether AI-assisted planning can provide clinically meaningful improvements in TAD placement accuracy, safety, treatment efficiency, and long-term outcomes compared with conventional approaches^{13–15}.

The convergence of temporary anchorage devices, three-dimensional imaging, and artificial intelligence represents a potential transition toward a more personalized model of orthodontic treatment planning. By integrating patient-specific anatomical information obtained from CBCT, biomechanical principles, and AI-based analytical tools, future digital workflows may improve insertion site selection, optimize miniscrew positioning, and reduce placement-related complications. Nevertheless, clinical implementation of these technologies requires stronger evidence regarding accuracy, reproducibility, external validity, and long-term effectiveness^{16,17}.

Therefore, this scoping review aims to comprehensively map the current evidence regarding the clinical applications of temporary anchorage devices in orthodontics, summarize factors influencing their stability and treatment outcomes, and explore the emerging role of digital workflows and artificial intelligence in

personalized TAD-assisted treatment planning.

By integrating established principles of skeletal anchorage with recent advances in digital dentistry and AI technologies, this review seeks to identify current knowledge gaps and highlight future directions for safer, more predictable, and individualized orthodontic care.

2. METHODS

2.1 Study Design and Methodological Framework

This study was conducted as a scoping review following the methodological recommendations of the Joanna Briggs Institute (JBI) and reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) guidelines^{18–20}. A scoping review methodology was selected because the field of temporary anchorage devices (TADs) in orthodontics includes a wide range of clinical applications, biomechanical approaches, and rapidly emerging digital technologies. Unlike systematic reviews focusing on a narrowly defined clinical question, scoping reviews allow comprehensive mapping of available evidence, identification of knowledge gaps, and exploration of emerging concepts such as artificial intelligence-assisted treatment planning. The primary objective of this review was to characterize the current evidence regarding the clinical applications of orthodontic TADs, factors affecting their stability and success, and the integration of digital technologies, including three-dimensional imaging and artificial intelligence (AI)-based planning approaches, into contemporary orthodontic practice.

2.2 Review Question and PCC Framework

The research question was developed according to the Population–Concept–Context (PCC) framework recommended by the JBI methodology¹⁸. The PCC framework was selected to ensure a structured approach for identifying relevant evidence and defining the scope of the review.

The Population included patients undergoing orthodontic treatment who required skeletal anchorage for controlled tooth movement. The Concept focused on temporary anchorage devices, including orthodontic mini-implants and miniscrews, their clinical applications, biomechanical principles, treatment outcomes, complications, and emerging AI-assisted planning methods. The Context included conventional orthodontic approaches as well as modern digital workflows incorporating cone-beam computed tomography (CBCT), three-dimensional imaging, computer-assisted planning, and artificial intelligence technologies. The detailed eligibility framework based on the PCC approach is presented in **Table 1**.

Category	Description
Population	Patients receiving orthodontic treatment requiring skeletal anchorage
Concept	TADs, mini-implants, biomechanics, complications, AI planning
Context	CBCT, 3D imaging, guided placement, AI
Evidence sources	RCTs, observational studies, case series, reviews
Publication period	Jan 2015–Jul 2026
Language	English
Inclusion	Clinical TAD or AI studies
Exclusion	Animal/lab/non-orthodontic/abstracts

2.3 Literature Search Strategy

A comprehensive literature search was performed in the electronic databases PubMed/MEDLINE, Scopus, Web of Science, Embase, and Google Scholar. The search strategy was developed using a combination of controlled vocabulary terms (MeSH terms where applicable) and free-text keywords related to temporary anchorage devices, orthodontic applications, digital imaging, and artificial intelligence.

The following Boolean search strategy was applied:

("temporary anchorage device" OR "orthodontic mini-implant" OR "orthodontic miniscrew*" OR miniscrew* OR "skeletal anchorage")
AND
(orthodontic* OR malocclusion* OR "orthodontic treatment" OR "tooth movement")
AND
(CBCT OR "cone beam computed tomography" OR "three-dimensional imaging" OR "digital orthodontics" OR "computer-assisted planning" OR "artificial intelligence" OR "machine learning")**

Additional searches were performed using related terms and reference list screening of relevant publications to identify potentially eligible studies. The search was limited to English-language publications published between January 2015 and July 2026.

2.4 Study Selection Process

All retrieved records were collected and screened after removal of duplicates. Two independent reviewers performed title and abstract screening according to predefined eligibility criteria. Potentially relevant studies were subsequently assessed through full-text evaluation. Studies were included when they provided clinical information regarding TAD application, treatment outcomes, biomechanical considerations, or digital and AI-based approaches related to orthodontic anchorage. Any disagreement between reviewers was resolved through discussion and consensus.

2.5 Data Extraction and Charting

Data extraction was performed using a standardized data-charting form developed according to the objectives of the review. Extracted variables included bibliographic information, study characteristics, patient demographics, TAD-related parameters, clinical indications, treatment outcomes, complications, and digital technologies used. For studies involving artificial intelligence, additional information was collected regarding the type of AI application, imaging modality, algorithmic function, clinical purpose, and reported advantages or limitations.

The complete data extraction framework is summarized in Table 2.

Data domain	Extracted variables
Bibliographic information	Author, year, country
Study characteristics	Design, sample, follow-up
Patient characteristics	Age, sex, diagnosis
TAD characteristics	Type, dimensions, site
Clinical application	Retraction, intrusion, distalization
Biomechanical factors	Force direction, anchorage
Treatment outcomes	Success, stability, complications
Digital/AI	CBCT, 3D, segmentation, prediction

2.6 Data Synthesis

Due to the expected heterogeneity among included studies regarding clinical protocols, patient populations, TAD designs, and outcome measures, a qualitative descriptive synthesis was performed rather than a quantitative meta-analysis. The findings were organized into major thematic categories, including clinical applications of TADs, factors influencing treatment success, complications, digital orthodontic workflows, and emerging AI-based approaches for personalized TAD planning.

3. RESULTS

3.1 Study Selection and Characteristics of Included Evidence

The literature search identified studies investigating the clinical applications of temporary anchorage devices (TADs), their biomechanical performance, treatment outcomes, complications, and recent developments in digital orthodontic planning. The study selection process was performed according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) framework (Figure 1). The initial search identified 96 records. After removal of 24 duplicate records, 72 studies remained for title and abstract screening. Following the screening process, 28 records were excluded due to irrelevance to the review objectives or failure to meet the predefined eligibility criteria. Subsequently, 44 full-text articles were assessed for eligibility, and 8 articles were excluded because of insufficient clinical information, inappropriate study design, or lack of relevance to TAD applications and AI-assisted orthodontic planning. Finally, 36 studies were included in the qualitative synthesis.

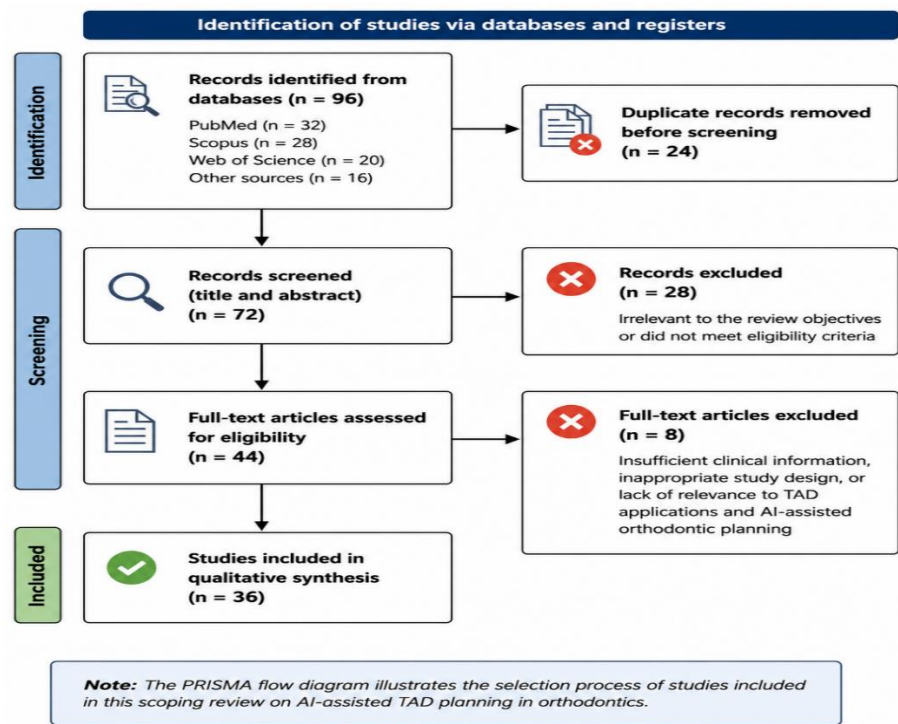


Figure 2. PRISMA-ScR flow diagram illustrating the study selection process.

The included evidence comprised randomized clinical trials, prospective and retrospective clinical studies, observational investigations, case series, and evidence-based reviews. The selected studies evaluated different orthodontic indications, including anterior retraction, molar distalization, intrusion, open-bite correction, asymmetric tooth movement, and anchorage reinforcement.

The main characteristics of the included studies, including study design, population, TAD application, digital technologies, and reported outcomes, are summarized in **Table 3**.

Table 3. Overview of the Characteristics of Included Studies

Evidence domain	Characteristics of included evidence
Study design	RCTs, prospective, retrospective, observational, reviews
Population	Adolescent and adult orthodontic patients
Applications	Retraction, distalization, intrusion, open bite
Outcomes	Anchorage, stability, complications
Biomechanics	Insertion site, cortical bone, loading
Digital/AI	CBCT, 3D planning, AI

3.2 Clinical Applications of Temporary Anchorage Devices

The analyzed evidence demonstrates that TADs have become an important component of contemporary orthodontic treatment by providing stable skeletal anchorage for complex tooth movements. The most frequently reported applications included anterior en-masse retraction, molar distalization, posterior intrusion, correction of open bite, management of asymmetric malocclusions, and reinforcement of anchorage during comprehensive orthodontic therapy.

The major advantage of TAD-assisted mechanics is the ability to apply orthodontic forces from a stable skeletal base, reducing unwanted reciprocal tooth movement and improving biomechanical control. The clinical applications and their treatment objectives are summarized in **Table 4**.

Table 4. Clinical Applications and Biomechanical Objectives of Temporary Anchorage Devices

Clinical application	Treatment objective	Biomechanical advantage
Anterior retraction	Correct protrusion	Absolute anchorage
Molar distalization	Sagittal correction	Controlled movement
Posterior intrusion	Open bite	Intrusive force
Molar mesialization	Space closure	Skeletal support
Asymmetry	Unilateral correction	Differential forces
Complex mechanics	Anchorage	Predictability

3.3 Factors Influencing TAD Stability and Clinical Outcomes

The clinical performance of TADs is influenced by a combination of mechanical, anatomical, and patient-related factors. The reviewed studies emphasized that successful placement depends not only on implant characteristics but also on careful evaluation of the surrounding anatomical environment.

Important factors include cortical bone thickness, insertion site selection, implant dimensions, loading protocol, peri-implant tissue condition, and operator experience. In particular, three-dimensional assessment of root position and available bone volume has become increasingly important for reducing placement-related complications.

The main factors affecting TAD success are summarized in **Table 5**.

Table 5. Factors Influencing Clinical Success and Failure Risk of Orthodontic Temporary Anchorage Devices

Factor	Influence on Clinical Outcome	Clinical relevance
Cortical bone thickness and density	Determines the primary mechanical stability of the temporary anchorage device after insertion	Adequate cortical bone improves initial stability and reduces the likelihood of early failure
Root proximity and interradicular space	Influences the availability of a safe insertion corridor and the risk of root injury	Preoperative CBCT evaluation facilitates accurate site selection and minimizes iatrogenic complications
Implant dimensions (diameter and length)	Affect bone engagement, mechanical retention, and resistance to orthodontic loading	Appropriate implant dimensions enhance stability while reducing the risk of loosening or fracture
Insertion site selection	Determines the quality of surrounding bone and soft tissues as well as biomechanical efficiency	Proper anatomical site selection contributes to predictable force application and long-term clinical success
Insertion technique and angulation	Influence placement accuracy, primary stability, and stress distribution around the implant	Correct insertion technique minimizes surgical complications and improves treatment outcomes
Orthodontic loading protocol	Determines the magnitude and direction of forces transmitted to the implant–bone interface	Appropriate loading protocols help maintain implant stability throughout treatment
Peri-implant soft tissue health and oral hygiene	Influence the development of peri-implant inflammation and soft tissue complications	Good oral hygiene reduces inflammation and contributes to long-term clinical success
Treatment planning and operator experience	Affect placement accuracy, biomechanical planning, and overall clinical decision-making	Careful planning supported by digital imaging improves treatment predictability and reduces failure risk

3.4 Digital Workflow and Artificial Intelligence-Assisted Personalized TAD Planning

The integration of digital technologies has introduced new possibilities for individualized orthodontic anchorage planning. CBCT-based three-dimensional reconstruction allows detailed visualization of dental roots, cortical bone morphology, and anatomical limitations before TAD placement.

Artificial intelligence-based systems may further enhance this process by assisting with automated segmentation of anatomical structures, identification of relevant landmarks, and analysis of patient-specific characteristics.

By integrating CBCT-derived information with orthodontic treatment objectives, AI-assisted platforms may support personalized selection of insertion sites, trajectories, and implant parameters. The proposed AI-assisted digital workflow for personalized TAD planning is illustrated in Figure 3.

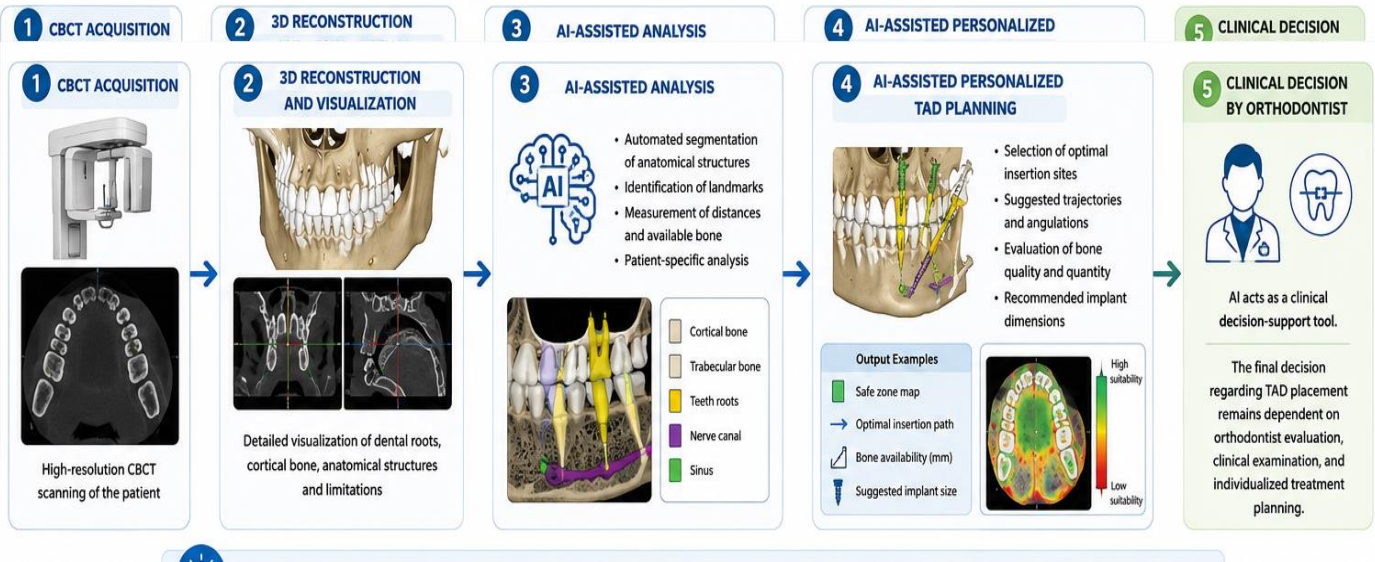


Figure 3. Digital Workflow of Artificial Intelligence–Assisted Personalized Temporary Anchorage Device (TAD) Planning.

Importantly, AI functions as a clinical decision-support tool rather than an autonomous treatment system. The final decision regarding TAD placement remains dependent on orthodontist evaluation, clinical examination, and individualized treatment planning.

The proposed AI-assisted personalized planning parameters are summarized in **Table 6**.

3.5 AI-Assisted Risk Stratification for Prevention of TAD-Related Complications

Beyond treatment planning, artificial intelligence may provide additional value through patient-specific risk assessment. By analyzing CBCT-derived anatomical information, AI-assisted systems may help identify conditions associated with increased risk of complications, including insufficient interradicular space, unfavorable root proximity, inadequate cortical support, or inappropriate insertion trajectories. Rather than applying universal placement rules, AI-assisted risk stratification allows individualized evaluation of anatomical variations and supports safer clinical decision-making. The proposed AI-assisted risk stratification framework for prevention of TAD-related complications is presented in Figure 4.

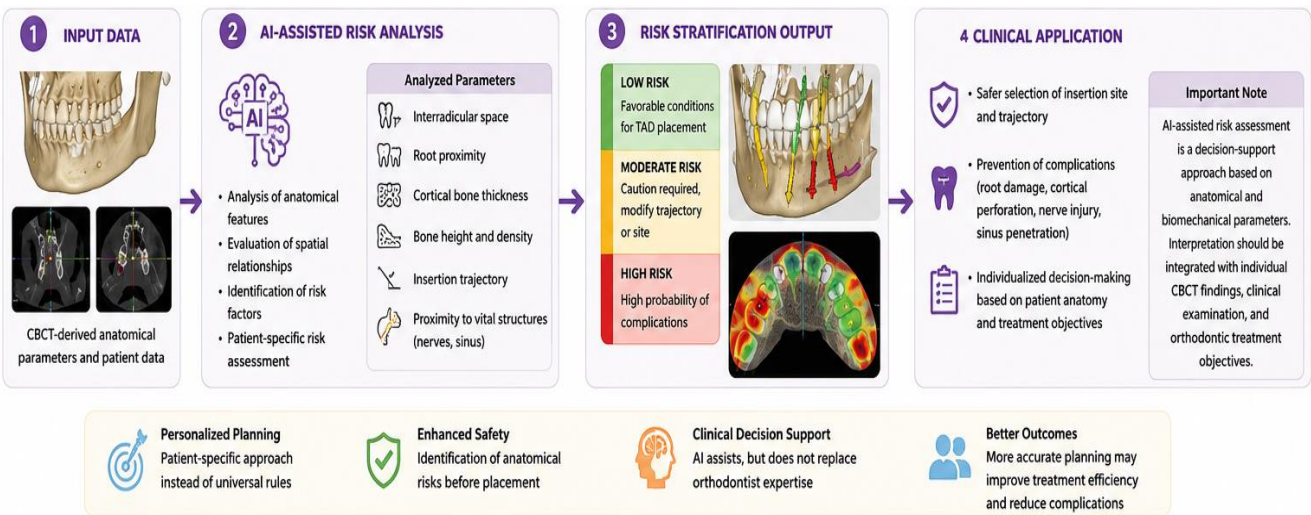


Figure 4. Artificial Intelligence–Assisted Risk Stratification Framework for Prevention of Temporary Anchorage Device (TAD)-Related Complications.

The potential safety parameters used for personalized risk assessment are summarized in **Table 7**.

Table 6. CBCT-Based Anatomical Parameters for AI-Assisted Personalized TAD Planning

CBCT Parameter	Clinical Importance	Role in AI-Assisted Planning
Interradicular space	Determines the availability of a safe insertion corridor between adjacent tooth roots	AI identifies optimal insertion pathways while minimizing the risk of root contact
Cortical bone thickness	Influences primary mechanical stability and implant retention	AI quantifies cortical bone dimensions to improve site selection and predict implant stability
Bone volume and morphology	Determines whether sufficient bone support is available for TAD placement	AI reconstructs three-dimensional bone anatomy and identifies suitable insertion sites
Root morphology and orientation	Influences insertion angulation and the likelihood of root interference	Automated segmentation enables precise localization of dental roots before implant placement
Maxillary sinus, nasal cavity, and neurovascular structures	Identifies critical anatomical structures that should be avoided during insertion	AI detects anatomical boundaries and supports safer treatment planning
Soft tissue thickness	Influences implant head position, patient comfort, and peri-implant tissue health	AI integrates soft tissue measurements into personalized placement planning
Three-dimensional insertion trajectory	Determines the optimal insertion angle and depth for biomechanical stability	AI simulates implant positioning to optimize accuracy and minimize procedural risks

Table 7. AI-Assisted Anatomical Risk Assessment Framework for Personalized TAD Placement

Risk Assessment Parameter	AI-Based Evaluation	Clinical Significance
Interradicular space availability	Automated three-dimensional measurement of the space between adjacent roots	Identifies safe insertion corridors and reduces the risk of root injury
Root proximity	Automatic root segmentation and distance analysis	Minimizes accidental root contact during TAD placement
Cortical bone thickness	Quantitative assessment of cortical bone dimensions	Predicts primary stability and assists in selecting the optimal insertion site
Bone morphology and	Three-dimensional	Supports personalized

Note: The proposed AI-assisted risk assessment framework represents a clinical decision-support approach based on anatomical and biomechanical parameters. These factors should be interpreted together with individual CBCT findings, clinical examination, and orthodontic treatment objective

5. DISCUSSION

Temporary anchorage devices have fundamentally changed modern orthodontic treatment by providing a reliable method of skeletal anchorage and expanding the range of predictable tooth movements. The findings of this scoping review demonstrate that TADs are now widely incorporated into orthodontic practice for managing complex clinical situations, including anchorage reinforcement, molar movement, intrusion mechanics, and correction of challenging malocclusions^{21–24}.

The increasing application of TADs reflects a shift from conventional anchorage concepts toward more controlled and individualized biomechanical approaches. In modern practice, skeletal anchorage can be integrated alongside specialized aligner solutions, such as the Smartee S4 technology. By employing rigid power arms and optimizing touch-and-aligner interface dynamics, clinicians can achieve precise control over force vectors and root torque, complementing the anchorage benefits provided by TADs^{24–26}. Unlike traditional anchorage methods, miniscrews provide clinicians with the ability to apply forces from strategically selected skeletal locations, reducing unwanted dental effects and improving treatment efficiency. However, successful outcomes depend on appropriate case selection, anatomical assessment, insertion technique, and maintenance of peri-implant health^{24–26}.

One of the important observations from the current evidence is the growing importance of three-dimensional treatment planning. Conventional two-dimensional radiographic assessment provides limited information regarding root proximity, cortical bone morphology, and anatomical restrictions. In contrast, CBCT-based evaluation enables more precise analysis of patient-specific anatomy and facilitates safer selection of insertion sites^{9,27}.

The integration of artificial intelligence into orthodontic workflows represents a further evolution of this personalized approach. Current literature suggests that AI-assisted systems may support clinicians by improving anatomical analysis, automated segmentation, landmark identification, and prediction of treatment-related outcomes. In the context of TAD placement, AI has particular potential for risk stratification by analyzing three-dimensional imaging data, identifying unfavorable anatomical conditions, and assisting clinicians in selecting safer and more biomechanically appropriate insertion pathways^{10–12}. However, AI should be considered an assistive technology rather than a replacement for clinical expertise. Orthodontic treatment involves complex biological responses, mechanical considerations,

and patient-specific objectives that cannot be fully determined by automated systems alone. The most appropriate future model is likely to involve collaboration between AI-based analytical tools and clinician decision-making, where artificial intelligence provides quantitative information while the orthodontist determines the final treatment strategy^{12,28–30}.

Furthermore, the clinical performance of AI-based systems depends strongly on the quality, accuracy, and diversity of the datasets used for model development. Algorithms trained on specific patient populations or limited imaging datasets may demonstrate reduced generalizability when applied to different clinical environments. The absence of external validation and multicenter evaluation remains an important challenge before AI-assisted orthodontic planning can be widely implemented in routine clinical practice. Future research should focus on developing standardized datasets, validating AI models across diverse populations, and determining whether AI-supported planning provides measurable improvements in treatment safety, efficiency, and clinical outcomes^{31–33}.

Another important aspect identified in this review is the need for standardization. Current studies evaluating TAD success frequently use different definitions of stability, failure criteria, insertion protocols, loading conditions, and outcome measures. This methodological heterogeneity limits direct comparison between studies and highlights the need for standardized reporting criteria. Future investigations should incorporate consistent parameters, including CBCT-based anatomical measurements, biomechanical variables, loading protocols, and long-term clinical outcomes to improve the reliability and comparability of evidence regarding TAD effectiveness^{34–36}.

6. Limitations

This scoping review has several limitations. First, the included studies demonstrated considerable heterogeneity regarding study design, patient populations, TAD characteristics, insertion protocols, and outcome assessment methods. Due to this variability, quantitative meta-analysis was not performed. Second, although digital orthodontics and artificial intelligence represent rapidly developing fields, the available evidence regarding AI-assisted TAD planning remains limited compared with conventional clinical research. Many AI-related studies are focused on technical development, image analysis, or preliminary validation rather than large-scale clinical implementation. Third, most available evidence originates from specialized orthodontic centers with experienced clinicians, which may limit generalizability to different clinical environments. Additional multicenter studies involving diverse patient populations are required to validate the

effectiveness and reliability of AI-assisted planning systems. Finally, the proposed AI-assisted risk assessment approach should be interpreted as a conceptual clinical decision-support approach based on current evidence rather than a universally validated algorithm. Further prospective studies are necessary to determine whether AI-guided planning leads to measurable improvements in safety, efficiency, and treatment outcomes.

7. Future Perspectives and Emerging Trends

The future development of TAD-assisted orthodontics is expected to be closely associated with advances in digital dentistry, artificial intelligence, and personalized treatment planning.

One emerging direction is the development of fully integrated digital orthodontic platforms combining CBCT imaging, intraoral scanning, three-dimensional simulation, and AI-based analysis. Such systems may allow automated evaluation of anatomical conditions and generation of patient-specific anchorage strategies.

Another promising area is the application of machine learning models for prediction of TAD stability and failure risk. By analyzing large datasets containing anatomical, mechanical, and patient-related variables, future AI systems may identify individuals at higher risk of complications and recommend preventive strategies.

Computer-guided TAD placement represents another important trend. Integration of AI-assisted planning with three-dimensional printing technologies may enable customized surgical guides that transfer virtual planning into clinical practice with improved accuracy. Furthermore, future research may focus on real-time clinical decision-support systems capable of continuously integrating treatment progress, orthodontic force application, and biological response. Such approaches could contribute to adaptive orthodontic treatment, where therapeutic strategies are modified according to individual patient response. Nevertheless, successful implementation of AI in orthodontics will require rigorous clinical validation, ethical considerations, data security protection, and collaboration between orthodontists, engineers, and data scientists.

8. CONCLUSION

Temporary anchorage devices have become an essential component of contemporary orthodontic treatment by providing predictable skeletal anchorage for a wide range of complex tooth movements. Their clinical success depends on appropriate anatomical evaluation, biomechanical

planning, and careful management of patient-specific factors. The integration of CBCT-based three-dimensional assessment and artificial intelligence introduces a new direction toward personalized TAD planning. AI-assisted systems may improve anatomical risk assessment, optimize insertion strategies, and support individualized treatment decisions while maintaining the essential role of orthodontic clinical expertise. Although current evidence demonstrates promising potential, further prospective and multicenter clinical studies are required to validate AI-based TAD planning systems and establish standardized protocols. The future of orthodontic anchorage is likely to involve a combination of advanced imaging, artificial intelligence, and clinician-guided personalized treatment approaches, leading toward safer, more predictable, and individualized orthodontic care.

DECLARATIONS

Ethical Approval

Not applicable.

Competing Interests

The authors declare no conflict of interest.

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REVIEW ARTICLE

HUMAN PAPILLOMAVIRUS-ASSOCIATED OROPHARYNGEAL SQUAMOUS CELL CARCINOMA: A SCOPING REVIEW OF CURRENT EVIDENCE AND FUTURE DIAGNOSTIC PERSPECTIVES

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ABSTRACT

Background: Human papillomavirus (HPV)-associated oropharyngeal squamous cell carcinoma (OPSCC) represents a rapidly evolving area in head and neck oncology. Although HPV16-driven carcinogenesis, epidemiological trends, vaccination strategies, and diagnostic approaches have been extensively investigated, evidence remains heterogeneous across molecular, clinical, and preventive domains. A comprehensive mapping of current knowledge is required to identify research trends, knowledge gaps, and future priorities.

Objective: To map current evidence regarding epidemiology, molecular mechanisms, prevention strategies, diagnostic approaches, and emerging technologies related to HPV-associated oropharyngeal cancer.

Methods: A scoping review was conducted according to Joanna Briggs Institute (JBI) methodology and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR). PubMed, Scopus, Web of Science and Google Scholar databases were searched for studies published from January 2000 to July 2026. Studies investigating HPV-associated oropharyngeal cancer, including epidemiological characteristics, viral mechanisms, diagnostic methods, prevention, and emerging technologies, were included. Data were extracted regarding study characteristics, HPV detection methods, molecular pathways, clinical outcomes, prevention strategies, and future diagnostic approaches.

Results: A total of 40 studies were included in the evidence mapping. Current literature demonstrates that HPV16 is the predominant oncogenic genotype associated with OPSCC. Major research domains included HPV prevalence, viral integration mechanisms involving E6/E7 oncogenic pathways, immune response, vaccination effectiveness, molecular detection techniques, and emerging artificial intelligence-based diagnostic approaches. Evidence gaps were identified regarding standardized screening strategies, global epidemiological variations, and clinical implementation of novel diagnostic technologies.

Conclusion: HPV-associated oropharyngeal cancer represents a multidisciplinary research field integrating virology, oncology, prevention, and precision medicine. Future studies should focus on standardized diagnostic pathways, long-term vaccine effectiveness, biomarker validation, and integration of emerging technologies into clinical practice.

Keywords: Head and neck cancer; human papillomavirus; HPV; oropharyngeal squamous cell carcinoma; carcinogenesis.

INTRODUCTION

Oropharyngeal squamous cell carcinoma (OPSCC) is a malignant epithelial tumor arising from the mucosal surfaces of the oropharynx, including the palatine tonsils, tonsillar crypts, base of the tongue, soft palate, and posterior pharyngeal wall. OPSCC represents a major subgroup of head and neck squamous cell carcinomas (HNSCCs) and contributes substantially to global cancer morbidity and mortality^{1,2}. Traditionally, tobacco smoking and excessive alcohol consumption have been considered the principal

environmental risk factors associated with oral and oropharyngeal malignancies. The synergistic carcinogenic effects of tobacco and alcohol exposure have historically accounted for the majority of cases of head and neck cancer; however, epidemiological patterns have changed considerably during recent decades, with human papillomavirus (HPV) infection emerging as an independent and increasingly important etiological factor, particularly in tumors originating from the tonsillar region and base of the tongue^{3,4,7}. According to the World Health Organization (WHO) and the International Agency for

Research on Cancer (IARC), persistent infection with high-risk HPV genotypes is a well-established cause of several malignancies, including cervical, anal, penile, vulvar, vaginal, and head and neck cancers^{15,23}. HPV-associated OPSCC has become recognized as a distinct molecular and clinical entity compared with conventional tobacco- and alcohol-related carcinomas. These tumors demonstrate unique biological characteristics, including specific molecular alterations, different patterns of disease progression, improved sensitivity to therapy, and generally more favorable prognosis when compared with HPV-negative OPSCC^{7,9}.

HPV is a small, non-enveloped, double-stranded DNA virus belonging to the Papillomaviridae family. The viral genome contains early genes responsible for regulation of viral replication and malignant transformation, including the oncogenes E6 and E7, as well as late genes encoding viral structural proteins⁷. Infection occurs primarily through microabrasions of the mucosal epithelium, allowing viral particles to reach basal epithelial cells. Persistent infection with oncogenic HPV types may result in abnormal expression of viral oncoproteins, leading to disruption of essential cellular regulatory mechanisms involved in proliferation, apoptosis, and genomic stability^{8,9}.

The carcinogenic activity of high-risk HPV is mainly mediated through the E6 and E7 proteins. HPV E6 promotes degradation of the tumor suppressor protein p53, resulting in impaired DNA damage repair and inhibition of apoptosis. HPV E7 interacts with the retinoblastoma (RB) tumor suppressor pathway, causing uncontrolled progression through the cell cycle and promoting cellular immortalization^{8,9}. Integration of HPV DNA into the host genome and continuous expression of E6/E7 oncogenes represent critical molecular events in HPV-driven carcinogenesis, contributing to genomic instability, immune escape, and malignant transformation of infected epithelial cells^{8,33}.

More than 200 HPV genotypes have been identified, with high-risk HPV16 representing the predominant oncogenic subtype associated with OPSCC worldwide. HPV16 accounts for the majority of HPV-positive oropharyngeal tumors and is strongly associated with cancers arising from lymphoid-rich anatomical sites, particularly the tonsillar crypts and base of the tongue^{7,12}. The susceptibility of these sites to HPV-mediated carcinogenesis is thought to be related to their specialized reticulated epithelium, which facilitates viral access to basal epithelial cells and persistence of infection²⁰.

The epidemiology of OPSCC has undergone

substantial transformation over the last several decades. While tobacco-related head and neck cancers have declined in many developed countries due to reduced smoking prevalence, HPV-associated OPSCC incidence has continued to increase^{12,27}. Current evidence indicates that HPV is detected in approximately 20–90% of OPSCC cases depending on geographic region, population characteristics, and diagnostic methodology used for HPV identification^{9,10}. In North America and several European countries, HPV-positive tumors constitute a large proportion of newly diagnosed OPSCC cases, whereas considerable regional differences remain across Asia, Africa, and other regions^{10,34}.

Unlike traditional head and neck cancers, HPV-associated OPSCC frequently affects younger patients with limited or absent exposure to tobacco and alcohol. A pronounced male predominance has consistently been reported, with epidemiological studies demonstrating substantially higher incidence rates among men compared with women^{7,16}. The observed sex differences may be associated with variations in HPV exposure, immune responses, sexual behavior patterns, and differences in the natural history and clearance of oral HPV infection¹⁶.

The acquisition of oral HPV infection is primarily related to sexual exposure. Multiple epidemiological studies have demonstrated associations between oral HPV positivity and sexual behaviors, including oral–genital contact, increased number of sexual partners, early sexual initiation, and other indicators of higher HPV exposure risk^{13,17}.

HPV is also implicated in a range of other malignancies, highlighting its significant oncogenic potential across multiple anatomical sites (figure 1)¹⁹.

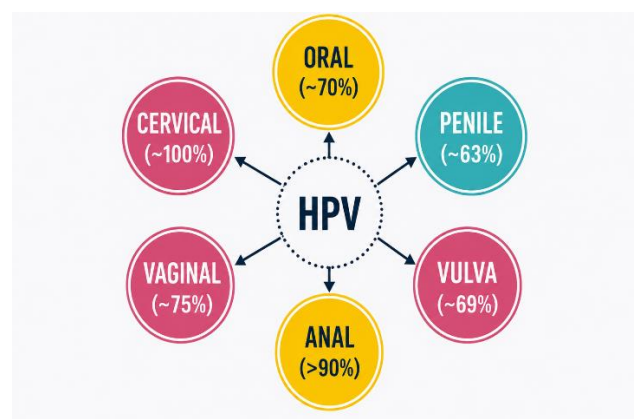


Figure 1. HPV-related malignancies

Studies have reported the HPV status of tumors located in different anatomical subregions of the oral cavity (at the base of the tongue, in the folds of the tonsils, or in the back of the throat) (fig.2)¹⁹.

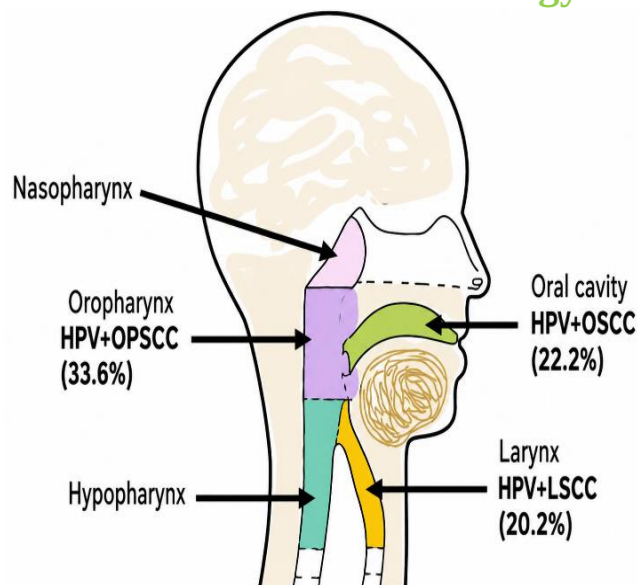


Figure 2. Distribution of human papillomavirus associated head and neck cancers (HPV + HNC) between anatomical sites. HPV is associated with 33.6% of OPSCC (lavender), 22.2% of OSCC (bright green), and 20.2% of LSCC (gold) worldwide

Studies conducted in large population-based cohorts have further demonstrated increased prevalence of oncogenic oral HPV infection among individuals with specific sexual behavior patterns, particularly among men ¹⁸. However, HPV infection is common in sexually active populations, and the majority of infections are transient due to effective host immune clearance.

Persistent infection with high-risk HPV types represents the critical biological event associated with malignant transformation ^{14,22}.

Sexually-transmitted HPV virus is a leading cause of lingual cancer, tonsil cancer, oropharyngeal cancer (fig3,4,5) and it spreads from person to person via oral sex.



Figure 3. Lingual cancer is caused by HPV



Figure 4 Tonsil cancer is caused by HPV



Figure 5. Oropharyngeal cancer is caused by HPV

The natural history of oral HPV infection is influenced by multiple viral, host, and environmental factors. Viral genotype, viral load, immune status, smoking exposure, age, and anatomical location of infection contribute to the probability of viral persistence and progression toward malignancy ^{14,22}. Most individuals are able to eliminate oral HPV infection spontaneously; however, failure of immune-mediated clearance may lead to prolonged viral persistence, accumulation of molecular abnormalities, and eventual development of invasive carcinoma ²².

From a pathological perspective, malignant transformation represents a multistep process involving epithelial dysplasia, accumulation of genetic alterations, invasion through the basement membrane, and metastatic potential. Oral epithelial dysplasia is characterized by cellular atypia, increased mitotic activity, abnormal maturation, and architectural disturbances that may precede invasive carcinoma ⁶.

Tumor progression is further regulated by interactions between malignant epithelial cells and the tumor microenvironment, including inflammatory pathways, angiogenesis, immune modulation, and cancer stem cell-related mechanisms that contribute to tumor survival and progression ^{5,22}.

Clinically, oral and oropharyngeal cancers may demonstrate different morphological patterns, including ulcerative, nodular, and papillary growth characteristics. Ulcerative lesions typically present as persistent non-healing ulcers with progressive enlargement, whereas nodular lesions appear as firm masses with gradual expansion. Papillary lesions demonstrate exophytic growth patterns and may exhibit different biological behavior compared with conventional invasive carcinomas⁴. Early identification of suspicious mucosal lesions remains essential because delayed diagnosis continues to represent a major factor contributing to poor clinical outcomes.

Prevention of HPV-associated OPSCC has become an important global health objective. Prophylactic HPV vaccination provides effective protection against persistent infection with high-risk HPV genotypes and has demonstrated substantial efficacy in preventing HPV-related anogenital cancers^{11,23,25}. Although HPV vaccination programs were initially developed primarily for cervical cancer prevention, increasing evidence supports their potential contribution to reducing the future burden of HPV-associated head and neck malignancies²⁴. Expanding vaccination coverage among adolescents and eligible adults remains a key strategy for reducing HPV-related cancer incidence worldwide²⁵.

Advances in diagnostic approaches have significantly improved the detection and characterization of HPV-associated tumors. Current diagnostic strategies include HPV DNA detection, RNA-based assays evaluating transcriptionally active HPV infection, p16 immunohistochemistry as a surrogate marker, and molecular profiling approaches^{9,10}.

More recently, artificial intelligence (AI)-based technologies have emerged as promising tools in oncology, enabling automated image analysis, molecular classification, early cancer detection, and integration of complex biological datasets for precision medicine applications^{31,32}.

Despite substantial advances in understanding HPV-driven OPSCC, important challenges remain, including geographic variation in disease prevalence, differences in diagnostic standards, incomplete vaccination coverage, limitations of current screening approaches, and the need for improved personalized treatment strategies. Emerging technologies, including artificial intelligence, machine learning, and computational pathology, may provide new opportunities for improving early diagnosis, risk stratification, and individualized patient management^{31,32}.

Therefore, this scoping review aims to systematically map the current evidence regarding HPV-associated oropharyngeal cancer, with particular emphasis on epidemiology, molecular mechanisms of carcinogenesis, transmission and risk factors, preventive strategies, diagnostic approaches, and emerging technologies shaping future clinical practice.

2. MATERIALS AND METHODS

2.1 Study Design and Reporting Framework

This scoping review was conducted using the methodological framework proposed by the Joanna Briggs Institute (JBI) for evidence synthesis and scoping reviews. The reporting of the review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) guidelines^{30,31}.

The objective of this review was to map the existing evidence regarding human papillomavirus (HPV)-associated oropharyngeal squamous cell carcinoma (OPSCC), with particular emphasis on epidemiological characteristics, molecular mechanisms of HPV-driven carcinogenesis, risk factors, prevention strategies, diagnostic approaches, and emerging technologies. A scoping review approach was selected because the available literature includes diverse types of evidence, including epidemiological studies, molecular investigations, clinical studies, diagnostic research, and emerging technology-based approaches. The purpose of this review was to characterize the scope and characteristics of current knowledge, identify major research trends, and highlight existing gaps in the field rather than to estimate pooled treatment effects or perform quantitative meta-analysis.

2.2 Review Question and PCC Framework

The review question was developed according to the Population–Concept–Context (PCC) framework recommended by the Joanna Briggs Institute for scoping reviews³⁰. The primary research question was: What is the current evidence regarding the epidemiology, molecular mechanisms, prevention strategies, diagnostic approaches, and emerging technologies associated with HPV-related oropharyngeal squamous cell carcinoma?

The PCC framework was defined as follows:

Population: Patients diagnosed with HPV-associated oropharyngeal cancer or head and neck squamous cell carcinoma, as well as clinically relevant biological samples derived from these populations.

Concept: HPV infection, viral oncogenesis, molecular mechanisms of carcinogenesis, epidemiology, risk factors, prevention strategies, diagnostic methods, and emerging technologies related to HPV-associated OPSCC.

Context: Clinical, epidemiological, molecular, diagnostic, and translational research settings.

2.3 Search Strategy

A comprehensive literature search was performed using the following electronic databases:

- PubMed/MEDLINE;
- Scopus;
- Web of Science;
- Google Scholar.

The search strategy was developed using a combination of Medical Subject Headings (MeSH) terms and free-text keywords related to HPV infection, head and neck cancer, and oropharyngeal malignancies. The following search terms were combined using Boolean operators (AND, OR):

("Human papillomavirus" OR HPV OR HPV16 OR "high-risk HPV")
AND
("oropharyngeal cancer" OR "oropharyngeal squamous cell carcinoma" OR OPSCC OR "head and neck squamous cell carcinoma")
AND
("epidemiology" OR "carcinogenesis" OR "molecular mechanisms" OR E6 OR E7 OR "HPV detection" OR vaccination OR prevention OR diagnosis OR "artificial intelligence").

The search was restricted to publications available in the English language. Studies published between January 2000 and July 2026 were considered eligible to capture contemporary developments in the understanding, diagnosis, prevention, and management of HPV-associated OPSCC. In addition, the reference lists of included studies and relevant publications were manually screened to identify additional potentially eligible studies.

2.4 Eligibility Criteria

Eligibility criteria were defined according to the PCC framework.

Inclusion Criteria

Studies were eligible for inclusion if they fulfilled the

following criteria:

- Original clinical, epidemiological, molecular, diagnostic, or translational studies;
- Studies investigating the association between HPV infection and oropharyngeal squamous cell carcinoma or head and neck cancers;
- Studies reporting HPV prevalence, HPV genotypes, molecular mechanisms, clinical characteristics, diagnostic approaches, or prevention strategies;
- Studies involving human participants or clinically relevant human-derived biological samples;
- Publications available in English;
- Studies published within the predefined search period.

Exclusion Criteria

Studies were excluded when they met any of the following criteria:

- Narrative reviews, systematic reviews, meta-analyses, editorials, commentaries, and letters;
- Case reports without relevant HPV-associated findings;
- Animal-only studies;
- Experimental studies without direct clinical relevance;
- Duplicate publications;
- Studies lacking sufficient information related to the objectives of the review.

2.5 Study Selection Process

All identified records were imported into reference management software, and duplicate records were removed before the screening process. Titles and abstracts were independently screened by two reviewers based on predefined eligibility criteria. Articles considered potentially relevant were subsequently evaluated through full-text assessment. Disagreements regarding study eligibility were resolved through discussion and consensus between reviewers. The initial database search identified 84 records. After removal of duplicate records and preliminary screening, potentially eligible studies underwent full-text evaluation. Following application of the predefined inclusion and exclusion criteria, 40 studies were included in the final scoping review. The study selection process followed the PRISMA-ScR reporting framework, and the stages of identification, screening, eligibility assessment, and final inclusion are presented in the PRISMA-ScR flow diagram (Figure 6).

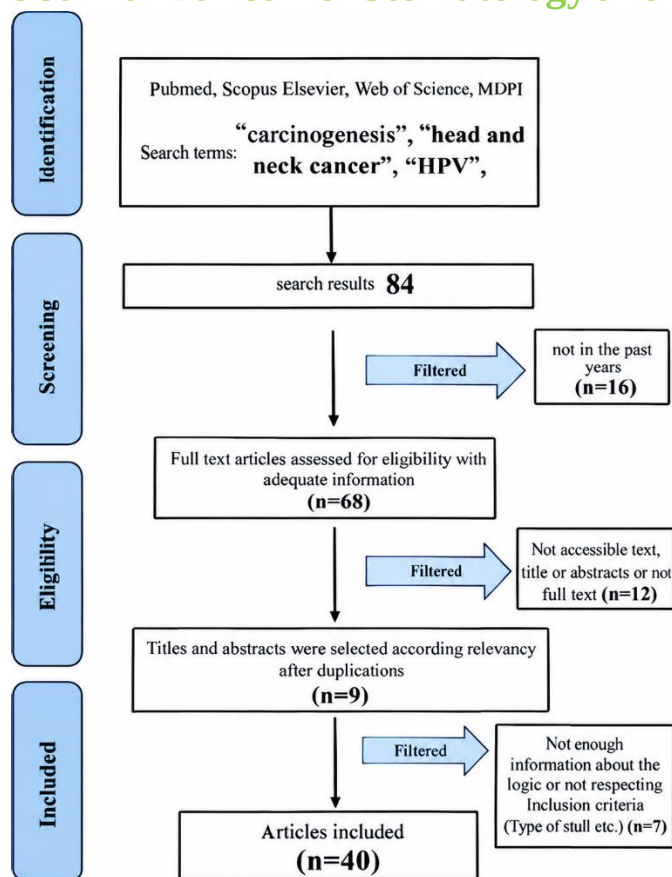


Figure 6. PRISMA-ScR flow diagram of study selection process

2.6 Data Extraction and Charting

Data extraction was performed using a standardized data-charting form developed in accordance with the Joanna Briggs Institute (JBI) methodology for scoping reviews³⁰.

The following characteristics were extracted from each included study:

- First author and year of publication;
- Country and geographic region of the study;
- Study design and methodological approach;
- Sample size and participant characteristics;
- Anatomical location of the tumor;
- HPV detection and genotyping methods;
- Distribution of HPV16 and other high-risk HPV genotypes;
- Molecular mechanisms involved in HPV-associated carcinogenesis;
- Clinical characteristics and reported outcomes;
- Prevention strategies, including HPV vaccination approaches;
- Diagnostic methods and biomarker-based approaches;

- Emerging technologies, including artificial intelligence-based diagnostic and analytical methods.

Data extraction was performed independently by two reviewers using the predefined data-charting framework. Any discrepancies identified during the extraction process were resolved through discussion and consensus.

2.7 Data Synthesis

A descriptive qualitative synthesis of the included studies was conducted.

The extracted evidence was organized into the following major thematic domains:

1. Epidemiology and global distribution of HPV-associated OPSCC;
2. HPV transmission pathways and associated risk factors;
3. Molecular mechanisms underlying HPV-mediated carcinogenesis;
4. Clinical characteristics, treatment response, and prognosis;
5. Prevention strategies and HPV vaccination;
6. Diagnostic approaches, HPV detection methods, and biomarker development;
7. Emerging technologies, including artificial intelligence and computational approaches in HPV-associated cancer research.

Because of the considerable heterogeneity among included studies regarding study populations, research designs, HPV detection techniques, diagnostic criteria, and reported outcomes, statistical pooling and quantitative meta-analysis were not considered appropriate.

2.8 Methodological Considerations

According to current Joanna Briggs Institute guidance for scoping reviews, formal methodological quality appraisal and risk-of-bias assessment were not performed³⁰.

The primary objective of this review was to systematically map the available evidence, describe current research trends, identify methodological differences between studies, and highlight existing knowledge gaps in HPV-associated oropharyngeal cancer research rather than to evaluate intervention effectiveness or generate pooled estimates.

3. RESULTS

3.1 Study Characteristics and Evidence Mapping

The literature search identified evidence describing multiple aspects of human papillomavirus (HPV)-associated oropharyngeal squamous cell carcinoma (OPSCC), including epidemiology, viral transmission, molecular mechanisms, clinical characteristics, prevention strategies, diagnostic approaches, and emerging technologies.

The included evidence consisted of epidemiological

studies, molecular investigations, clinical studies, diagnostic studies, and translational research.

The reviewed studies demonstrated that HPV-associated OPSCC represents a biologically distinct subgroup of head and neck squamous cell carcinoma (HNSCC), with different etiological factors, molecular alterations, and clinical behavior compared with HPV-negative tumors.

The main characteristics of the included studies, including study focus, methodological approach, and investigated HPV-related factors, are summarized in **Table 1**.

Table 1. Characteristics of Included Evidence on HPV-Associated Oropharyngeal Cancer

Study area	Main evidence identified	Representative references
Epidemiology of oral and oropharyngeal cancer	Global burden of oral cancer and changing epidemiological patterns	[1,2]
Traditional risk factors	Association of tobacco and alcohol exposure with oral and pharyngeal cancer	[3]
HPV-associated head and neck cancer	HPV as an independent etiological factor in OPSCC	[7,12,33]
HPV detection and diagnosis	Molecular detection methods and clinical implications	[9,10]
HPV vaccination and prevention	Vaccine effectiveness and preventive strategies	[11,23,25]
Artificial intelligence and digital diagnostics	AI applications in cancer detection and precision medicine	[31]

3.2 Epidemiology of HPV-Associated Oropharyngeal Cancer

HPV-associated OPSCC has become one of the most rapidly increasing subsets of head and neck malignancies worldwide. Unlike conventional HNSCC, which is strongly associated with tobacco and alcohol exposure, HPV-positive OPSCC represents a distinct disease entity driven primarily by persistent infection with oncogenic HPV types. Current evidence indicates substantial geographic variation in HPV prevalence among OPSCC cases, with reported HPV positivity ranging approximately from 20% to 90%, depending on population characteristics, geographic region, and detection methodology. The highest prevalence rates have been reported in North America and several European countries ^{9,12,33}

Among oncogenic HPV types, HPV16 is the predominant genotype identified in HPV-associated OPSCC. HPV16 accounts for the majority of HPV-positive tumors, whereas HPV18 and other high-risk genotypes are detected less frequently ^{7,12}.

HPV-positive OPSCC demonstrates characteristic demographic features. The disease predominantly affects middle-aged adults, commonly between 40 and 60 years of age, and shows a marked male predominance. Epidemiological studies have demonstrated substantially higher prevalence among men compared with women, which may reflect differences in HPV exposure, sexual behavior patterns, immune responses, and viral persistence mechanisms ^{13,16,18}. The epidemiological characteristics of HPV-associated OPSCC are summarized in **Table 2**.

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Table 2. Epidemiological and Clinical Characteristics of HPV-Associated OPSCC

Characteristic	Reported findings	References
HPV contribution to OPSCC	Approximately 20–90% of OPSCC cases depending on region and detection method	[9,12,33]
Predominant HPV genotype	HPV16 is the dominant oncogenic subtype	[7,12]
Age distribution	Most commonly affects individuals aged 40–60 years	[12]
Sex distribution	Strong male predominance reported in epidemiological studies	[16,18]
Main anatomical sites	Tonsillar crypts and base of tongue are predominant locations	[7]
Traditional risk factors	Frequently occurs without heavy tobacco or alcohol exposure	[12,27]

3.3 Transmission and Risk Factors

Oral HPV infection is primarily acquired through sexual exposure, particularly oral–genital contact. Population-based studies have demonstrated significant associations between oral HPV positivity and sexual behavior characteristics, including increased number of sexual partners, early sexual debut, and oral sexual practices ^{16–18}. However, HPV infection is relatively common among sexually active individuals, and most infections are transient due to effective host immune clearance. Persistent infection with high-risk HPV types represents the critical step associated with malignant transformation ^{19,22}. Additional factors influencing HPV persistence include immune status, smoking exposure, viral genotype, viral load, and anatomical site of infection. Immunosuppression and coexisting environmental risk factors may facilitate progression from persistent infection to malignant disease ^{20,22}.

3.4 Molecular Mechanisms of HPV-Mediated Carcinogenesis

High-risk HPV-associated carcinogenesis is primarily mediated through continuous expression of viral oncogenes E6 and E7. These viral proteins interfere with essential cellular regulatory pathways by targeting tumor suppressor mechanisms. HPV E6 promotes degradation of p53, resulting in impaired DNA repair mechanisms and inhibition of apoptosis. HPV E7 interacts with the retinoblastoma protein (pRb), leading to uncontrolled cell-cycle progression and cellular immortalization ^{7,8}.

Integration of HPV DNA into the host genome represents an important molecular event associated with malignant transformation. Persistent viral oncogene expression promotes genomic instability, immune escape, and progressive epithelial transformation ^{8,29}.

The major molecular pathways involved in HPV carcinogenesis are summarized in **Table 3**.

Table 3. Molecular Mechanisms, Diagnosis, Prevention and Emerging Technologies

Domain	Main findings	References
Viral oncogenesis	E6-mediated p53 degradation and E7-mediated pRb inhibition	[7,8]
Viral persistence	Failure of immune clearance promotes malignant progression	[21,22]
HPV detection	PCR, molecular assays, p16 immunohistochemistry	[9,28]
Vaccination	Effective prevention against high-risk HPV infection	[11,23,25]
Artificial intelligence	AI-assisted cancer detection and precision oncology applications	[31]

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3.5 Diagnosis, Prevention and Emerging Technologies

Current diagnostic approaches for HPV-associated OPSCC include HPV DNA detection, RNA-based assays, and p16 immunohistochemistry as a surrogate marker of transcriptionally active HPV infection. However, unlike cervical cancer, standardized population-based screening programs for oral HPV infection are currently unavailable^{9,28}.

Prevention strategies primarily focus on HPV vaccination. Available evidence demonstrates that prophylactic vaccination effectively reduces persistent infection with high-risk HPV genotypes and may contribute to reducing future HPV-associated malignancies^{11,23,25}.

The orogenital route of transmission has been shown to be the most documented route of oral HPV infection. Prevention of HPV - HNSCC is based on the prevention of oral infection with high-risk HPV types. The strategy for the prevention of HPV-HNSCC involves the education of health workers and public health education about the viral nature of this cancer variant, routes of HPV infection, patterns of corresponding dangerous sexual activity and possibilities of mechanical protection against infection, but the main expectations are associated with the systematic vaccination of the population against HPV, recommended by WHO for the “prevention of cervical cancer, as well as cancer of the vagina, vulva, anus, penis, oropharynx and other HPV-associated diseases” (fig.7).

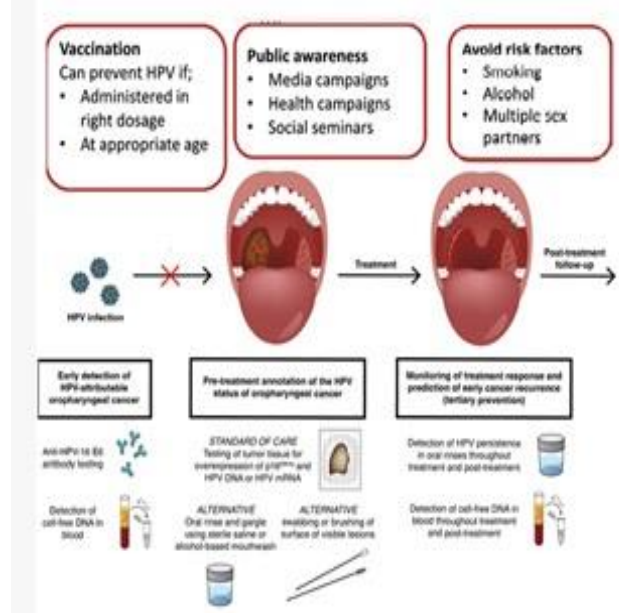


Figure 7. Schematic pictuars prevention of oropharyngeal cancer

Three vaccines containing self-assembling empty "shells" of high-risk HPV L1 capsid proteins have been developed to date: the bivalent vaccine "Cervarix" (licensed in 2007) with L1 types 16 and 18, the tetravalent vaccine "Gardasil-4" (2006) with L1 types 16, 18, 6, 11, and the nonavalent vaccine "Gardasil 9" (2014) with L1 types 16, 18, 6, 11, 31, 33, 45, 52, and 58. The vaccine, administered intramuscularly in two or three doses, provides adaptive immunity to HPV infection of both the anogenital and oral tissues: after the first (and second) vaccine injection, within 4-6 months, memory B cells mature, which, after reactivation by the last injection, differentiate into long-lived plasma cells capable of secreting specific antibodies over the next 10-20 years and maintaining their circulation in the body's biological environments, including in serous exudate in the area of microdamage to the epithelium, effectively blocking the connection of L1 of infectious HPV with epithelial cells of the basal layer preventing infection.

Formation of collective immunity against HPV (significant reduction in virus circulation in the population, including a reduction in the risk of infection of the male population) is expected with regular vaccination of $\geq 80\%$ of girls aged 9–14 years, before the debut of sexual activity (the primary target population group in WHO documents); corresponding state programs operate in 71 countries around the world.

HPV can be transmitted by self-vaccination from the genital area to the mouth area through infected nails. Therefore, HPV in the head and neck is transmitted orally through oral sex, contributing to the majority of HPV transmission/infections associated with the head and neck³⁰.

Almost all of these cancers are caused by HPV16, a subtype of the HPV virus. Studies show that approximately 70 percent of oropharyngeal cancers are caused by HPV.

Recent advances in artificial intelligence and computational oncology have introduced new possibilities for early cancer detection, automated image interpretation, molecular classification, and personalized clinical decision-making. Although these technologies remain under investigation, they represent promising future approaches for improving diagnosis and risk stratification in HPV-associated cancers³¹.

4. DISCUSSION

4.1 HPV as a Distinct Molecular and Epidemiological Entity in OPSCC

The findings of this scoping review confirm that human papillomavirus, particularly HPV16, represents a major etiological factor in the development of oropharyngeal squamous cell carcinoma. Over recent decades, HPV-positive OPSCC has emerged as a clinically and

biologically distinct subgroup of head and neck cancer, differing substantially from traditional tobacco- and alcohol-associated malignancies. The increasing incidence of HPV-positive OPSCC, particularly in North America and Europe, contrasts with the declining incidence of tobacco-related head and neck cancers. This epidemiological transition reflects changes in population behavior, reduced tobacco exposure, and increasing recognition of HPV as an independent carcinogenic factor^{7,12,33}. Large population-based analyses have demonstrated that HPV-associated tumors account for a growing proportion of OPSCC cases, particularly among younger and middle-aged patients without substantial exposure to conventional carcinogens^{27,35}.

Unlike HPV-negative OPSCC, HPV-positive tumors frequently demonstrate improved biological behavior and better clinical outcomes. The favorable prognosis is associated with preserved treatment sensitivity, distinct molecular characteristics, and enhanced immune recognition of viral-associated tumor antigens³⁵.

4.2 Molecular Basis of HPV-Driven Carcinogenesis

The carcinogenic mechanism of HPV-associated OPSCC is primarily mediated by persistent expression of viral oncogenes E6 and E7. These proteins disrupt essential cellular regulatory pathways through inactivation of p53 and retinoblastoma protein (pRb), resulting in impaired apoptosis, uncontrolled cellular proliferation, and genomic instability^{7,8}.

Integration of HPV DNA into the host genome represents a critical event in malignant transformation. Continuous expression of viral oncogenes contributes to accumulation of molecular alterations and facilitates immune escape, allowing progression from persistent infection to invasive carcinoma^{8,29}.

Compared with HPV-negative cancers, HPV-positive OPSCC demonstrates different molecular profiles, including increased immune activity and higher levels of viral antigen expression. These characteristics provide a biological explanation for the improved response to treatment and the growing interest in immune-based therapeutic strategies^{35,37}.

4.3 Transmission, Persistence, and Risk Factors

The reviewed evidence indicates that oral HPV acquisition is strongly associated with sexual exposure, particularly oral-genital contact. Epidemiological studies have consistently demonstrated associations between oral HPV infection and sexual behavior patterns, including increased

number of partners and early sexual initiation^{16–18}.

However, the presence of HPV infection alone is insufficient for carcinogenesis. Most oral HPV infections are transient and are eliminated by host immune mechanisms. Persistent infection with high-risk HPV genotypes represents the essential prerequisite for malignant transformation^{20,22}.

Several cofactors may influence viral persistence and progression, including smoking, immune suppression, age, viral genotype, and local tissue characteristics. These factors may contribute to differences in disease development among infected individuals^{19,22}.

4.4 Clinical Implications and Prognostic Differences

HPV-positive OPSCC differs clinically from conventional HNSCC. Patients are often younger, have limited tobacco and alcohol exposure, and frequently present with small primary tumors accompanied by cervical lymph node metastases.

Despite advanced nodal disease at diagnosis, HPV-positive OPSCC generally demonstrates improved survival outcomes compared with HPV-negative disease. The landmark study by Ang et al. demonstrated that HPV status represents one of the strongest prognostic biomarkers in OPSCC, with HPV-positive patients showing significantly improved overall survival³⁵.

These findings have influenced current treatment strategies and stimulated research into individualized therapeutic approaches aimed at maintaining oncological control while reducing treatment-related morbidity.

4.5 Treatment De-intensification and Modern Therapeutic Strategies

Because HPV-positive OPSCC patients generally have better prognosis, treatment de-intensification has become an important research direction. The objective of these approaches is to reduce long-term complications such as swallowing dysfunction, xerostomia, and speech impairment without compromising tumor control. Clinical studies evaluating reduced-intensity radiotherapy, modified chemotherapy regimens, and response-adapted approaches suggest that selected patients may benefit from less aggressive treatment strategies; however, these approaches require careful patient selection and remain under clinical investigation^{36,39}.

Immunotherapy represents another important development in HPV-associated head and neck cancer. Immune checkpoint inhibitors targeting PD-1/PD-L1

pathways, including nivolumab and pembrolizumab, have demonstrated clinical benefit in recurrent or metastatic HNSCC and may be particularly relevant in HPV-positive tumors because of their viral antigen expression and immune activation profile^{37,38}.

Surgical management has also evolved with the introduction of minimally invasive techniques such as transoral robotic surgery (TORS) and transoral laser microsurgery. These approaches aim to preserve organ function while maintaining oncological safety in selected early-stage patients⁴⁰.

4.6 Prevention, Screening Challenges, and Future Perspectives

HPV vaccination remains the most effective preventive strategy against HPV-associated malignancies. Although current vaccination programs were primarily developed for cervical cancer prevention, increasing evidence suggests potential long-term benefits in reducing HPV-related OPSCC incidence^{11,23,25}. A major unresolved challenge is the absence of a standardized screening strategy for oral HPV infection. Unlike cervical cancer, where established screening programs allow early detection of precancerous lesions, OPSCC currently lacks validated population-based screening methods^{9,28}.

Future research should focus on improving early detection through molecular biomarkers, salivary diagnostics, and computational approaches. Artificial intelligence-based technologies may provide additional opportunities for automated image interpretation, risk prediction, and integration of complex clinical and molecular data^{31,32}.

4.7 Limitations of Current Evidence

Several limitations should be considered when interpreting the available evidence. First, most epidemiological studies originate from North America and Europe, limiting global generalizability. Second, variability in HPV detection methods, including differences between DNA, RNA, and p16-based approaches, contributes to heterogeneity among studies^{9,10}. Additionally, although HPV vaccination demonstrates strong efficacy against infection with high-risk HPV genotypes, direct evidence regarding reduction of OPSCC incidence remains limited because of the long latency period between infection and cancer development^{23,25}.

4.8 Future Research Directions

Future investigations should prioritize the

development of standardized oral HPV screening strategies, longitudinal studies evaluating vaccine impact on OPSCC incidence, and personalized treatment approaches integrating molecular biomarkers. The combination of HPV molecular profiling, immunotherapy, minimally invasive surgery, and artificial intelligence-based diagnostic systems may contribute to a more individualized management model for HPV-associated OPSCC.

CONCLUSION

Human papillomavirus, particularly HPV16, is a major etiological factor in oropharyngeal squamous cell carcinoma and represents a distinct molecular and clinical subtype of head and neck cancer. This scoping review highlights the central role of persistent high-risk HPV infection and viral oncogenes E6 and E7 in carcinogenesis, as well as the changing epidemiology of HPV-positive OPSCC, which increasingly affects younger patients without traditional risk factors. HPV vaccination remains the most effective preventive strategy, while the absence of standardized oral HPV screening continues to represent an important clinical challenge. Advances in molecular diagnostics, immunotherapy, minimally invasive surgery, and artificial intelligence-based technologies provide promising opportunities for improving early detection, risk stratification, and personalized management. Future research should focus on establishing effective screening approaches, evaluating the long-term impact of vaccination on OPSCC incidence, and integrating emerging technologies into multidisciplinary care to further improve patient outcomes.

DECLARATION

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Conflict of interest

The author declares that he has no Conflict of interest.

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Ethical Approval

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REVIEW ARTICLE

ORGANIZATIONAL AND CLINICAL PRINCIPLES OF SURGICAL DENTAL CARE IN PATIENTS WITH TYPE 2 DIABETES MELLITUS: A SCOPING REVIEW

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ABSTRACT

Background: The aim of this scoping review was to map the current evidence regarding the organization and provision of surgical dental care for patients with type 2 diabetes mellitus, with particular emphasis on oral manifestations, wound healing, dental implant therapy, peri-implant diseases, and preventive management strategies.

Methods: A comprehensive literature search was conducted in MEDLINE, Scopus, Web of Science, PubMed, and Google Scholar. The review included studies addressing the organization of dental care in patients with type 2 diabetes mellitus, the relationship between glycemic control and oral complications, oral manifestations of diabetes, wound healing following dental procedures, implant therapy, osseointegration, and peri-implant diseases. A total of 132 publications were identified. Following title and abstract screening and full-text assessment according to predefined eligibility criteria, 64 articles were included in the final scoping review. The evidence was mapped and synthesized thematically according to the main clinical areas of surgical dental care.

Results: The reviewed literature demonstrated that patients with type 2 diabetes mellitus may present with a broad spectrum of oral complications, including periodontal disease, xerostomia and salivary dysfunction, taste disturbances, oral infections, impaired wound healing, tooth loss, and postoperative complications such as alveolar osteitis. Hyperglycemia was associated with impaired wound healing, altered bone metabolism, compromised osseointegration, and an increased susceptibility to peri-implant inflammatory complications. The evidence also highlighted the importance of glycemic control, periodontal and oral hygiene status, appropriate patient selection, preventive protocols, implant surface modification, vitamin D status, and long-term maintenance in the management of diabetic patients undergoing surgical dental treatment.

Conclusion: This scoping review demonstrates that surgical dental care in patients with type 2 diabetes mellitus requires individualized treatment planning, adequate metabolic control, comprehensive preventive strategies, and long-term clinical monitoring. Although diabetes mellitus may increase the risk of postoperative and peri-implant complications, current evidence indicates that dental surgical and implant treatment can be successfully performed in appropriately selected and adequately controlled patients. Further well-designed clinical studies are needed to clarify optimal protocols for surgical dental management and implant therapy in this population.

Keywords: Type 2 diabetes mellitus; surgical dental care; glycemic control; oral manifestations; wound healing; dental implants; peri-implantitis; osseointegration; preventive dental management; scoping review

INTRODUCTION

Diabetes mellitus is a chronic metabolic disorder characterized by impaired glucose regulation and disturbances in carbohydrate, lipid, and protein metabolism. It remains a major global health problem and is associated with substantial medical and social consequences.¹⁻³ The worldwide prevalence of diabetes has increased considerably over recent decades, and current estimates indicate that hundreds of millions of people are living with the disease.⁴⁻⁶

Persistent hyperglycemia contributes to the development of both microvascular and macrovascular complications and is also associated with impaired immune function, delayed tissue repair, vascular dysfunction, and alterations in bone metabolism.⁷⁻¹¹

The effects of diabetes extend beyond the major systemic complications of the disease and involve a wide range of oral tissues and functions. Chronic hyperglycemia can impair vascularization, alter inflammatory and immune

responses, reduce fibroblast activity and collagen synthesis, and interfere with normal tissue repair. These changes may increase susceptibility to infection and contribute to poorer healing following dental and oral surgical procedures.^{7–11}

A broad spectrum of oral manifestations has been reported in patients with diabetes mellitus, including periodontal disease, xerostomia, salivary gland dysfunction, oral fungal infections, taste disturbances, delayed wound healing, and tooth loss.^{12–14} Periodontal disease is particularly important because it represents one of the most common chronic inflammatory conditions affecting patients with diabetes.^{15,16} The relationship between diabetes and periodontal disease is bidirectional: poor glycemic control may promote periodontal tissue destruction, while persistent periodontal inflammation may adversely affect metabolic control.^{17,18}

The biological mechanisms underlying this relationship involve dysregulated inflammatory and immune responses. Hyperglycemia and the accumulation of advanced glycation-related products can contribute to an exaggerated inflammatory response, with increased production of mediators such as tumor necrosis factor alpha, interleukin-1 beta, and prostaglandin E2. These mediators can stimulate osteoclastic activity and promote destruction of periodontal supporting tissues.¹⁹ Consequently, patients with diabetes may have an increased need for surgical dental interventions, including tooth extraction, periodontal procedures, and implant-supported rehabilitation.

Tooth extraction presents particular challenges in patients with diabetes because normal socket healing depends on adequate vascularization, inflammatory regulation, fibroblast activity, collagen formation, and bone remodeling. Diabetes-related microvascular changes and impaired tissue repair may delay epithelialization and connective tissue regeneration and may increase susceptibility to postoperative infection.^{20–23} These problems are especially relevant during the early postoperative period, when stable clot formation, vascularization, and tissue repair are essential for uncomplicated healing.

Alveolar osteitis is an important postoperative complication following tooth extraction and may be particularly problematic in patients with impaired healing capacity. Delayed socket healing, altered angiogenesis, impaired host defense, and increased bacterial colonization may contribute to its development in patients with diabetes.^{20–23} Clinically, alveolar osteitis can cause considerable postoperative pain and delayed recovery and may negatively affect

oral function and quality of life. Appropriate preventive and therapeutic approaches are therefore an important component of surgical dental care in patients with diabetes.²⁴

Diabetes-related impairment of wound healing is not limited to soft tissues. Hyperglycemia can also interfere with osteoblastic differentiation, bone formation, and normal bone remodeling.^{7,8} These alterations are particularly relevant when surgical procedures involve bone healing, such as tooth extraction and dental implant placement. Because progressive periodontal disease and tooth loss may lead to functional impairment and reduced oral rehabilitation options, prosthetic treatment is frequently required. Conventional removable prostheses may be limited by alveolar bone resorption and reduced prosthetic stability.²⁵ Dental implants therefore represent an important treatment option for restoring mastication, oral function, and quality of life in appropriately selected patients with diabetes mellitus.²⁶

The use of dental implants in patients with diabetes has increased, and available evidence indicates that implant therapy can provide satisfactory clinical outcomes when patients are appropriately selected and metabolic control is adequately managed.^{26–29} Nevertheless, diabetes remains an important biological risk factor that may influence osseointegration and implant survival.^{30,31} Persistent hyperglycemia may suppress osteoblastic activity, increase osteoclastic bone resorption, alter calcium and phosphorus metabolism, impair collagen formation, and interfere with normal bone remodeling. These changes may reduce bone-implant contact and delay the establishment of stable osseointegration.

Peri-implant disease represents another important concern in diabetic patients receiving implant therapy. Evidence from systematic reviews and observational studies suggests that diabetes, particularly when poorly controlled, may be associated with an increased risk of peri-implant inflammation and marginal bone loss.^{32–36} The biological basis of this association includes chronic inflammation, altered immune defense, oxidative stress, impaired tissue repair, and disturbances in bone remodeling.^{32–36} At the same time, the magnitude of the association varies among studies, indicating that diabetes should not be considered an absolute contraindication to implant treatment. Glycemic control, oral hygiene, periodontal status, smoking, and other patient-related factors may substantially influence clinical outcomes.

The management of implant patients with diabetes has therefore shifted from considering diabetes itself as a contraindication toward identifying and controlling modifiable risk factors. Appropriate patient selection, optimization of glycemic control, periodontal treatment, maintenance of oral hygiene, careful surgical planning,

and regular supportive follow-up are important components of successful implant therapy.^{26, 29, 32–36}

In addition to patient-related factors, implant surface characteristics may influence the biological response to implantation. Modern surface modification techniques, including sandblasted large-grit acid-etched surfaces, hydroxyapatite and calcium-phosphate coatings, anodic oxidation, and other surface treatments, have been developed to improve early bone response and osseointegration.^{37–39} These approaches may be particularly relevant in patients with compromised bone-healing capacity.

Ultraviolet photofunctionalization is one of the surface modification approaches that has received increasing attention. Ultraviolet treatment can alter the physicochemical properties of titanium surfaces, increasing surface hydrophilicity and improving the interaction between the implant surface and biological tissues. Experimental and clinical studies have reported enhanced osteoblast attachment and improved early osseointegration following photofunctionalization, together with potential reductions in bacterial adhesion.^{40–44} Such approaches may have particular relevance for patients with diabetes, although further clinical evidence is required to determine their long-term benefits in this population.

Diabetes also affects skeletal metabolism and bone quality. Alterations in bone formation and remodeling have been described in patients with diabetes mellitus and may influence the biological environment surrounding dental implants.^{45–48} Biochemical markers of bone turnover, including osteocalcin and beta-CrossLaps, have attracted interest as potential indicators of bone metabolic activity. Recent clinical research involving patients with type 2 diabetes and dental implants suggests that assessment of bone metabolism markers may provide additional information regarding the biological processes associated with implant therapy.⁴⁹

Vitamin D represents another potentially relevant factor in the management of diabetic patients undergoing implant treatment. Vitamin D participates in calcium and phosphate homeostasis, bone mineralization, immune regulation, and bone remodeling. Several studies have investigated the relationship between vitamin D status and implant osseointegration and have suggested that vitamin D deficiency may be associated with impaired bone healing and an increased risk of early implant complications.^{50–53} Clinical investigations have also explored whether correction of vitamin D deficiency before implant placement may improve the biological

conditions required for osseointegration.^{54–57} Although the available evidence remains heterogeneous, assessment of vitamin D status may be considered as part of a broader evaluation of patients with diabetes who are planned for implant therapy.

The provision of surgical dental care to patients with type 2 diabetes therefore requires an integrated approach that considers both oral and systemic factors. Assessment of glycemic control, medical history, medication use, periodontal status, oral hygiene, smoking status, and potential metabolic risk factors should form part of treatment planning.^{58–63} Close communication between dental professionals and the physicians responsible for the patient's diabetes management may facilitate safer surgical care and reduce the risk of postoperative complications. Long-term professional maintenance is also particularly important for patients receiving implant-supported prostheses.⁶⁴

Taken together, the available literature demonstrates that diabetes mellitus can influence several interconnected aspects of surgical dental care, from periodontal inflammation and extraction-socket healing to bone metabolism, osseointegration, peri-implant disease, and long-term implant maintenance. However, the evidence is distributed across different clinical and biological fields, and the factors influencing treatment outcomes are not uniformly characterized. A comprehensive mapping of the available evidence is therefore warranted.

The aim of this scoping review was to map and synthesize the available evidence regarding the organizational and methodological principles of providing surgical dental care to patients with type 2 diabetes mellitus, with particular emphasis on oral manifestations, wound healing and alveolar osteitis after tooth extraction, dental implant therapy and osseointegration, peri-implant diseases, bone metabolism, vitamin D status, implant surface modification, and preventive and supportive management strategies.

2. METHODOLOGY

2.1 Search Strategy

A comprehensive literature search was conducted to identify published evidence concerning the organization and provision of surgical dental care for patients with type 2 diabetes mellitus. The search was performed in PubMed, MEDLINE, Scopus, Web of Science, and Google Scholar.

The search strategy was developed around the principal concepts addressed in this review, including diabetes mellitus, type 2 diabetes mellitus, oral manifestations, glycemic control, dental care, surgical dental care, wound healing, tooth extraction, alveolar osteitis, periodontal disease, dental implants, osseointegration, peri-

implantitis, bone metabolism, vitamin D, and implant surface modification.

The following keywords and combinations of keywords were used:

- Diabetes mellitus
- Type 2 diabetes mellitus
- Oral manifestations
- Dental care
- Surgical dental care
- Tooth extraction
- Wound healing
- Alveolar osteitis
- Periodontal disease
- Dental implants
- Dental implantation
- Osseointegration
- Peri-implantitis
- Bone metabolism
- Vitamin D
- Glycemic control

The search terms were combined using Boolean operators (AND and OR), where appropriate, to identify studies addressing the principal clinical and biological aspects of surgical dental care in patients with type 2 diabetes mellitus.

Additional relevant studies were identified by manually reviewing the reference lists of eligible publications and relevant systematic and narrative review articles. Reference-list screening was performed to identify potentially relevant publications that may not have been retrieved through the electronic database searches.

The search process was designed to identify evidence concerning both clinical outcomes and the organizational principles of surgical dental management, including preoperative assessment, glycemic control, periodontal management, postoperative wound care, implant therapy, peri-implant disease prevention, and long-term supportive maintenance.

2.2 Eligibility Criteria and Study Selection

Studies were considered eligible when they investigated one or more aspects of dental or surgical dental care in patients with diabetes mellitus, with particular emphasis on type 2 diabetes mellitus. The review included human studies addressing oral manifestations of diabetes, periodontal disease, wound healing following dental procedures, tooth extraction and alveolar osteitis, dental implant therapy, osseointegration, peri-implant diseases, bone metabolism, vitamin D status, implant surface modification, or preventive and supportive dental management.

The review considered randomized controlled trials, clinical trials, cohort studies, case-control studies, cross-sectional studies, observational studies, and relevant systematic or narrative reviews when they provided information directly relevant to the objectives of the review.

Studies were excluded when they were unrelated to dental care in patients with diabetes mellitus, were conducted exclusively in animals or in vitro, or were conference abstracts, letters to the editor, book chapters, or duplicate publications. Case reports were also excluded from the main evidence synthesis.

The titles and abstracts of the identified publications were independently screened by two reviewers. Potentially relevant articles were subsequently assessed in full text against the predefined eligibility criteria. Disagreements regarding study eligibility were resolved through discussion and consensus.

The study selection process was documented according to the principles of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR).

The numbers of identified, screened, assessed, excluded, and included publications are presented in the PRISMA-ScR flow diagram (Figure 1).

2.3 Data Charting and Extraction

Data from the included publications were independently extracted by two reviewers using a standardized data extraction form.

The information collected included:

- first author and year of publication;
- study design;
- study population;
- sample characteristics;
- diabetes-related characteristics;
- duration and/or control of diabetes where reported;
- dental intervention or clinical condition investigated;
- principal clinical outcomes;
- biological or biochemical outcomes;
- implant-related outcomes where applicable; and
- major findings relevant to surgical dental care.

Particular attention was given to evidence concerning oral manifestations, periodontal disease, postoperative wound healing, alveolar osteitis, dental implant survival, osseointegration, peri-implantitis, bone metabolism, vitamin D status, implant surface modification, and preventive management.

Where relevant, information regarding glycemic control, HbA1c levels, duration of diabetes, periodontal status, oral hygiene, smoking, and other patient-related factors potentially influencing dental treatment outcomes was also recorded.

For implant-related studies, information concerning implant survival, implant failure, marginal bone loss,

peri-implant inflammation, osseointegration, implant surface characteristics, and other relevant clinical or radiographic outcomes was extracted.

For studies addressing bone metabolism and vitamin D, information concerning biochemical markers, vitamin D status, supplementation, bone turnover, osseointegration, and implant-related outcomes was recorded where available.

2.4 Evidence Characterization

As this study was designed as a scoping review, the included evidence was characterized according to study design, clinical topic, patient population, intervention or exposure, and principal outcomes.

The purpose of this process was to identify and map the breadth and characteristics of the available evidence rather than to calculate a pooled effect estimate or perform a quantitative meta-analysis.

The evidence was organized into the following major thematic areas:

- Oral manifestations of diabetes mellitus;
- Periodontal disease and inflammatory complications;
- Wound healing and complications following tooth extraction;
- Alveolar osteitis;
- Dental implant therapy and osseointegration;
- Peri-implantitis and peri-implant diseases;
- Bone metabolism and biochemical markers;
- Vitamin D and implant-related outcomes;
- Implant surface modification; and
- Preventive and supportive dental management.

The thematic organization was used to facilitate synthesis of the available evidence and to identify areas in which diabetes mellitus may influence surgical dental outcomes.

Because the primary objective of a scoping review is to map the available evidence rather than to estimate a pooled treatment effect, no meta-analysis was performed.

2.5 Data Synthesis

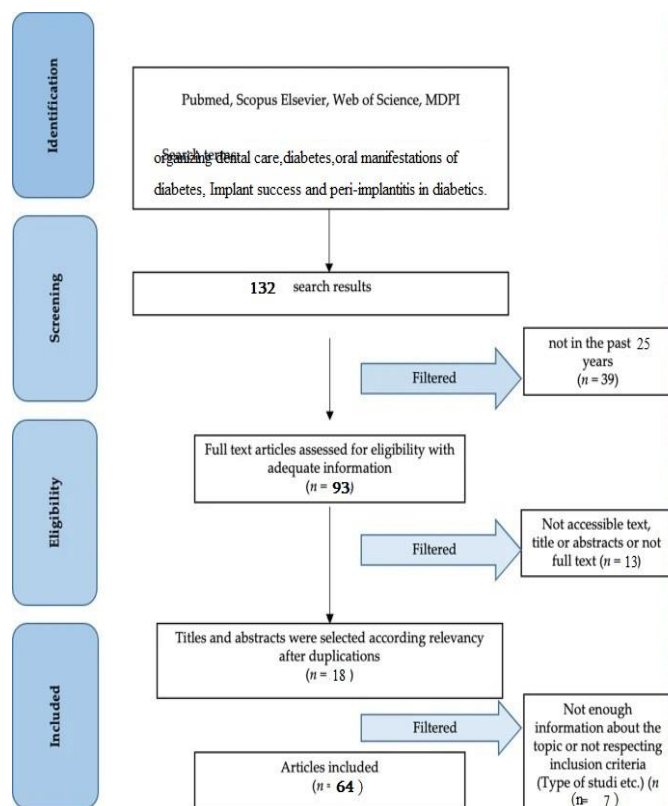
The findings of the included studies were synthesized narratively and organized according to the major clinical and methodological themes identified during the review process.

The synthesis focused on the relationship between diabetes mellitus and oral health, the effects of glycemic control on surgical dental outcomes, postoperative wound healing, tooth extraction and alveolar osteitis, implant therapy and osseointegration, peri-implant diseases, bone metabolism, vitamin D status, implant surface modification, and preventive and supportive management.

The evidence was compared qualitatively across the different study designs and clinical populations, with

particular attention to consistent findings, areas of heterogeneity, and clinically relevant factors that may modify treatment outcomes.

The review process and reporting were guided by the principles of the PRISMA-ScR framework for scoping reviews. The study selection process is presented in the PRISMA-ScR flow diagram (Figure 1).



3.2 Oral Manifestations of Diabetes Mellitus

A total of 132 publications were identified, and 64 articles were included in the final evidence synthesis after application of the predefined eligibility criteria.

No quantitative pooling of effect estimates was performed because of the heterogeneity of study designs, populations, interventions, clinical outcomes, and definitions of glycemic control and implant-related outcomes.

3. RESULTS

3.1 Search Results

A total of 132 publications were identified through the electronic database search and additional identification procedures. Following removal of duplicate records and screening of titles and abstracts, potentially relevant publications were assessed for eligibility in full text. After application of the predefined inclusion and exclusion criteria, 64 articles were included in the final evidence synthesis.

The included publications covered a broad range of clinical and biological aspects of surgical dental care in patients with diabetes mellitus, including oral

manifestations, periodontal disease, postoperative wound healing, tooth extraction and alveolar osteitis, dental implant therapy, osseointegration, peri-implant diseases, bone metabolism, vitamin D, implant surface modification, and preventive and supportive management. The overall study identification, screening, eligibility assessment, and inclusion process is presented according to the PRISMA-ScR framework in Figure 1.

3.2 Oral Manifestations of Diabetes Mellitus

The reviewed literature demonstrated that patients with diabetes mellitus may experience a broad range of oral manifestations and complications. These include periodontal disease, dental caries, salivary gland dysfunction, xerostomia, taste disturbances, fungal and bacterial infections, delayed wound healing, and tooth loss. The main oral manifestations identified in patients with type 2 diabetes mellitus and their relevance to surgical dental care are presented in

Figure 2 and summarized in Table 1.

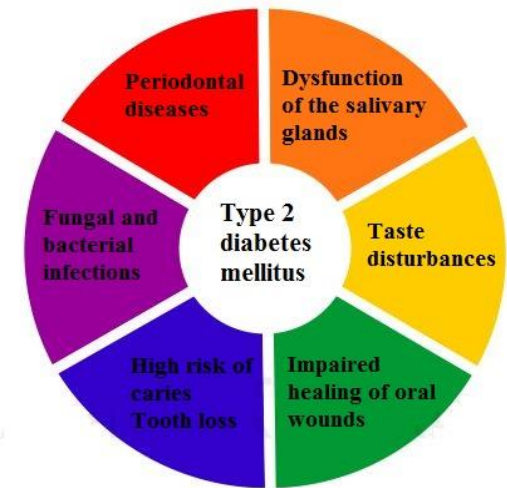


Figure 2. Oral manifestations in patients with diabetes mellitus

Table 1. Oral manifestations of type 2 diabetes mellitus

Oral manifestation	Main characteristics	Surgical dental relevance
Periodontal disease	Chronic inflammatory periodontal destruction	Increased risk of periodontal and peri-implant complications
Xerostomia	Reduced salivary flow	Increased caries and infection risk
Delayed wound healing	Impaired tissue repair	Important after extraction and oral surgical procedures
Candida infection	Increased susceptibility to fungal infection	Requires appropriate infection prevention and management
Tooth loss	Frequently associated with periodontal disease and other oral complications	May require implant-supported or other prosthetic rehabilitation

Periodontal disease was consistently identified as one of the most important oral complications associated with diabetes mellitus. Patients with diabetes may experience more pronounced periodontal tissue destruction because of impaired neutrophil function, persistent low-grade inflammation, vascular alterations, and dysregulation of the host immune response.

These mechanisms may reduce the ability of periodontal tissues to respond adequately to bacterial challenge and may contribute to more severe and progressive periodontal damage. Patients with diabetes mellitus and periodontitis have been reported to exhibit increased levels of inflammatory mediators, including tumor necrosis factor alpha (TNF-α), interleukin-1 beta (IL-1β), and prostaglandin E2. Increased inflammatory activity promotes osteoclast activation and contributes to progressive destruction of periodontal supporting tissues. At the same time, chronic periodontal inflammation may adversely affect glycemic control, creating a bidirectional relationship in which diabetes increases the severity of periodontal disease while periodontal inflammation may further complicate metabolic control.

The reviewed evidence therefore supports the consideration of periodontal treatment in diabetic patients not simply as a local dental intervention but as an important component of comprehensive disease management. Appropriate periodontal therapy, effective oral hygiene, regular professional maintenance, and continued periodontal monitoring may help reduce oral inflammatory burden and support better overall health outcomes.

3.3 Wound Healing Disturbances

The literature demonstrated that persistent hyperglycemia adversely affects several stages of the normal wound-healing process. Diabetes-related alterations in angiogenesis, collagen synthesis, fibroblast proliferation, immune function, and extracellular matrix remodeling can delay the repair of oral soft tissues and impair bone regeneration. Reduced vascularization, compromised local blood flow, altered growth-factor activity, and increased apoptosis of gingival fibroblasts collectively contribute to delayed connective tissue repair and prolonged postoperative recovery. Following

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dental surgical procedures, these abnormalities may result in delayed epithelialization, increased susceptibility to infection, and impaired healing of both soft and hard tissues. The extraction socket is particularly vulnerable because successful healing requires an adequate inflammatory response, formation and stabilization of a blood clot, angiogenesis, granulation tissue formation, and subsequent bone remodeling. Disturbances in these processes may increase the likelihood of postoperative complications in patients with diabetes mellitus.

Alveolar osteitis is among the clinically important postoperative complications reported after tooth extraction in diabetic patients. Delayed healing of the extraction socket, impaired angiogenesis, altered immune defense, and increased bacterial colonization may contribute to its development. The condition may cause substantial postoperative pain and delay normal socket healing, thereby increasing the need for additional local treatment and follow-up. Various local therapeutic approaches have been investigated to improve postoperative healing in diabetic patients. These include antiseptic protocols, specialized wound dressings, regenerative approaches, and laser-based treatment modalities. The principal mechanisms by which type 2 diabetes mellitus may impair oral wound healing, including impaired angiogenesis, altered immune responses, reduced fibroblast activity, and disturbed tissue repair, are illustrated in Figure 3.

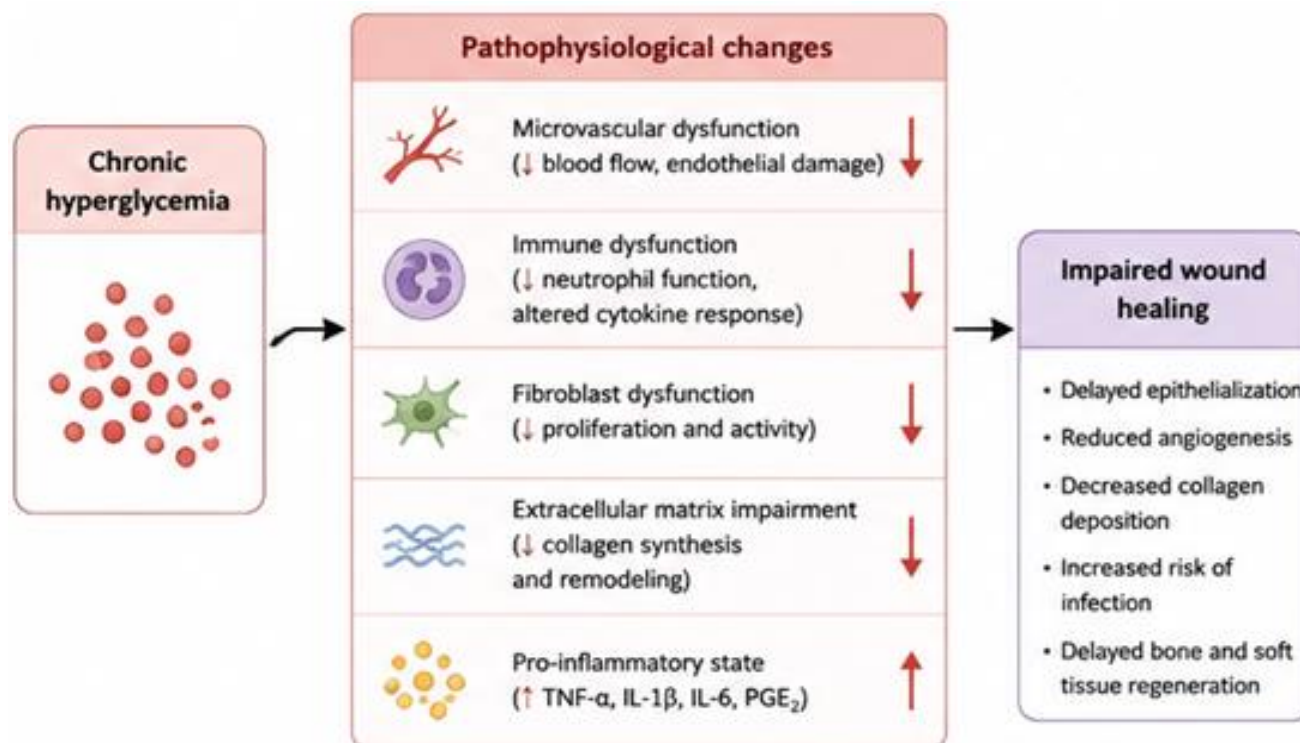


Figure 3. Mechanisms of impaired wound healing in patients with type 2 diabetes mellitus.

3.4 Dental Implant Osseointegration in Patients with Type 2 Diabetes Mellitus

Tooth loss in patients with diabetes mellitus may adversely affect nutrition, mastication, speech, and overall quality of life. Dental implantation provides an important option for prosthetic rehabilitation and functional restoration. However, the biological environment associated with prolonged hyperglycemia may negatively influence bone healing, osseointegration, implant stability, and long-term implant survival.

Persistent hyperglycemia may suppress osteoblastic activity while increasing osteoclastic activity, alter calcium and phosphorus metabolism, reduce collagen synthesis, and interfere with normal bone remodeling. These effects are accompanied by diabetes-related molecular and cellular changes, including increased oxidative stress, elevated production of pro-inflammatory cytokines, endothelial dysfunction, and accumulation of advanced glycation end products (AGEs).

The combined effects of these mechanisms may compromise the biological response of bone tissue to the implant surface. The interaction between hyperglycemia, inflammation, impaired bone metabolism, and implant healing is illustrated in Figure 4.

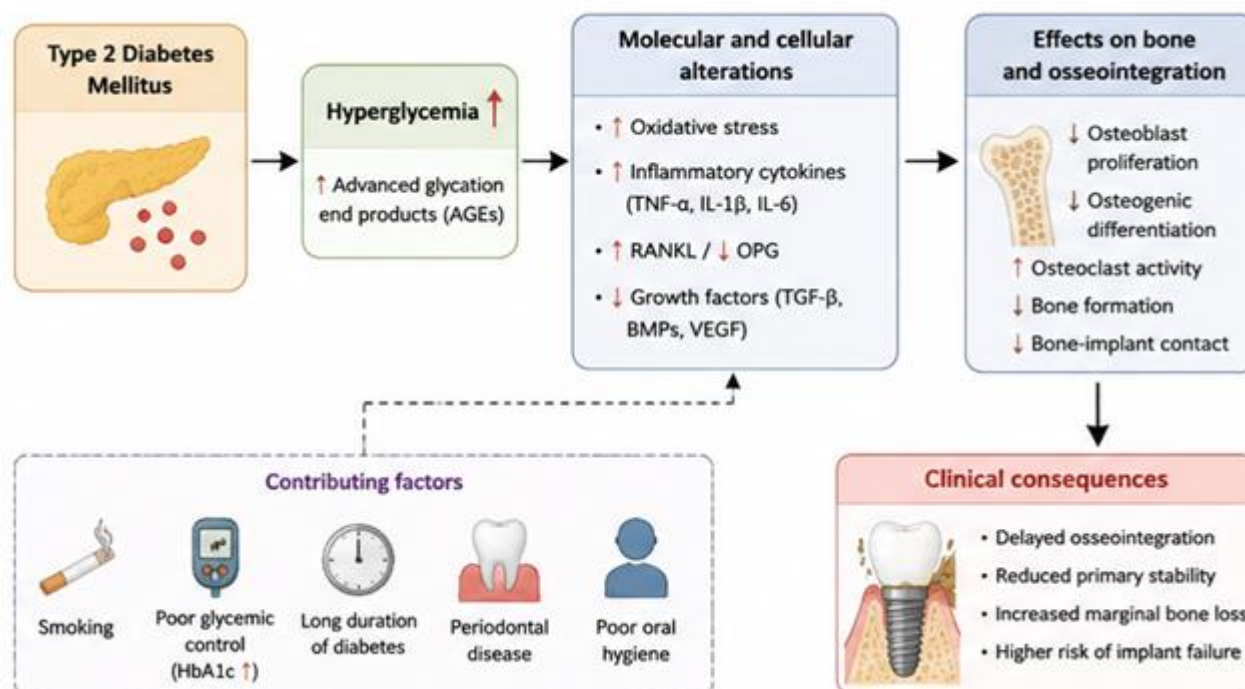


Figure 4. Effects of type 2 diabetes mellitus on osseointegration and implant success.

These changes may reduce bone-implant contact, delay the early stages of osseointegration, compromise implant stability, and increase the likelihood of implant failure in susceptible patients.

Several studies have demonstrated that optimization of implant surface characteristics may improve the biological response to implants in diabetic patients.

Surface modification techniques such as plasma-sprayed titanium coatings, hydroxyapatite deposition, calcium phosphate coatings, sandblasted large-grit acid-etched (SLA) surfaces, and anodic oxidation have been investigated as approaches to enhance bone integration. These technologies are designed to modify surface roughness, chemical composition, surface energy, and biological interactions at the bone-implant interface. Among more recent approaches, ultraviolet (UV) photofunctionalization has attracted particular interest. UV treatment modifies the physicochemical characteristics of titanium surfaces and converts relatively hydrophobic implant surfaces into highly hydrophilic or superhydrophilic surfaces.

This modification may improve protein adsorption, osteoblast attachment, cellular activity, and early bone formation around the implant. In addition to its effects on cellular attachment and osseointegration, UV photofunctionalization may reduce bacterial adhesion to titanium surfaces. This property may be particularly relevant in patients with diabetes mellitus because impaired immune responses and altered tissue healing can increase susceptibility to peri-implant infection.

Thus, optimization of implant surface characteristics represents a potentially useful component of implant treatment in appropriately selected diabetic patients.

3.5 Peri-implantitis and Diabetes Mellitus

The relationship between diabetes mellitus and peri-implantitis has been examined in numerous clinical studies and systematic reviews.

Although the magnitude of the association varies among studies, the available evidence generally suggests that diabetes mellitus, particularly when glycemic control is inadequate, may increase susceptibility to peri-implant inflammatory complications.

Persistent hyperglycemia may contribute to chronic systemic and local inflammation, impaired immune function, increased oxidative stress, vascular dysfunction, and alterations in bone metabolism. These changes can affect peri-implant tissue homeostasis and may interfere with the ability of the tissues to control bacterial biofilm. In the presence of dental biofilm, an altered inflammatory response may promote soft-tissue inflammation, progressive marginal bone loss, and impaired bone remodeling around the implant.

The principal mechanisms underlying the development of peri-implantitis in patients with type 2 diabetes mellitus are illustrated in Figure 5.

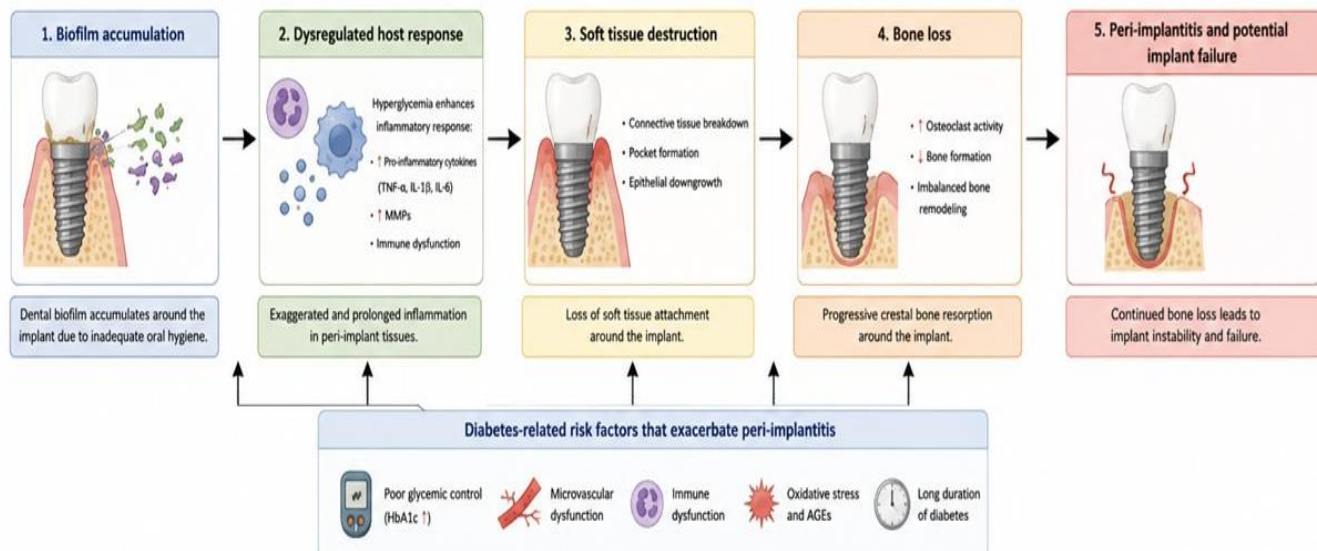


Figure 5. Pathogenesis of peri-implantitis in patients with type 2 diabetes mellitus.

A systematic review and meta-analysis reported an increased risk of peri-implantitis among patients with diabetes mellitus compared with non-diabetic individuals, whereas a significant association between diabetes and peri-implant mucositis was not consistently demonstrated³⁴. These findings suggest that the influence of diabetes may become particularly evident once inflammatory disease progresses from the peri-implant mucosa to the supporting peri-implant tissues. Poor glycemic control appears to be an important factor in this process. Elevated HbA1c levels have been associated with less favorable peri-implant clinical and radiographic findings, including increased probing depth, bleeding on probing, and crestal bone loss^{32,34}. These observations support the importance of metabolic control as part of the long-term management of diabetic patients receiving implant therapy. Several patient-related and clinical characteristics may influence implant outcomes in patients with diabetes mellitus. These include glycemic control, smoking, periodontal status, oral hygiene, and general metabolic control. The influence of diabetes duration is less clear, and the available evidence does not establish disease duration as an independent predictor of implant failure²⁶. The principal clinical and disease-related factors potentially affecting implant outcomes in patients with diabetes mellitus are summarized in Table 2.

Table 2. Risk factors and clinical characteristics influencing implant outcomes in patients with diabetes mellitus.

Risk factor / clinical characteristic	Evidence-based effect on implant outcomes	Reference(s)
Poor glycemic control (elevated HbA1c)	Associated with poorer peri-implant clinical and radiographic parameters, including increased probing depth, bleeding on probing, and crestal bone loss; may increase susceptibility to peri-implant inflammatory complications	[32,34]
Smoking	May adversely affect osseointegration and peri-implant tissue health and may increase the risk of implant complications	[34]
Diabetes mellitus / inadequate metabolic control	Diabetes mellitus is associated with a higher overall risk of implant failure and greater marginal bone loss in meta-analytic evidence, although outcomes may be more favorable when glycemic control is maintained	[26,29]
Long duration of diabetes	Current evidence is insufficient to	[26]

	establish diabetes duration as an independent predictor of implant failure or peri-implant complications	
History of periodontal disease	May increase susceptibility to peri-implant inflammatory complications and peri-implantitis, particularly in patients with diabetes	[33,34,36]
Poor oral hygiene / inadequate plaque control	Promotes dental biofilm accumulation and may contribute to peri-implant mucosal inflammation and peri-implantitis	[34,36]
Peri-implant inflammatory disease	May lead to progressive marginal bone loss, impaired implant stability, and, in advanced cases, implant failure	[32,34,36]

Despite the increased susceptibility to peri-implant complications observed in some diabetic patients, diabetes mellitus should not be considered an absolute contraindication to dental implant therapy.

The available evidence indicates that implant treatment can be performed successfully when appropriate precautions are implemented, particularly when glycemic control is adequate and oral hygiene and periodontal health are maintained^{26,29}.

The systematic review by Wagner et al. reported that poorly controlled diabetes was associated with more frequent peri-implantitis and greater long-term implant loss, whereas patients with controlled diabetes demonstrated outcomes that were closer to those observed in individuals without diabetes²⁶.

These findings emphasize the importance of individualized patient selection, metabolic assessment, periodontal stabilization, appropriate surgical planning, and long-term supportive maintenance.

3.6 Bone Metabolism Markers and Vitamin D

Diabetes mellitus is associated with clinically relevant alterations in bone metabolism.

Chronic hyperglycemia may affect osteoblast and osteoclast activity, bone turnover, mineral metabolism, and the quality of the bone surrounding dental implants.

These alterations may be particularly important during the early stages of osseointegration, when active bone formation and remodeling are required to establish a stable bone-implant interface.

Biochemical markers of bone turnover, including osteocalcin and β -CrossLaps, have therefore attracted attention in the assessment of bone metabolism in patients with diabetes mellitus.

Reduced levels of osteocalcin and β -CrossLaps have been reported in diabetic patients and may be related to alterations in glucose metabolism. Assessment of these markers may provide additional information regarding bone metabolic activity and may potentially have prognostic value when evaluating

osseointegration and implant outcomes⁴⁹.

Recent clinical evidence has also highlighted the possible relevance of bone metabolism markers in patients with type 2 diabetes mellitus receiving dental implants.

The relationship between systemic metabolic alterations, bone turnover, and implant healing suggests that biochemical assessment may complement conventional clinical and radiographic evaluation in selected patients.

Vitamin D is another factor of potential importance in this context.

Vitamin D plays a central role in calcium and phosphorus homeostasis, bone mineralization, osteoblast function, and regulation of inflammatory responses.

Vitamin D deficiency is frequently reported in patients with type 2 diabetes mellitus and may therefore represent an additional factor that could negatively influence bone healing and implant integration.

Several studies have investigated the relationship between vitamin D status and dental implant outcomes^{50–57}.

Experimental and clinical evidence suggests that adequate vitamin D availability may support bone formation and osseointegration, whereas severe deficiency may be associated with impaired bone healing and a potentially greater risk of early implant complications.

Vitamin D supplementation before implant placement has therefore been proposed as a possible strategy in patients with documented deficiency.

Some studies have reported improved bone formation and implant healing following correction of vitamin D deficiency, although the available evidence remains heterogeneous and does not support routine supplementation in all patients irrespective of their vitamin D status.

Consequently, assessment of vitamin D status and correction of clinically significant deficiency may be considered as part of individualized preoperative assessment, particularly in diabetic patients with additional risk factors for impaired bone healing.

3.7 Preventive Dental Management

The reviewed evidence indicates that successful surgical dental care in patients with type 2 diabetes mellitus

requires an individualized and preventive approach. Treatment planning should take into consideration the patient's degree of glycemic control, medical history, diabetes-related systemic complications, current medications, periodontal condition, oral hygiene, and previous history of postoperative complications.

Before surgical dental procedures, the clinician should assess the patient's metabolic status and determine whether additional medical consultation is necessary. Particular attention should be given to patients with poorly controlled diabetes, significant systemic complications, active periodontal disease, or a history of impaired wound healing.

Preventive management should include regular dental examinations, professional oral hygiene procedures, appropriate periodontal maintenance, monitoring of glycemic control, reduction of treatment-related stress, and communication with the patient's physician when indicated. In patients undergoing implant therapy, prevention should continue after implant placement through regular clinical assessment, professional maintenance, monitoring of peri-implant tissues, and reinforcement of individualized oral hygiene measures. Long-term supportive care is particularly important because the risk of peri-implant inflammation does not end after successful osseointegration. Maintenance of adequate plaque control and metabolic stability may reduce the likelihood of peri-implant complications and support the long-term function of dental implants^{26,29,32–36,64}.

The principal elements of an individualized preventive and supportive management approach for surgical dental care in patients with type 2 diabetes mellitus are summarized in Figure 6.

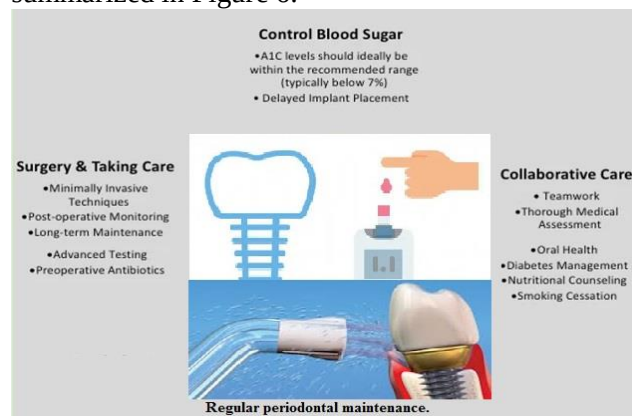


Figure 6. Integrated preventive and supportive management approach for surgical dental care in patients with type 2 diabetes mellitus.

4. DISCUSSION

This scoping review demonstrates that type 2 diabetes mellitus has a substantial influence on the oral environment and on the outcomes of surgical dental treatment. The available literature indicates that persistent hyperglycemia affects several biological

processes that are essential for maintaining oral tissue health and for successful recovery after dental procedures. In particular, diabetes mellitus is associated with alterations in immune function, microvascular circulation, inflammatory responses, collagen metabolism, wound repair, and bone remodeling. These systemic and local changes may explain why patients with diabetes are more susceptible to periodontal disease, delayed healing after tooth extraction, postoperative complications, peri-implant inflammation, and impaired osseointegration^{6–11,15–19,30,31,45–48}.

One of the most consistently reported findings in the reviewed literature is the close relationship between diabetes mellitus and periodontal disease. Periodontal disease is among the most common oral complications observed in patients with diabetes and appears to be influenced by both the duration and degree of metabolic control. Diabetes may impair neutrophil function, alter the host inflammatory response, and promote vascular and connective tissue changes within the periodontium^{15–18}. At the same time, persistent periodontal inflammation may contribute to deterioration of glycemic control, supporting the well-established bidirectional relationship between diabetes and periodontal disease^{15–17}. Increased production of inflammatory mediators, including tumor necrosis factor alpha, interleukin-1 beta, and prostaglandin E2, may stimulate osteoclastic activity and contribute to progressive periodontal tissue destruction^{18,19}.

These findings indicate that periodontal assessment and treatment should form an integral part of the overall dental management of patients with type 2 diabetes rather than being considered an isolated dental issue. The findings concerning oral surgery are also clinically important. Patients with diabetes may experience delayed healing following tooth extraction because hyperglycemia interferes with angiogenesis, fibroblast proliferation, collagen synthesis, epithelialization, and immune defense^{20–23}. Impaired vascularization and altered inflammatory responses may prolong the inflammatory phase of healing and interfere with normal regeneration of the extraction socket. These mechanisms may increase susceptibility to postoperative infection and other healing complications. The reviewed evidence therefore supports careful preoperative assessment and postoperative monitoring of diabetic patients undergoing dental extraction. Particular attention should be given to patients with inadequate metabolic control or other factors that may further compromise healing. Alveolar osteitis represents a clinically relevant postoperative complication in this population. The development of this condition may be influenced by impaired tissue repair, altered local vascularization, reduced host defense, and increased microbial activity within the extraction socket^{21–24}. Recent work addressing regenerative approaches to the management of alveolar osteitis in patients with type 2

diabetes further emphasizes the need for individualized postoperative protocols and appropriate local management²⁴. Thus, prevention of postoperative complications should begin before surgery and continue throughout the healing period rather than being limited to treatment after complications have developed. The literature reviewed in this scoping review also supports the use of dental implants as an important option for rehabilitation of patients with type 2 diabetes mellitus. Tooth loss associated with periodontal disease and other oral complications can adversely affect mastication, nutrition, and quality of life, making implant-supported rehabilitation clinically valuable^{25–29}.

However, diabetes mellitus should be considered an important modifying factor when planning implant treatment. A systematic review by Wagner et al. demonstrated that diabetes, particularly when poorly controlled, may be associated with less favorable implant-related outcomes, while acceptable results can be achieved in appropriately selected and adequately controlled patients²⁶. Other studies have similarly indicated that implant therapy should not be regarded as contraindicated solely because a patient has diabetes mellitus^{27–29}. The biological basis for these findings is closely related to the effects of hyperglycemia on bone metabolism and osseointegration. Persistent hyperglycemia may suppress osteoblastic activity, increase osteoclastic bone resorption, interfere with collagen formation, and disturb normal calcium and phosphorus metabolism^{30,31,45–48}. Diabetes-associated oxidative stress, chronic inflammation, and accumulation of advanced glycation end products may further impair bone remodeling and the formation of a stable bone-implant interface^{30,31,45}. Consequently, inadequate metabolic control may delay osseointegration, reduce implant stability, and increase the possibility of implant-related complications.

The relationship between diabetes mellitus and peri-implant diseases is another important finding of this review. Evidence from systematic reviews and meta-analyses indicates that diabetes mellitus and hyperglycemia may be associated with an increased risk of peri-implantitis, although the strength of this association varies between individual studies^{32–36}. Poor glycemic control appears to be particularly important, as elevated glycated hemoglobin levels have been associated with less favorable peri-implant clinical and radiographic parameters, including increased probing depth, bleeding on probing, and crestal bone loss^{32,34}. Hyperglycemia may promote chronic inflammation, impair immune defense, increase oxidative stress, and interfere with bone

remodeling, while dental biofilm may further stimulate an altered inflammatory response in susceptible patients^{32–36}. Several additional factors should be considered when assessing the risk of peri-implant complications in patients with diabetes. Smoking, periodontal status, oral hygiene, glycemic control, and general metabolic status may all influence treatment outcomes^{26,29,34–36}. A previous history of periodontal disease is particularly relevant because periodontal inflammation and inadequate plaque control may increase the risk of peri-implant inflammatory disease. In contrast, the available evidence is less conclusive regarding the independent influence of the duration of diabetes on implant failure²⁶. Therefore, clinical decision-making should be based on an overall assessment of the patient's metabolic and oral condition rather than on the diagnosis of diabetes alone. An additional area of interest identified in this scoping review is the modification of implant surfaces. Contemporary implant research has investigated several approaches intended to improve bone formation and implant integration, including titanium surface modification, hydroxyapatite and calcium phosphate coatings, sandblasted large-grit acid-etched surfaces, anodic oxidation, and other surface treatments^{37–39}. These approaches are designed to improve the interaction between the implant surface and surrounding biological tissues and may be particularly relevant in patients in whom bone healing is compromised.

Ultraviolet photofunctionalization represents a further development in this field. Studies have reported that ultraviolet treatment can alter the physicochemical properties of titanium surfaces, increase surface hydrophilicity, enhance osteoblast attachment, and promote early osseointegration^{40–44}. The potential reduction in bacterial adhesion is also of interest in diabetic patients because impaired immune responses and altered tissue healing may increase susceptibility to peri-implant infection. Although these technologies are promising, their clinical effectiveness specifically in patients with type 2 diabetes mellitus requires further long-term investigation.

The findings concerning bone metabolism provide another potentially useful direction for individualized implant management. Diabetes mellitus may alter bone turnover and the activity of bone-forming and bone-resorbing cells, with changes in biochemical markers such as osteocalcin and beta-CrossLaps reported in diabetic populations^{45–48}. Recent clinical research has also investigated bone metabolism markers in patients with type 2 diabetes receiving dental implants, suggesting that such biomarkers may provide additional information regarding bone remodeling and the biological response to implant treatment⁴⁹.

However, the clinical application of these markers as

routine predictors of implant success remains insufficiently established and requires further prospective research. Vitamin D may also have an important role in the management of diabetic patients undergoing implant therapy. Vitamin D contributes to calcium and phosphorus homeostasis, bone mineralization, immune regulation, and bone remodeling⁵⁰⁻⁵³.

Several studies have investigated the relationship between vitamin D status and implant healing, and some have suggested that correction of vitamin D deficiency may support bone formation and osseointegration⁵⁰⁻⁵⁵. The available evidence therefore provides a rationale for assessing vitamin D status in selected patients, particularly when deficiency is suspected or when additional risk factors for impaired bone healing are present. Nevertheless, vitamin D supplementation should be considered an adjunctive measure rather than a substitute for adequate glycemic control and appropriate surgical and periodontal management. Evidence concerning the broader metabolic effects of vitamin D supplementation remains heterogeneous^{56,57}. From an organizational and methodological perspective, the reviewed evidence emphasizes that successful surgical dental care for patients with type 2 diabetes requires an individualized and multidisciplinary approach. Preoperative assessment should include evaluation of glycemic control, medical history, diabetes-related complications, current medication, periodontal condition, oral hygiene, and other relevant risk factors⁵⁸⁻⁶³. Dental treatment should be planned according to the patient's systemic condition, with appropriate preventive measures before and after surgical procedures. Long-term maintenance is particularly important for patients receiving dental implants because continued plaque control and professional monitoring may reduce the risk of peri-implant inflammatory complications⁶⁴.

The findings of this scoping review also demonstrate that diabetes mellitus should not be considered an absolute contraindication to surgical dental treatment or implant rehabilitation. Instead, the diagnosis should prompt more careful patient selection, assessment of metabolic control, prevention of infection, optimization of oral hygiene, periodontal management, and appropriate postoperative follow-up^{26,29,58-64}. When these principles are followed, satisfactory clinical outcomes can be achieved in many patients with type 2 diabetes mellitus. At the same time, several limitations of the available evidence should be recognized. The studies included in the literature vary considerably in design, patient characteristics, definitions of glycemic control, implant systems, follow-up periods, and clinical

outcome measures. This heterogeneity makes direct comparison between studies difficult. In addition, some aspects of surgical dental management in diabetic patients remain supported primarily by observational studies or limited clinical evidence. Further well-designed prospective studies with standardized definitions of glycemic control, peri-implant disease, bone turnover, and implant success are therefore needed. Overall, the evidence identified in this scoping review supports an integrated model of surgical dental care in patients with type 2 diabetes mellitus. Such an approach should combine metabolic assessment, prevention and treatment of periodontal disease, careful management of extraction wounds, individualized implant planning, attention to bone metabolism and vitamin D status where clinically appropriate, and long-term peri-implant maintenance. This integrated strategy may reduce complications and improve the predictability of surgical dental treatment in this growing patient population.

5. CONCLUSION

Patients with type 2 diabetes mellitus require individualized and multidisciplinary dental management because diabetes may influence oral health, wound healing, bone metabolism, osseointegration, and peri-implant tissue stability. The findings of this scoping review indicate that persistent hyperglycemia is an important factor contributing to periodontal inflammation, delayed healing after dental extraction, postoperative complications, impaired bone remodeling, and increased susceptibility to peri-implant diseases. Nevertheless, diabetes mellitus should not be regarded as an absolute contraindication to surgical dental treatment or dental implant therapy. Successful treatment is achievable when patients are appropriately selected and when glycemic control, periodontal health, oral hygiene, surgical planning, and postoperative maintenance are adequately addressed. Modern implant surface modification technologies may provide additional benefits for osseointegration, while assessment of bone metabolism and vitamin D status may contribute to more individualized treatment planning in selected patients. The evidence therefore supports a comprehensive organizational and methodological approach to surgical dental care in patients with type 2 diabetes mellitus. Such an approach should include preoperative medical and dental assessment, optimization of modifiable risk factors, prevention of postoperative complications, careful implant planning, professional maintenance, and long-term clinical monitoring.

Further prospective and long-term clinical studies are required to establish standardized protocols for surgical dental care, determine the predictive value of bone metabolism markers and vitamin D status, and clarify the long-term effects of glycemic control and implant surface

modification on implant survival and peri-implant health in patients with type 2 diabetes mellitus.

DECLARATIONS

Ethical Approval

Not applicable.

Competing Interests

The authors declare no conflict of interest.

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RESEARCH ARTICLE

COMPARATIVE CLINICAL EVALUATION AND HISTOPATHOLOGICAL ASSESSMENT OF ORAL MUCOSA IN CIGARETTE SMOKERS AND HEATED TOBACCO PRODUCT USERS

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Abstract

Background: Conventional cigarette smoking (CS) is a well-established risk factor for oral mucosal diseases, whereas the biological effects of heated tobacco products (HTPs) remain not fully understood. This study aimed to compare the clinical manifestations and histopathological characteristics of the oral mucosa in conventional CS and exclusive users of HTPs.

Methods: This cross-sectional comparative study included 83 tobacco users (47 conventional CS and 36 exclusive HTP users, all of whom had previously smoked conventional cigarettes) and 40 healthy nonsmoking controls. All participants underwent standardized oral clinical examination. For histopathological assessment, 20 participants were randomly selected from each tobacco-use group (20 CS and 20 HTP users), and incisional biopsies were obtained from oral mucosa in these participants. Histopathological evaluation was performed using hematoxylin-eosin and Van Gieson's picrofuchsin staining to assess epithelial architecture, inflammatory infiltration, vascular alterations, and connective tissue remodeling. Statistical analyses were conducted using IBM SPSS Statistics, with $p < 0.05$ considered statistically significant.

Results: Conventional CS exhibited significantly more frequent clinical oral lesions than HTP users, including diffuse erythema (21.3% vs. 5.6%), hyperkeratosis (12.8% vs. 0%), and leukoplakia (8.5% vs. 0%).

Histopathological examination demonstrated significantly higher rates of epithelial hyperkeratosis (60.0% vs. 15.0%), acanthosis (55.0% vs. 10.0%), epithelial atrophy (35.0% vs. 5.0%), chronic inflammatory infiltration (80.0% vs. 30.0%), vascular congestion (75.0% vs. 20.0%), stromal edema (50.0% vs. 15.0%), collagen disorganization (65.0% vs. 10.0%), and early fibrosis (45.0% vs. 5.0%) in cigarette smokers compared with HTP users (all $p < 0.05$). Mild epithelial dysplasia was identified only among cigarette smokers (20.0%). Histological architecture remained largely preserved in HTP users, although mild inflammatory and connective tissue changes were occasionally observed.

Conclusions: Conventional CS was associated with substantially greater clinical and histopathological alterations to the oral mucosa than HTP use. Nevertheless, HTPs were also associated with measurable epithelial and stromal alterations, indicating that they are not biologically harmless. Regular oral examination of all tobacco users is warranted for the early detection of tobacco-associated mucosal lesions, while complete tobacco cessation remains the most effective strategy for preserving oral health.

Keywords: cleft lip; pediatric craniofacial surgery; cheiloplasty; multidisciplinary treatment; nasoalveolar molding; virtual surgical planning; three-dimensional imaging

1. INTRODUCTION

Smoking remains one of the leading preventable causes of morbidity and mortality worldwide and continues to represent a major public health challenge. In addition to its well-established association with cardiovascular disease, chronic respiratory disorders, and malignancies, tobacco use exerts profound adverse effects on the oral cavity. Cigarette smoking (CS) is recognized as an important etiological factor in the development of oral mucosal lesions, periodontal disease, delayed wound healing, and oral squamous cell carcinoma through chronic exposure to carcinogens, oxidative stress, and persistent inflammation¹⁻³.

The oral mucosa is among the first tissues directly exposed to tobacco smoke and therefore undergoes continuous physical and chemical irritation². Long-term smoking induces a broad spectrum of clinical and microscopic alterations, including hyperkeratosis, epithelial hyperplasia, acanthosis, epithelial dysplasia, vascular congestion, inflammatory cell infiltration, and connective tissue remodeling. These histopathological changes may precede clinically detectable lesions and contribute to the development of potentially malignant disorders^{1, 2, 16, 17}.

In recent years, heated tobacco products (HTPs) have gained worldwide popularity as an alternative to conventional cigarettes. Unlike combustible cigarettes, HTPs heat processed tobacco without combustion, thereby reducing the formation of numerous toxic combustion products. Nevertheless, HTP aerosols still contain nicotine together with some potentially harmful chemicals capable of affecting oral tissues. Current evidence suggests that although HTPs may reduce exposure to some toxicants compared with conventional cigarettes, they cannot be considered harmless, and their long-term biological effects remain insufficiently characterized^{5, 6, 20, 23}.

Recent clinical investigations have reported differences in oral health status between cigarette smokers and HTP users. Conventional smokers generally demonstrate a higher prevalence of smoker's melanosis, nicotine stomatitis, periodontal inflammation, and oral mucosal lesions, whereas HTP users may exhibit milder clinical manifestations. However, microscopic alterations have also been described in users of alternative nicotine products, including epithelial hyperparakeratosis, acanthosis, chronic inflammatory infiltration, and stromal edema, indicating that these products are not biologically inert^{4, 7-10}.

Despite the growing number of studies evaluating the clinical effects of HTPs, direct comparative investigations of both the clinical manifestations and histopathological characteristics of the oral mucosa in CS and HTP users remain limited^{3, 7-9}. Histopathological assessment provides objective evidence of tissue alterations and allows the identification of early epithelial, vascular, and inflammatory alterations that may not yet be clinically apparent^{1, 11}. Therefore, comparative clinicopathological evaluation is essential for improving our understanding of the biological effects of different tobacco products on the oral mucosa and for guiding preventive and therapeutic strategies in dental practice.

The aim of the study was to compare the clinical manifestations and histopathological features of the oral mucosa in cigarette smokers and users of heated tobacco products.

MATERIAL AND METHODS

Study design and participants

This cross-sectional comparative study was conducted at the Scientific Educational Dental Center No. 1 of Yerevan State Medical University, Yerevan, Armenia, from November 2025 to August 2026.

A total of 83 participants aged 19–62 years were enrolled in the study. The study population consisted of 47 conventional cigarette smokers (CS) and 36 users of heated tobacco products (HTPs).

Participants were classified according to their current tobacco-use pattern. The conventional cigarette smoking (CS) group consisted of current cigarette smokers, whereas the HTP group consisted of participants who were currently using heated tobacco products exclusively and had completely switched from conventional cigarettes to HTPs (reported duration of exclusive HTP use ranging from 5 to 8 years before enrollment). Importantly, all participants in the HTP group had a previous history of conventional cigarette smoking, having smoked conventional cigarettes for approximately 4–6 years before switching to HTPs. The reported duration of current conventional cigarette smoking among CS participants ranged from 9 to 14 years.

Thus, the HTP group represented former conventional cigarette smokers who had transitioned to exclusive HTP use. The study group included 45 men (54.2%) and 38 women (45.8%), with a mean age of 35.0 ± 15.6 years (mean $\pm$ SD).

The control group comprised 40 healthy volunteers who had never smoked cigarettes or used HTPs. Their ages ranged from 20 to 68 years and included 23 men (57.5%) and 17 women (42.5%), with a mean age of 42.4 ± 15.5 years (mean $\pm$ SD).

All participants provided written informed consent prior to enrollment in the study.

Clinical examination

All participants underwent a comprehensive oral examination performed by the same investigator under standardized clinical conditions. Clinical assessment included a systematic examination of the lips, buccal mucosa, tongue, floor of the mouth, hard and soft palate, and gingival tissues¹².

Particular attention was paid to the color, surface texture, moisture, and consistency of the oral mucosa, as well as to the presence or absence of primary and secondary oral lesions. Clinical findings, including hyperkeratosis, leukoplakia, smoker's melanosis, erythema, erosions, ulcerations, traumatic lesions, and inflammatory changes, were recorded according to internationally accepted diagnostic criteria¹¹⁻¹³

Histopathological examination

For histopathological assessment, 20 participants were randomly selected from each tobacco-use group (20 conventional cigarette smokers and 20 exclusive HTP users). All selected participants underwent incisional biopsy of oral mucosa. Thus, the histopathological analysis was performed on a randomly selected subset of participants from each tobacco-use group and represents the characteristics of both clinically identified oral mucosal lesions, as well as from clinically normal oral mucosa in these participants. The findings should not be interpreted as a histological assessment of the entire oral mucosa of all study participants.

For histological reference, one archival specimen of clinically normal oral mucosa from a nonsmoking individual was examined. This specimen was used solely as a morphological reference for normal oral mucosal architecture and was not considered a participant-level histological control group. The clinical control group consisted of 40 healthy nonsmoking volunteers; however, histopathological biopsies were not obtained from these individuals. The corresponding image is shown in Figure 1. Tissue samples were fixed in 10% neutral buffered formalin,

dehydrated through graded alcohols, embedded in paraffin, and sectioned at a thickness of 4 μ m. Sections were routinely stained with hematoxylin-eosin for the evaluation of general tissue architecture, epithelial morphology, inflammatory cell infiltration, vascular alterations, and degenerative changes¹⁴. Additional sections were stained with Van Gieson's picrofuchsin stain to differentiate collagen fibers from other connective tissue elements and to assess connective tissue organization, stromal remodeling, and the degree of fibrosis. Histological examination was performed using a ZEISS Primo Star trinocular microscope (ZEISS Microscopy, Germany) at $\times 100$ and $\times 400$ magnifications. Digital microphotographs were obtained using a ZEISS Axiocam ERc 5s camera system (Carl ZEISS Microscopy, Germany). Histopathological evaluation was performed according to internationally accepted histological criteria and the recommendations of the WHO¹¹.

Statistical analysis

Statistical analyses were performed using IBM SPSS Statistics (IBM Corp., Armonk, NY, USA). Continuous variables are presented as mean $\pm$ standard deviation (SD), whereas categorical variables are expressed as frequencies and percentages. Comparisons between groups were performed using the Student's t-test or the Mann-Whitney U test, depending on data distribution. Categorical variables were analyzed using the chi-square (χ^2) test or Fisher's exact test, as appropriate. All statistical tests were two-tailed, and a p-value < 0.05 was considered statistically significant.

Ethical Considerations

This work was approved by the Ethical Committee at Yerevan State Medical University, done in compliance with the Helsinki Declaration, and written informed consent was obtained from the patients.

MATERIALS AND METHODS

Study design and setting

This cross-sectional comparative study was conducted at the Scientific Educational Dental Center No. 1 of Yerevan State Medical University, Yerevan, Armenia, between November 2025 and August 2026. The study was designed to compare clinical manifestations and histopathological characteristics of the oral mucosa among conventional cigarette smokers, exclusive heated tobacco product (HTP) users, and healthy nonsmoking controls.

Study participants

A total of 123 participants were included in the clinical component of the study: 47 conventional cigarette smokers (CS), 36 exclusive HTP users, and 40 healthy nonsmoking controls. Participants were 19–68 years of age.

The conventional cigarette smoking group comprised current cigarette smokers. The HTP group comprised participants who were currently using HTPs exclusively and who had previously smoked conventional cigarettes. According to the reported tobacco-use history, exclusive HTP use had continued for approximately 5–8 years before enrollment, whereas previous conventional cigarette smoking among HTP users had lasted approximately 4–6 years. Participants in the conventional cigarette smoking group reported current cigarette smoking for approximately 9–14 years.

Thus, the HTP group represented former conventional cigarette smokers who had subsequently transitioned to exclusive HTP use rather than tobacco-naïve HTP users. This distinction was considered when interpreting between-group differences.

The study population included 45 men (54.2%) and 38 women (45.8%) among the tobacco-use groups, with a mean age of 35.0 ± 15.6 years. The healthy control group consisted of 40 volunteers who reported never having smoked conventional cigarettes or used HTPs. The control group included 23 men (57.5%) and 17 women (42.5%), with a mean age of 42.4 ± 15.5 years.

All participants provided written informed consent before enrollment in the study.

Clinical oral examination

All participants underwent a comprehensive clinical examination of the oral cavity performed by the same investigator under standardized clinical conditions. The examination included systematic assessment of the lips and oral commissures, buccal mucosa, tongue, floor of the mouth, hard and soft palate, and gingival tissues.

The oral mucosa was assessed with particular attention to color, surface characteristics, moisture, consistency, and the presence or absence of clinically detectable pathological changes.

Clinical findings recorded during the examination included hyperkeratotic lesions, leukoplakia, smoker's melanosis, diffuse erythema, erosions, ulcerations, traumatic lesions, mucosal edema, xerostomia-related findings, and inflammatory changes.

Gingival bleeding on probing was also recorded as part of the clinical oral examination. Clinical findings were documented according to established clinical diagnostic principles and relevant internationally accepted criteria for oral mucosal lesions. Because the present study was observational and cross-sectional, the clinical findings were interpreted as observed associations rather than evidence of causality.

Histopathological assessment

Histopathological assessment was performed in a subset of participants from the two tobacco-use groups. Twenty participants were selected from the conventional cigarette smoking group and 20 from the exclusive HTP group, resulting in a total histopathological sample of 40 tobacco users.

The selected participants underwent incisional biopsy of oral mucosal tissue. The histopathological subset therefore represented a sample of the clinical study population rather than the entire cohort. The biopsy specimens included tissue obtained from clinically identified oral mucosal lesions as well as clinically normal-appearing oral mucosa in selected participants. Accordingly, the histopathological findings should not be interpreted as representing the histological status of the entire oral mucosa of all participants.

For morphological reference, one archival specimen of clinically normal oral mucosa obtained from a nonsmoking individual was examined. This archival specimen was used exclusively as a morphological reference for normal oral mucosal architecture and was not considered a participant-level histopathological control group. No inferential statistical comparison was performed between the archival specimen and the participant groups.

The clinical control group consisted of 40 healthy nonsmoking volunteers; however, histopathological biopsies were not obtained from these individuals. Consequently, the nonsmoking control group served as a clinical control group, whereas the archival specimen served only as a morphological histological reference. Tissue samples were fixed in 10% neutral buffered formalin, processed through graded concentrations of alcohol for dehydration, embedded in paraffin, and sectioned at a thickness of 4 μm .

Sections were routinely stained with hematoxylin and eosin (H&E) for assessment of overall tissue architecture, epithelial morphology, inflammatory-cell infiltration, vascular alterations, and degenerative or structural changes. Additional sections were stained with Van Gieson's picrofuchsin stain to facilitate differentiation of collagen fibers from other connective-tissue elements and to assess connective-tissue organization, stromal remodeling, and fibrotic changes.

Histological examination was performed using a ZEISS Primo Star trinocular microscope (ZEISS Microscopy, Germany) at $\times 100$ and $\times 400$ magnifications. Digital microphotographs were obtained using a ZEISS Axiocam ERc 5s camera system (Carl ZEISS Microscopy, Germany).

The histopathological parameters evaluated included epithelial hyperkeratosis, epithelial acanthosis, epithelial atrophy, chronic inflammatory-cell infiltration, vascular congestion, stromal edema, collagen-fiber disorganization, early fibrosis, and epithelial dysplasia.

Statistical analysis

Statistical analyses were performed using IBM SPSS Statistics (IBM Corp., Armonk, NY, USA). Continuous variables were summarized using the mean and standard deviation (SD), while categorical variables were summarized using absolute frequencies and percentages.

For continuous variables, assessment of distributional assumptions should precede selection of the statistical test. Normally distributed continuous variables were compared using the Student's *t*-test, whereas non-normally distributed variables were compared using the Mann–Whitney U test, as appropriate.

Categorical variables were compared using Pearson's chi-square test when the expected cell frequencies were adequate. For sparse contingency tables, Fisher's exact test was used. Because several clinical outcomes contained small expected frequencies, the choice of the exact test should be explicitly reported in the final statistical output for each affected comparison.

For the histopathological comparison between the conventional cigarette smoking and exclusive HTP groups, Fisher's exact test is preferred because of the small sample size (20 participants per group) and the

presence of low expected cell frequencies.

All statistical tests were two-tailed. A nominal *p* value <0.05 was considered statistically significant. Because multiple histopathological endpoints were evaluated, the final analysis should additionally report an appropriate multiplicity-adjusted significance assessment, preferably using the Holm procedure, or explicitly identify the histopathological analysis as exploratory if no multiplicity adjustment was performed.

Where feasible, effect estimates with 95% confidence intervals should be reported in addition to *p* values to provide information about the magnitude and precision of between-group differences.

No causal inference was intended because of the cross-sectional study design.

Ethical considerations

The study was approved by the Ethics Committee of Yerevan State Medical University and was conducted in accordance with the principles of the Declaration of Helsinki. Written informed consent was obtained from all participants before enrollment.

RESULTS

Clinical characteristics and findings of the oral mucosa

A total of 123 participants were included in the clinical analysis: 40 healthy nonsmoking controls, 36 exclusive heated tobacco product (HTP) users, and 47 conventional cigarette smokers (CS). All participants underwent a standardized clinical examination of the oral cavity, including assessment of the lips and oral commissures, buccal mucosa, tongue, floor of the mouth, palate, and gingival tissues. Participants reported a range of subjective oral symptoms, including oral discomfort, xerostomia, lip tightness, soreness at the oral commissures, burning or tingling sensations of the tongue, taste alterations, tongue coating, and a rough sensation of the oral mucosa. These complaints were recorded descriptively during the clinical examination and were not incorporated into a composite symptom score.

The distribution of clinically detected oral mucosal findings across the three study groups is presented in **Table 1**.

Table 1. Clinical findings of the oral mucosa in cigarette smokers (CS), heated tobacco product (HTP) users, and healthy controls

Clinical finding	Control (n=40) n (%)	HTPs (n=36) n (%)	CS (n=47) n (%)	p value**
Normal oral mucosa*	36 (90.0)	28 (77.8)	9 (19.1)	<0.001
Diffuse mucosal erythema	1 (2.5)	2 (5.6)	10 (21.3)	0.009
Hyperkeratotic lesions	0 (0.0)	0 (0.0)	6 (12.8)	0.006
Smoker's melanosis	0 (0.0)	0 (0.0)	3 (6.4)	0.083
Leukoplakia	0 (0.0)	0 (0.0)	4 (8.5)	0.035
Gingival bleeding on probing	1 (2.5)	3 (8.3)	7 (14.9)	0.129
Xerostomia	1 (2.5)	1 (2.8)	3 (6.4)	0.591
Mucosal edema	1 (2.5)	2 (5.6)	5 (10.6)	0.097

Notes: Values are presented as *n* (%).

- *p* values represent the overall comparison among the three study groups and were calculated using the Pearson χ^2 test.
- † Normal oral mucosa indicates absence of clinically detectable pathological alterations at the time of examination.

Abbreviations: CS, conventional cigarette smokers; HTP, heated tobacco product users; CI, confidence interval.

Overall *p* values represent the three-group comparison. Categorical comparisons were performed using Pearson's χ^2 test or Fisher's exact test, as appropriate. Cramer's *V* is reported as a measure of overall association. Risk differences represent CS prevalence minus HTP prevalence and are presented with approximate 95% confidence intervals. Pairwise CS-versus-HTP comparisons were performed using Fisher's exact test when sparse cell counts were present. No correction for multiple comparisons was applied.

*Normal oral mucosa was defined as the absence of clinically visible pathological changes, including inflammatory, keratotic, pigmented, erosive, ulcerative, edematous, or clinically detectable gingival abnormalities.

Clinical findings

Clinically normal oral mucosa was observed in 36 of 40 healthy controls (90.0%), 28 of 36 HTP users (77.8%), and 9 of 47 CS participants (19.1%). The overall distribution differed significantly among the three groups ($p < 0.001$; Cramer's *V* = 0.651). Compared with HTP users, CS participants had a 58.6-percentage-point lower prevalence of clinically normal oral mucosa (95% CI, -76.3 to -41.0; $p < 0.001$).

Diffuse mucosal erythema was identified in 1 control participant (2.5%), 2 HTP users (5.6%), and 10 CS participants (21.3%). The overall three-group comparison was statistically significant ($p = 0.009$; Cramer's *V* = 0.277). The prevalence was 15.7 percentage points higher among CS participants than among HTP users (95% CI, 1.8 to 29.6); however, the direct CS-versus-HTP comparison did not reach conventional statistical significance ($p = 0.060$). Thus, the overall three-group difference should not be interpreted as definitive evidence of a statistically significant difference specifically between CS and HTP users. Hyperkeratotic lesions were detected in 6 CS participants (12.8%) and in none of the HTP users or controls. The overall association was statistically significant ($p = 0.006$; Cramer's *V* = 0.288). The prevalence difference between CS and HTP users was 12.8 percentage points (95% CI, 3.2 to 22.3; $p = 0.034$).

Smoker's melanosis was observed in 3 CS participants (6.4%) but in none of the HTP users or controls. The overall comparison did not reach statistical significance ($p = 0.083$; Cramer's *V* = 0.201), and the direct CS-versus-HTP comparison was also not statistically significant ($p = 0.254$). Leukoplakia was observed exclusively in the CS group, occurring in 4 of 47 participants (8.5%). No cases were identified among HTP users or controls. Although the overall three-group comparison reached statistical significance ($p = 0.035$; Cramer's *V* = 0.233), the direct CS-versus-HTP comparison did not reach statistical significance by Fisher's exact test ($p = 0.129$). The observed prevalence difference was 8.5 percentage points (95% CI, 0.5 to 16.5). Because of the small number of events, this finding should be interpreted cautiously.

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Gingival bleeding on probing was recorded in 1 control participant (2.5%), 3 HTP users (8.3%), and 7 CS participants (14.9%). The overall difference was not statistically significant ($p = 0.129$; Cramer's $V = 0.183$). The prevalence difference between CS and HTP users was 6.6 percentage points (95% CI, -7.0 to 20.2 ; $p = 0.502$).

Xerostomia was reported in 1 control participant (2.5%), 1 HTP user (2.8%), and 3 CS participants (6.4%). No significant overall association was observed ($p = 0.591$; Cramer's $V = 0.092$). The CS-versus-HTP prevalence difference was 3.6 percentage points (95% CI, -5.2 to 12.4 ; $p = 0.629$).

Mucosal edema was present in 1 control participant (2.5%), 2 HTP users (5.6%), and 5 CS participants (10.6%). The overall comparison was not statistically significant ($p = 0.297$; Cramer's $V = 0.141$), and the direct CS-versus-HTP comparison was also not significant ($p = 0.693$).

Overall, conventional cigarette smokers had the lowest prevalence of clinically normal oral mucosa and the highest observed prevalence of several pathological findings. HTP users showed an intermediate clinical profile between conventional cigarette smokers and healthy controls. These findings demonstrate an association between current tobacco-use category and clinical oral mucosal status but do not establish causality.

Histopathological findings

Histopathological examination was performed in a randomly selected subset of 40 tobacco users, comprising 20 conventional cigarette smokers and 20 exclusive HTP users. The histopathological analysis therefore represents a participant-level subset and should not be interpreted as a histological assessment of all 123 clinically examined participants. An archival specimen of clinically normal oral mucosa from a nonsmoking individual was examined solely as a morphological reference. Because this specimen did not represent a participant-level control group, it was not included in inferential statistical analyses.

The distribution of predefined histopathological findings among HTP users and CS participants is presented in **Table 2**.

Table 2 Semiquantitative histopathological evaluation of oral mucosal alterations in cigarette (CS) smokers, and heated tobacco product (HTP) users

Pathomorphological signs / Histopathological finding	HTPs (n=20) n (%)	CS (n=20) n (%)	p value*
Mild hyperkeratosis	3 (15.0)	12 (60.0)	0.008
Epithelial acanthosis	2 (10.0)	11 (55.0)	0.006
Epithelial atrophy	1 (5.0)	7 (35.0)	0.044
Chronic inflammatory infiltration	6 (30.0)	16 (80.0)	0.004
Vascular congestion	4 (20.0)	15 (75.0)	<0.001
Stromal edema	3 (15.0)	10 (50.0)	0.036
Collagen fiber disorganization	2 (10.0)	13 (65.0)	<0.001
Early fibrosis	1 (5.0)	9 (45.0)	0.006
Mild epithelial dysplasia	0 (0.0)	4 (20.0)	0.035

* Data are presented as n (%). Between-group comparisons were performed using the two-sided Fisher's exact test because of the small sample size and low expected cell frequencies. A P value <0.05 was considered statistically significant.

Abbreviations: CS, conventional cigarette smokers; HTP, heated tobacco product users; CI, confidence interval.

Data are presented as n (%). Because of the small sample size and sparse cell counts, two-sided Fisher's exact tests were used for group comparisons. Risk differences represent CS prevalence minus HTP prevalence and are presented with approximate 95% confidence intervals. The archival nonsmoking specimen was not included in statistical comparisons.

An archival specimen of clinically normal oral mucosa demonstrated preserved stratified squamous epithelial

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architecture, regular epithelial maturation, an intact epithelial-connective tissue interface, and relatively uniform collagen organization with only occasional inflammatory cells (**Figure 1**). This specimen served exclusively as a morphological reference and was not used as a statistical control.

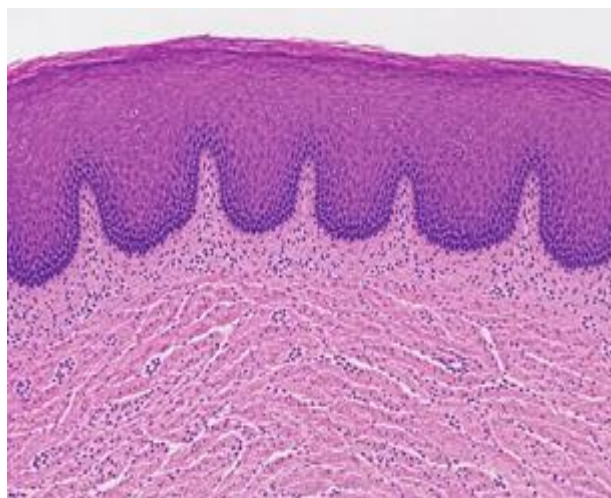


Figure 1. Representative histological appearance of clinically normal oral mucosa from an archival nonsmoking specimen used as a morphological reference.

Hematoxylin and eosin staining, $\times 100$. The specimen demonstrates normally stratified squamous epithelium with preserved maturation and thickness, an intact epithelial-connective tissue interface, and no substantial inflammatory or stromal abnormalities.

In conventional cigarette smokers, hyperkeratosis was identified in 12 of 20 specimens (60.0%), compared with 3 of 20 HTP specimens (15.0%). The absolute prevalence difference was 45.0 percentage points (95% CI, 18.4 to 71.6; $p = 0.008$). Epithelial acanthosis was identified in 11 CS specimens (55.0%) compared with 2 HTP specimens (10.0%), corresponding to a 45.0-percentage-point difference (95% CI, 19.5 to 70.5; $p = 0.006$). Epithelial atrophy was present in 7 CS specimens (35.0%) and 1 HTP specimen (5.0%), with an absolute difference of 30.0 percentage points (95% CI, 7.0 to 53.0; $p = 0.044$).

The CS specimens demonstrated prominent inflammatory and vascular alterations. Chronic inflammatory infiltration was observed in 16 of 20 CS specimens (80.0%) compared with 6 of 20 HTP specimens (30.0%), yielding an absolute prevalence difference of 50.0 percentage points (95% CI, 23.3 to 76.7; $p = 0.004$). The inflammatory infiltrate was predominantly lymphoplasmacytic in morphology.

Vascular congestion was identified in 15 CS specimens (75.0%) compared with 4 HTP specimens (20.0%), corresponding to an absolute difference of 55.0 percentage points (95% CI, 29.2 to 80.8; $p = 0.001$). Stromal edema was observed in 10 CS specimens (50.0%) and 3 HTP specimens (15.0%), representing an absolute difference of 35.0 percentage points (95% CI, 8.1 to 61.9; $p = 0.041$).

Van Gieson's picrofuchsin staining demonstrated greater connective tissue remodeling in the CS group (**Figures 2C and 2D**). Collagen fiber disorganization and fragmentation were identified in 13 CS specimens (65.0%) compared with 2 HTP specimens (10.0%), corresponding to an absolute prevalence difference of 55.0 percentage points (95% CI, 30.3 to 79.7; $p < 0.001$). Early fibrotic changes with increased collagen deposition were present in 9 CS specimens (45.0%) and 1 HTP specimen (5.0%), yielding an absolute difference of 40.0 percentage points (95% CI, 16.2 to 63.8; $p = 0.008$).

Representative histopathological findings in conventional cigarette smokers are shown in **Figure 2**. Hematoxylin and eosin staining demonstrated epithelial hyperkeratosis, acanthosis, inflammatory infiltration, vascular congestion, and stromal changes, whereas Van Gieson's staining demonstrated collagen disorganization and increased collagen deposition.

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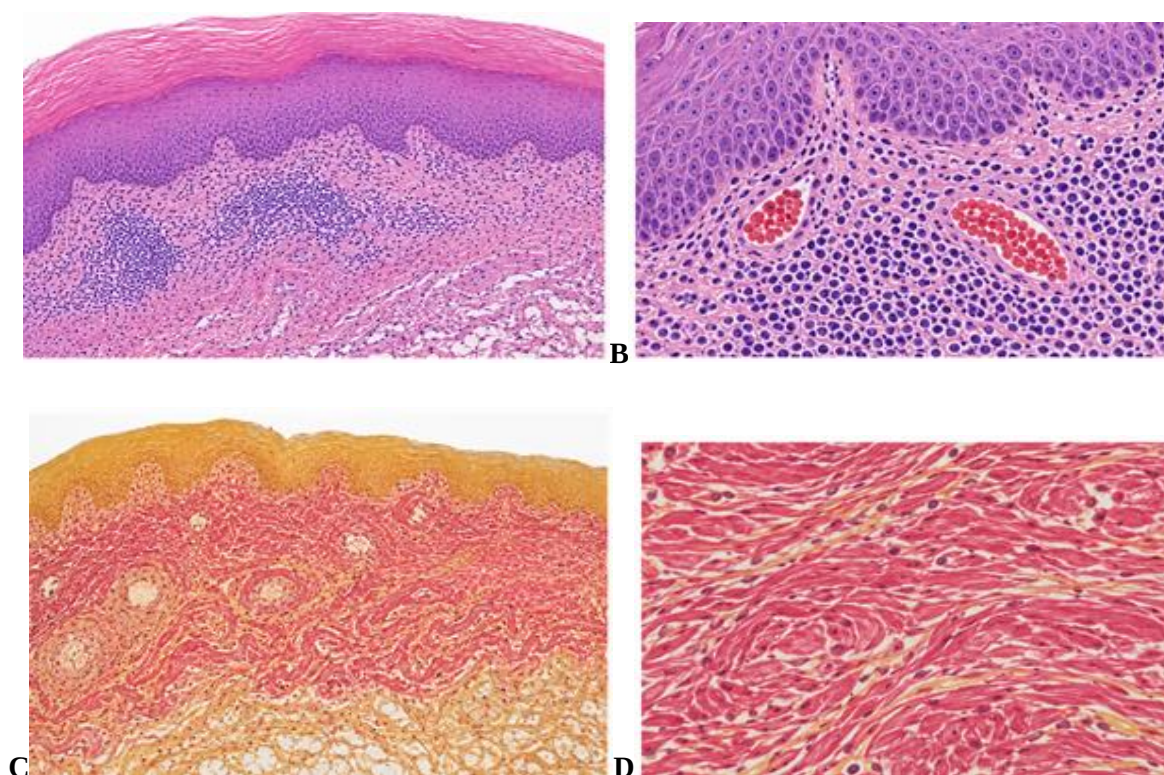
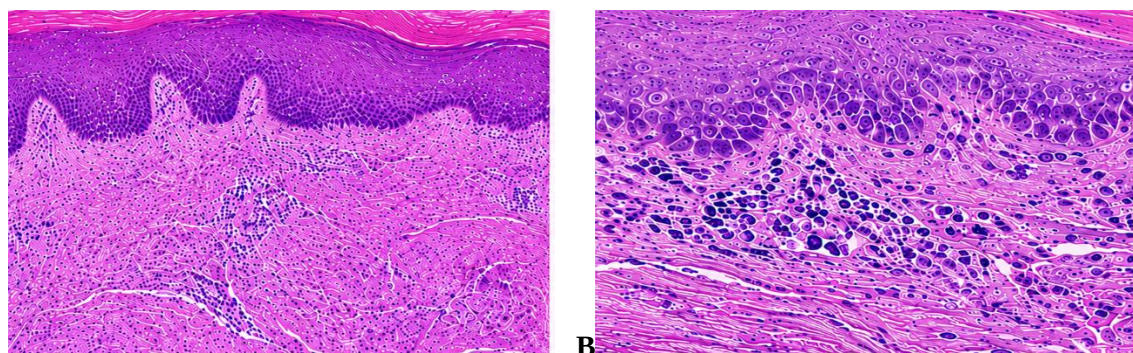


Figure 2. Histopathological alterations in conventional CS. **(A)** Hematoxylin-eosin stain (×100): diffuse epithelial hyperkeratosis and inflammatory infiltration. **(B)** Hematoxylin-eosin stain (×400): acanthosis, vascular congestion, and chronic inflammatory infiltrate. **(C)** Van Gieson's stain (×100): irregular collagen bundles. **(D)** Van Gieson's stain (×400): dense collagen deposition and early fibrosis.

In contrast, HTP users generally demonstrated preserved epithelial and stromal architecture (**Figure 3**). Mild focal hyperkeratosis was observed in 3 specimens (15.0%), epithelial acanthosis in 2 (10.0%), and epithelial atrophy in 1 (5.0%). Chronic inflammatory infiltration was present in 6 specimens (30.0%), while vascular congestion and stromal edema were identified in 4 (20.0%) and 3 (15.0%) specimens, respectively. Collagen fiber disorganization was present in 2 specimens (10.0%), whereas early fibrosis was identified in 1 specimen (5.0%).

No case of mild epithelial dysplasia was identified among HTP users, compared with 4 cases (20.0%) among CS participants. Although the observed absolute difference was 20.0 percentage points (95% CI, 2.5 to 37.5), the direct comparison did not reach statistical significance ($p = 0.106$), reflecting the small number of biopsy specimens and the limited number of dysplastic events. Accordingly, the absence of dysplasia in the HTP subgroup should not be interpreted as evidence that HTP exposure is associated with zero risk of epithelial dysplasia.

Representative findings in HTP users are presented in **Figure 3**. The majority of specimens showed preserved epithelial maturation and connective tissue organization, with only focal inflammatory and collagen alterations.



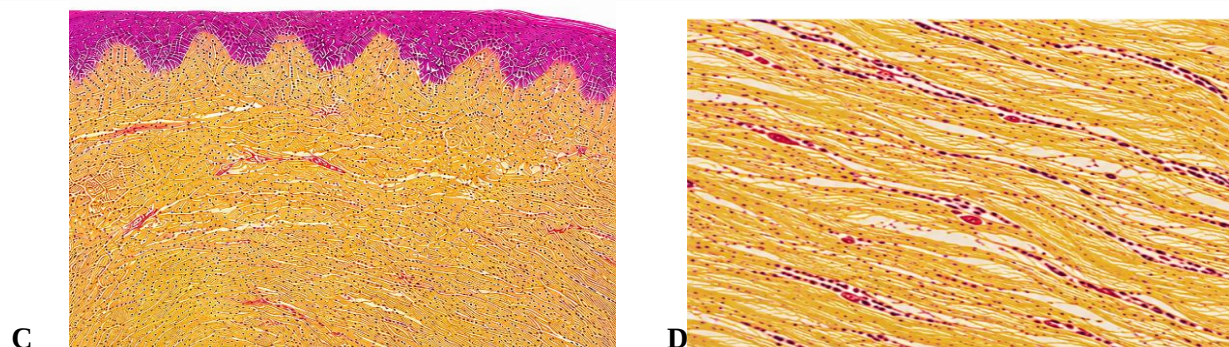


Figure 3. Histopathological alterations in heated tobacco product users.

(A) Hematoxylin and eosin staining, ×100, demonstrating largely preserved epithelial architecture with mild focal hyperkeratosis. (B) Hematoxylin and eosin staining, ×400, demonstrating mild inflammatory infiltration. (C) Van Gieson's picrofuchsin staining, ×100, demonstrating relatively preserved connective tissue organization. (D) Van Gieson's picrofuchsin staining, ×400, demonstrating minimal focal collagen remodeling without established fibrosis.

Overall, histopathological examination demonstrated a higher frequency of epithelial, inflammatory, vascular, and connective tissue alterations in the CS group than in the HTP group. The largest absolute between-group differences were observed for vascular congestion (+55.0 percentage points), collagen fiber disorganization (+55.0 percentage points), chronic inflammatory infiltration (+50.0 percentage points), hyperkeratosis (+45.0 percentage points), and epithelial acanthosis (+45.0 percentage points). These findings indicate substantially greater histopathological alteration among the biopsied CS participants. However, because the histopathological analysis was based on a small, randomly selected subset and the study was cross-sectional, the observed differences should be interpreted as associations rather than causal effects

4. DISCUSSION

The present study found that conventional cigarette smoking was associated with a significantly higher frequency of clinical and histopathological alterations of the oral mucosa than HTP use. Conventional cigarette smokers exhibited a higher prevalence of clinically detectable lesions, including diffuse erythema, hyperkeratosis, and leukoplakia, together with more pronounced epithelial hyperkeratosis, acanthosis, chronic inflammatory infiltration, vascular congestion, collagen disorganization, and early fibrosis. In contrast, HTP users exhibited only mild epithelial and stromal alterations, suggesting that although HTP use may be associated with less pronounced tissue alterations than conventional cigarette smoking, HTPs cannot be considered biologically harmless.

Our clinical findings are consistent with epidemiological studies demonstrating that conventional cigarette smoking remains one of the strongest risk factors for oral mucosal lesions, periodontal destruction, delayed wound healing, and oral potentially malignant disorders (OPMDs)12-13,16-17. Cigarette smoke contains thousands of chemical compounds, including polycyclic aromatic hydrocarbons, tobacco-specific nitrosamines,

aldehydes, and reactive oxygen species, which can continuously irritate the oral epithelium and promote chronic inflammatory responses. The exclusive occurrence of leukoplakia and diffuse hyperkeratosis among conventional cigarette smokers in our cohort supports the concept that prolonged exposure to combustible tobacco products may induce adaptive epithelial responses that can precede the development of potentially malignant changes.

Histopathological examination demonstrated a higher frequency of epithelial and stromal alterations in oral mucosal biopsy specimens from conventional cigarette smokers. Hyperkeratosis, epithelial acanthosis, epithelial atrophy, and mild dysplastic changes were significantly more frequent among conventional cigarette smokers than among HTP users. Similar microscopic alterations have been reported in studies evaluating tobacco-associated oral lesions, in which chronic exposure to cigarette smoke was associated with abnormal epithelial differentiation, increased keratinization, and disruption of epithelial homeostasis17,18. These epithelial changes are considered early indicators of chronic mucosal injury and may reflect continuous adaptation to chemical and thermal irritation.

One of the most prominent findings of our study was the dense chronic inflammatory infiltration observed in the

lamina propria of conventional cigarette smokers. Experimental studies have demonstrated that cigarette smoke can activate oxidative stress pathways, stimulate NF- κ B signaling, and increase the expression of pro-inflammatory cytokines, including IL-1 β , IL-6, IL-8, and TNF- α ^{16,19}. Persistent inflammatory activation may contribute to extracellular matrix degradation, endothelial dysfunction, impaired tissue repair, and increased susceptibility to carcinogenic processes. The predominance of lymphoplasmacytic inflammatory infiltrates observed in our specimens is therefore consistent with the chronic inflammatory response described in molecular studies of tobacco-associated oral mucosal alterations.

An important observation of the present study was the marked connective tissue remodeling identified by Van Gieson's staining. Conventional cigarette smokers demonstrated collagen fragmentation, architectural disorganization, and early fibrosis significantly more frequently than HTP users. Cigarette smoke exposure has been shown to impair fibroblast proliferation, reduce collagen synthesis, increase matrix metalloproteinase activity, and alter extracellular matrix turnover through oxidative stress-related mechanisms²¹⁻²². These biological processes may explain the connective tissue abnormalities observed in our biopsy specimens and may indicate progressive stromal remodeling associated with chronic tobacco exposure. Although HTP users exhibited substantially milder histopathological alterations, microscopic evidence of tissue changes was nevertheless present. Mild focal hyperkeratosis, slight inflammatory infiltration, and limited collagen disorganization indicate that exposure to heated tobacco aerosols can be associated with biological responses in the oral mucosa. These findings are consistent with in vitro and clinical investigations demonstrating that aerosols generated by HTPs contain nicotine and other potentially harmful constituents, including formaldehyde, acetaldehyde, acrolein, volatile organic compounds, and ultrafine particles, which may contribute to oxidative stress, inflammatory cytokine production, and epithelial alterations despite generally lower concentrations of several toxicants than those generated by conventional cigarettes^{3,8,20,23}. Consequently, lower exposure to selected toxicants should not be interpreted as an absence of biological risk. The comparatively milder histopathological alterations observed among HTP users in this study should be interpreted in the context of the study design. Importantly, HTP users had a history of previous conventional cigarette smoking. Therefore, the observed differences may reflect differences in

current tobacco exposure as well as differences in cumulative exposure history and other participant characteristics. The present findings demonstrate an association between current tobacco-use category and the histopathological characteristics of the oral mucosa, but they do not establish that HTP use itself is responsible for the observed alterations or that switching from conventional cigarettes to HTPs definitively reduces long-term oral disease risk.

Heating tobacco at temperatures below those associated with combustion reduces the formation of many combustion-derived toxicants, including several carcinogenic compounds^{23,24}. Nevertheless, HTP use continues to provide substantial nicotine exposure, and nicotine has been shown to influence keratinocyte proliferation, angiogenesis, inflammatory responses, and fibroblast metabolism²⁰. Therefore, although switching from conventional cigarettes to HTPs may potentially reduce the magnitude of some tobacco-related tissue alterations, complete normalization of oral mucosal histology should not be expected. The strengths of this study include the combined clinical and histopathological evaluation of oral mucosal changes, together with assessment of connective tissue remodeling using both hematoxylin and eosin and Van Gieson's staining. Furthermore, the direct comparison of exclusive HTP users with conventional cigarette smokers provides additional evidence in an area in which comparative histopathological data remain relatively scarce. Several limitations should be acknowledged.

First, the cross-sectional design does not permit conclusions regarding causality or the progression of tissue alterations over time. Second, the relatively small number of biopsy specimens limits the statistical power to detect uncommon histopathological findings. This limitation was partly attributable to the high costs associated with histopathological processing and analysis.

Third, an important consideration is that all participants in the HTP group had previously smoked conventional cigarettes. Consequently, the HTP group cannot be considered a tobacco-naïve population, and the observed oral mucosal findings may reflect both current HTP exposure and residual effects of previous combustible cigarette exposure. The present study therefore does not permit the effects of HTP use to be isolated from those associated with cumulative previous cigarette exposure. Longitudinal studies following individuals from the time of transition from conventional cigarettes to HTPs would be better suited to assessing changes in oral mucosal health following switching.

Finally, immunohistochemical and molecular biomarkers of proliferation, oxidative stress, inflammation, and extracellular matrix remodeling were not evaluated.

Future longitudinal studies integrating histopathological assessment with molecular analyses, including Ki-67, p53, IL-6, TNF- α , matrix metalloproteinases, and oxidative stress biomarkers, would further clarify the mechanisms underlying tobacco-associated oral mucosal alterations.

CONCLUSION

In this cross-sectional study, conventional cigarette smokers demonstrated a higher frequency of clinically detectable oral mucosal abnormalities and more frequent histopathological alterations of the oral mucosa than exclusive HTP users. Conventional cigarette smokers exhibited a markedly higher prevalence of epithelial hyperkeratosis, acanthosis, chronic inflammatory infiltration, vascular congestion, collagen disorganization, and early fibrotic changes, whereas HTP users demonstrated comparatively milder epithelial, inflammatory, and connective tissue alterations. These findings indicate an association between current tobacco-use category and the characteristics of the oral mucosa, with greater clinical and histopathological alterations observed among conventional cigarette smokers. However, the findings should not be interpreted as evidence of causality or as definitive evidence regarding the long-term oral health effects of HTP use.

The presence of measurable epithelial, inflammatory, and connective tissue alterations among HTP users indicates that these products should not be considered biologically inert. At the same time, interpretation of the observed differences is limited by the cross-sectional design, the relatively small number of biopsied specimens, and the previous cigarette-smoking history of the HTP users. Therefore, the histopathological findings observed among HTP users cannot necessarily be attributed exclusively to current HTP exposure.

The observed relationship between clinical and histopathological findings supports the value of microscopic evaluation for characterizing tobacco-associated oral mucosal alterations that may not be clinically apparent. From a clinical perspective, regular oral examinations may be warranted for both conventional cigarette smokers and HTP users to facilitate the early identification of potentially malignant and other tobacco-associated oral mucosal lesions.

Further prospective longitudinal studies with larger, adequately powered cohorts are needed to clarify the long-term biological effects of HTP use and to determine whether oral mucosal alterations change following cessation of conventional cigarette smoking or transition to exclusive HTP use. Future studies should incorporate standardized assessment of tobacco exposure, appropriate histological control groups, blinded histopathological evaluation, adjustment for relevant confounding factors, and integrated molecular and immunohistochemical analyses. Ultimately, complete cessation of tobacco use remains the most effective strategy for reducing tobacco-associated oral health risks.

DECLARATIONS

Ethical Approval

Not applicable.

Competing Interests

The authors declare no conflict of interest.

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RESEARCH ARTICLE

CLINICAL AND RADIOGRAPHIC OUTCOMES OF TRIOXIDENT AND MINERAL TRIOXIDE AGGREGATE FOR VITAL PULPOTOMY IN IMMATURE PERMANENT TEETH WITH INCOMPLETE ROOT DEVELOPMENT

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ABSTRACT

Background: Vital pulp therapy is an important treatment strategy for immature permanent teeth with pulp inflammation because preservation of the remaining vital radicular pulp may permit continued physiological root development, increasing root length, thickening of dentinal walls, and eventual closure of the apical foramen. Calcium silicate-based biomaterials, particularly mineral trioxide aggregate (MTA), are widely used because of their biocompatibility, bioactivity, sealing ability, and capacity to promote hard-tissue formation. However, the clinical evidence concerning alternative calcium silicate materials remains comparatively limited, particularly in immature permanent teeth.

Objective: To clinically and radiographically evaluate the outcomes of vital pulpotomy using Trioxident (VladMiVa) and ProRoot MTA (Dentsply) in immature permanent molars with incomplete root formation.

Materials and Methods: Twenty children aged 7–13 years with a clinical diagnosis of pulpitis involving immature permanent molars were treated in two dental clinics of Yerevan State Medical University. Twenty-seven permanent molars were included in the analysis. Fourteen teeth (51.9%) received Trioxident (VladMiVa), while 13 teeth (48.1%) were treated with ProRoot MTA (Dentsply). Following local anesthesia and rubber dam isolation, carious dentin was removed, coronal pulpotomy was performed, and hemostasis was achieved before placement of the calcium silicate-based material over the canal orifices. The teeth were subsequently restored with glass-ionomer cement, compomer, or composite restorative materials. Clinical and radiographic follow-up examinations were performed at approximately 3 months, 6 months, and 2 years, depending on the stage of root development. Clinical success was assessed according to the absence of spontaneous or provoked pain, percussion tenderness, and clinical signs of soft-tissue inflammation. Radiographic outcomes included absence of pathological root resorption or periapical/furcation bone destruction and evidence of continued root development and apical closure.

Results: The mean age of the patients was 9.5 ± 1.59 years. The treated teeth comprised 10 maxillary molars (37.0%) and 17 mandibular molars (63.0%). During follow-up, clinical and radiographic findings demonstrated continued root development in successfully treated teeth. Periodontal/periapical complications were identified in 4 of 27 treated teeth (14.8%). One complication occurred among the 13 teeth treated with ProRoot MTA (7.7%), compared with three among the 14 teeth treated with Trioxident (21.4%); this difference was not statistically significant ($p > 0.10$). Crown discoloration was observed in 8 of 14 teeth (57.1%) treated with Trioxident. Among the successfully treated teeth, radiographic examination demonstrated continued root elongation, progressive narrowing of the root canal space, and apical maturation; complete root formation was documented in 13 teeth.

Keywords: immature permanent teeth; vital pulp therapy; pulpotomy; apexogenesis; mineral trioxide aggregate; MTA; Trioxident; calcium silicate cement; pediatric dentistry; pulpitis.

INTRODUCTION

The management of pulpal disease in immature permanent teeth remains a particular clinical challenge in pediatric dentistry. Unlike fully developed

permanent teeth, immature teeth have an incompletely formed root, relatively thin dentinal walls, and a wide apical foramen. Consequently, treatment should not be directed solely toward elimination of pulpal symptoms or

infection but, whenever biologically feasible, toward preservation of the remaining vital pulp and continuation of physiological root development. Maintenance of pulp vitality may allow further root elongation, progressive thickening of the dentinal walls, narrowing of the root canal space, and physiological closure of the apical foramen, thereby improving the structural and functional prognosis of the developing tooth ¹⁻³.

The treatment concept for immature permanent teeth has changed considerably over the past decade. Conventional endodontic approaches, including root canal treatment and apexification, can provide control of pulpal and periapical disease but do not preserve the biological potential of the remaining pulp for continued physiological root maturation. Contemporary endodontic practice therefore increasingly emphasizes biologically conservative treatment approaches that aim to preserve viable pulp tissue whenever the clinical condition of the tooth permits. Vital pulp therapy (VPT), including partial and complete pulpotomy, has consequently become an important treatment option for selected permanent teeth ^{1,2}.

The American Association of Endodontists recognizes vital pulp therapy as a group of procedures intended to preserve the vitality and function of the dental pulp following injury caused by caries, trauma, or restorative procedures. Although VPT was historically associated primarily with immature permanent teeth, where preservation of radicular pulp was intended to facilitate apexogenesis, contemporary concepts have expanded its indications to appropriately selected mature permanent teeth as well ². Current treatment decisions are based on the overall clinical and radiographic assessment of the tooth, rather than on symptoms alone, and include consideration of pulp status, restorability, bleeding control, and the possibility of maintaining viable radicular pulp tissue ^{2,3}.

Pulpotomy is particularly relevant in immature permanent teeth because removal of the inflamed coronal pulp while preserving the vital radicular pulp may provide a biologically favorable environment for continued root formation. Successful treatment therefore involves more than the resolution of pain or the absence of periapical pathology. Radiographic evidence of continued root development, progressive maturation of the root canal system, and closure of the apical foramen are important indicators of the biological success of treatment in developing permanent teeth ^{1,3}.

The development of calcium silicate-based

biomaterials has substantially influenced the clinical application of vital pulp therapy. Mineral trioxide aggregate (MTA) became one of the most extensively studied materials because of its biocompatibility, hydraulic setting reaction, sealing ability, high alkalinity, and capacity to promote hard-tissue formation. These characteristics have supported its use in pulp capping and pulpotomy procedures and have made MTA an important reference material for the evaluation of newer calcium silicate-based cements ^{4,5}.

Evidence accumulated during the last several years supports the use of calcium silicate-based materials in vital pulp therapy. A 2021 systematic review and meta-analysis of randomized controlled trials reported a pooled VPT success rate of approximately 93% when contemporary materials, including MTA and other calcium silicate-based materials, were used. Importantly, no significant difference was identified between MTA and other calcium silicate materials at the evaluated follow-up periods, although the certainty of evidence was considered low ⁴. These findings support the biological potential of calcium silicate-based materials while also indicating that further comparative clinical studies are required.

More recent evidence has reinforced the role of calcium silicate materials in VPT. A 2024 systematic review and meta-analysis evaluating 40 randomized controlled trials and 3,168 teeth found generally favorable clinical and radiographic outcomes for calcium silicate-based cements used in vital pulp therapy in both primary and permanent dentitions. However, substantial variation among materials, treatment procedures, follow-up periods, and outcome definitions was observed, making direct comparisons between individual materials difficult ⁵.

The contemporary evidence is particularly relevant to immature permanent teeth. A systematic review and meta-analysis published in 2022 emphasized that preservation of pulpal vitality in immature permanent posterior teeth is essential for continued root development and apical closure. The available evidence supported vital pulp therapy as a biologically rational approach for selected immature teeth with deep carious lesions, although the authors also highlighted limitations in the quality and quantity of available clinical evidence [6]. More recently, a 2026 meta-analysis comparing VPT with root canal treatment in immature permanent teeth found higher odds of clinical and radiographic success following VPT, particularly in immature teeth and in cases treated with complete or coronal pulpotomy. Nevertheless, the cumulative evidence was considered insufficient to establish definitive superiority because the number and size of comparative studies remained limited ⁷.

Despite the favorable biological and clinical properties of MTA, its use is associated with certain practical and clinical limitations. Handling characteristics, setting behavior, material manipulation, and the potential for discoloration of tooth structure may influence material selection, particularly in anterior teeth and in situations where esthetic considerations are important. Recent evidence has confirmed that tooth discoloration remains an important adverse outcome associated with some MTA formulations. A 2025 systematic review and meta-analysis of premixed calcium silicate-based materials reported clinical success rates ranging from 76.6% to 97.1%, with no significant overall differences compared with MTA or calcium hydroxide; however, MTA was associated with greater tooth discoloration in permanent teeth [8].

The continued development of calcium silicate-based materials has therefore focused not only on biological activity but also on handling properties, setting characteristics, accessibility, and clinical applicability. Current evidence suggests that newer calcium silicate materials may achieve clinical outcomes comparable to MTA in selected VPT procedures, although the available evidence does not consistently demonstrate superiority of one calcium silicate material over another ^{5,8,9}.

A recent network meta-analysis of bioactive materials similarly found high success rates across contemporary VPT materials, while differences among calcium silicate-based materials remained uncertain ⁹.

Trioxident (VladMiVa) is a calcium-containing dental material that has been used for vital pulp therapy and other endodontic procedures. Its clinical use has been proposed as an alternative to conventional MTA-based materials, particularly where accessibility, handling characteristics, and cost are important considerations. However, compared with ProRoot MTA, the contemporary clinical evidence supporting the use of Trioxident in immature permanent teeth remains limited. In particular, there is a lack of clinical studies directly evaluating the ability of Trioxident to maintain the vitality of the radicular pulp and support continued physiological root development after pulpotomy in young permanent teeth with incomplete root formation.

The outcome of vital pulpotomy depends not only on the biological properties of the pulp-capping material but also on several clinical factors. Accurate diagnosis, appropriate case selection, effective isolation of the operative field, complete removal of inflamed coronal pulp tissue, adequate control of pulpal bleeding, correct placement of the biomaterial, and an effective

coronal seal are essential components of the treatment protocol ^{2,3}. In immature permanent teeth, these factors are particularly important because the therapeutic objective extends beyond short-term symptom control to preservation of the developmental capacity of the tooth.

Clinical and radiographic follow-up is therefore essential for evaluating treatment success. The absence of spontaneous or provoked pain, percussion sensitivity, swelling, or other clinical signs of inflammation represents an important component of clinical success. Radiographically, successful treatment should be associated with the absence of pathological internal or external root resorption and periapical or furcation bone destruction, together with evidence of continued physiological root maturation. In immature permanent teeth, continued root development and apical closure provide particularly meaningful evidence of successful preservation of pulp vitality ^{3,6,7}.

Although the evidence base for contemporary vital pulp therapy has expanded substantially, direct clinical comparisons between individual calcium silicate-based materials in immature permanent teeth remain limited. Most recent systematic reviews evaluate calcium silicate materials collectively or focus predominantly on mature permanent teeth, while relatively few clinical investigations have specifically examined continued root development following pulpotomy in young permanent teeth ^{4,5,7}.

This evidence gap is clinically relevant because the biological objective of treatment in an immature permanent tooth is not simply the elimination of symptoms but preservation of the tooth's capacity for physiological maturation.

Therefore, the present clinical study was designed to evaluate the clinical and radiographic outcomes of vital pulpotomy using Trioxident (VladMiVa) and ProRoot MTA in immature permanent teeth with incomplete root development.

The study assessed postoperative clinical findings, the occurrence of periapical complications, changes in crown color, and radiographic evidence of continued root formation and apical maturation during follow-up. The findings were intended to provide clinical evidence regarding the potential use of Trioxident as an accessible alternative calcium silicate-based material for vital pulp therapy in developing permanent teeth.

Aim: The aim of this study was to present the clinical results of the use of Trioxident and MTA in the treatment of pulpitis in young permanent teeth with incomplete roots, based on clinical and radiological findings.

In two dental clinics of YSMU, permanent molars at various stages of formation with a confirmed diagnosis of pulpitis were treated in 20 patients (13 males [65%] and 7 females [35%]) aged 7–13 years, followed by clinical and radiological examination. A total of 27 teeth were treated, of which 10 (37.03%) were located in the upper jaw and 17 (62.97%) in the lower jaw. Following pulpotomy, Trioxident (VladMiVa) was used in 14 teeth (51.9%), while ProRoot MTA (Dentsply) was used in the remaining teeth. The main characteristics of the study population are presented in Table 1.

Table 1. Baseline demographic and clinical characteristics

Characteristic	Value
Study population	
Patients, n	20
Age range, years	7–13
Male patients, n (%)	13 (65%)
Female patients, n (%)	7 (35%)
Mean age, years	9.5 ± 1.59
Treated teeth, n	27
Maxillary teeth, n (%)	10 (37.03%)
Mandibular teeth, n (%)	17 (62.97%)
Clinical diagnosis	Pulpitis
Root development	Incomplete
Trioxident-treated teeth, n (%)	14 (51.9%)
ProRoot MTA-treated teeth, n (%)	13 (48.1%)

ProRoot MTA (Mineral Trioxide Aggregate) is a powder consisting of small hydrophilic particles that harden after being mixed with water. The powder turns into a gel after hydration.

Composition: tricalcium aluminate, tricalcium silicate, calcium oxide, silicon oxide, and bismuth oxide.

Trioxident consists of calcium oxide, silicon oxide, aluminum oxide, and copper-calcium hydroxide. It is an easy-to-use material that does not lose its plasticity within 10–15 minutes. It is prepared by mixing a finely ground hydrophilic powder with distilled water at a 3:1 weight ratio.

All patients underwent standard diagnostic and treatment procedures:

1. Diagnostic radiograph.
2. Administration of anesthesia.
3. Isolation of the tooth with a rubber dam.
4. Preparation of the cavity according to the topography of the tooth, with removal of all carious dentin.
5. Opening of the pulp chamber.
6. Pulpotomy of the coronal pulp using a sharp excavator or a round bur.
7. Assessment and control of bleeding. The tooth cavity was thoroughly rinsed with distilled water and dried with sterile cotton pellets. Sterile cotton pellets slightly moistened with distilled water were applied to the root canal orifices, and dry pellets were placed over them and pressed gently. After 2–3 minutes, the pellets were removed. The subsequent stage of pulpotomy was performed after hemostasis had been achieved.
8. The root canal orifices were closed with MTA or Trioxident after bleeding had been controlled. The tooth was then finally restored with glass-ionomer cement, compomer, or composite materials.

Long-term results were assessed by clinical and radiographic examinations.

The criteria for successful treatment in the immediate postoperative period were:

- absence of pain (spontaneous pain, night pain, pain from thermal stimuli, or pain while biting);
- painless percussion;
- gingival mucosa without visible pathological changes.

The criteria for long-term successful treatment were:

- absence of pain;
- absence of discoloration of the tooth crown;
- gingival mucosa without visible pathological changes.

Continued root formation, including growth in length, closure of the apical foramen, and narrowing of the root canals, was considered the radiological indicator of treatment effectiveness.

Control examinations were carried out at different periods after treatment, including 3 months, 6 months, and 2 years, depending on the stage of root formation before treatment, but always until complete root formation, to establish the effectiveness of the pulpotomy performed.

Statistical Analysis

Statistical data processing was performed using SPSS version 16.0. The analysis included calculation of percentages, mean values, and standard deviations, as well as Student's *t*-test.

RESULTS

The mean age of the children at the time of treatment was 9.5 ± 1.59 years. During history taking, it was found that 9 children (45%) had no complaints at the first visit, 6 children (30%) complained of the presence of a deep carious cavity, and 11 children (55%) reported prolonged pain after eating.

Clinical examination of the treated molars revealed deep carious cavities containing softened, pigmented dentin. The lesions were localized on the proximal surfaces in 9 teeth (33.3%), on the occlusal surfaces in 14 teeth (51.85%), and on both the occlusal and proximal surfaces in 4 molars (14.81%). Sharp localized pain was elicited during probing of the cavity floor in all teeth, whereas percussion was negative. Pain following removal of the cold stimulus subsided slowly. The mucous membrane in the region of the examined teeth was pink, clean, and painless on palpation. Radiographic examination did not reveal internal or external root resorption or destruction of bone tissue in the furcation or periapical regions.

During dental follow-up examinations, changes in crown color were observed in 8 teeth (57.1%) among the children treated with Trioxident. Percussion of the treated teeth and palpation of the mucogingival junction in the projection of the roots were painless, and no signs of inflammation of the oral mucosa were observed. Overall, complications in the periapical tissues during the follow-up period were detected in 4 teeth (14.81%). Among the 13 teeth treated with ProRoot MTA, one tooth (7.69%) developed a complication in the form of periodontitis. Among the 14 teeth treated with Trioxident, complications were observed in 3 cases (21.4%). The difference between the groups was statistically insignificant ($p > 0.1$).

In the remaining cases, radiographic examination demonstrated positive dynamics, including the absence of internal or external root resorption, absence of destruction of the cortical plate and periapical bone tissue, and continued root development. Continued root formation was manifested by an increase in root length, narrowing of the root canals, and closure of the apical foramen. Complete root formation was observed in 13 cases (57%). The clinical and radiographic findings are summarized in Table 2.

Table 2. Clinical and radiographic findings during follow-up

Outcome	n (%)
Total treated teeth	27 (100%)
Maxillary teeth	10 (37.03%)
Mandibular teeth	17 (62.97%)
Deep carious lesions on proximal surfaces	9 (33.3%)
Deep carious lesions on occlusal surfaces	14 (51.85%)
Combined occlusal and proximal lesions	4 (14.81%)
Internal/external root resorption at baseline	0
Furcation/periapical bone destruction at baseline	0
Periapical complications during follow-up	4 (14.81%)
ProRoot MTA: periapical complications	1/13 (7.69%)
Trioxident: periapical complications	3/14 (21.4%)
Statistical significance of group difference	* $p > 0.1$
Crown discoloration after Trioxident treatment	8/14 (57.1%)
Continued root development	Reported in remaining cases
Complete root formation	13 (57%)

The findings demonstrate that the treated immature permanent teeth showed generally favorable clinical and radiographic responses during follow-up. The absence of internal or external root resorption and the absence of furcation or periapical bone destruction indicate that no radiographic progression of destructive pathology was observed in the examined teeth.

The occurrence of periapical complications was relatively limited in the overall study population. Although complications were more frequent in the Trioxident group than in the ProRoot MTA group (21.4% vs 7.69%), the difference did not reach statistical significance ($p > 0.1$). Therefore, the present results do not demonstrate a statistically significant difference between the two materials with respect to periapical complications.

An important clinical observation was crown discoloration in 8 of the 14 teeth treated with Trioxident (57.1%). This finding represents a relevant clinical outcome of the present investigation and should be considered when assessing the overall clinical performance of the material.

The radiographic findings were characterized by continued root development in the remaining cases, including root elongation, narrowing of the root canals, and closure of the apical foramen. These findings are consistent with continued maturation of immature permanent teeth following vital pulpotomy. Complete root formation was reported in 13 cases (57%), indicating that root development continued in a substantial proportion of the treated teeth during follow-up.

Clinical Case

A representative clinical case demonstrating continued root development after vital pulpotomy with ProRoot MTA is presented below. (Doctor: Badeyan E.)

A patient, A.A., born on 05.11.2009, presented with complaints of nocturnal pain for two days. An objective examination of tooth 46 revealed a deep carious cavity filled with softened dentin and food debris. Probing was very painful throughout the entire floor of the cavity, but there was no communication between the carious cavity and the pulp chamber. X-ray examination showed root development corresponding to the age of the child. Based on the clinical and radiological findings, irreversible pulpitis of tooth 46 was diagnosed, and a decision was made to perform vital pulpotomy with MTA to achieve apexogenesis (**Figure 1a,b and Figure 2**).

The pulpotomy procedure and hemostasis followed by application of MTA are shown in **Figure 1a,b**. **Figure 2** demonstrates the packing of MTA into the pulp chamber. There were no signs of complications two weeks after treatment. Control X-ray examinations revealed signs of apexogenesis, and complete formation of the roots was observed two years after treatment (**Figure 3a,b,c,d**).

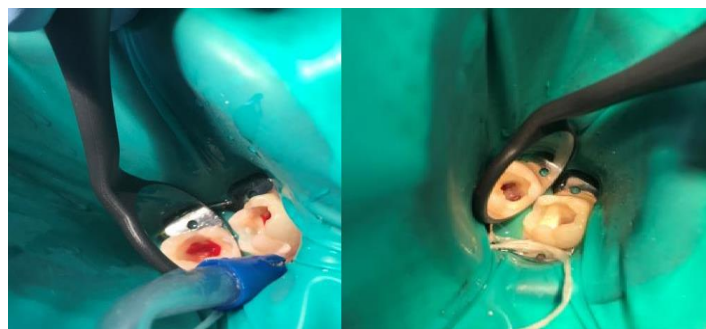


Figure 1. Pulpotomy of tooth 46. (a) Pulpotomy; (b) hemostasis and application of MTA.



Figure 2. Packing of MTA in the pulp chamber.



Figure 3. Serial X-ray examinations demonstrating root development after vital pulpotomy with MTA. (a) X-ray 1 (31.01.2018); (b) X-ray 3 (29.06.2019); (c) X-ray 4 (20.02.2020); (d) X-ray examination demonstrating complete root formation.

Thereby, the use of MTA in the treatment of pulpitis among children by the method of vital pulpotomy allowed positive results to be obtained in 44.4% of cases, while the use of Trioxident resulted in positive outcomes in 40.7% of cases.

DISCUSSION

The present study evaluated the clinical and radiographic outcomes of vital pulpotomy using Trioxident and ProRoot MTA in young permanent teeth with incomplete root development. The principal finding was that both materials were associated with continued root development during follow-up, while the frequency of periapical complications differed numerically between the treatment groups but did not reach statistical significance. These findings are clinically relevant because the primary objective of vital pulp therapy in an immature permanent tooth is preservation of viable radicular pulp and maintenance of the biological potential for continued physiological root maturation¹⁻⁴.

The absence of pathological internal or external root resorption and the lack of furcation or periapical bone destruction in the radiographic assessments provide evidence of a favorable response in the treated teeth. In

addition, the absence of percussion sensitivity and clinically detectable inflammatory changes during follow-up supports the clinical stability observed in most cases. Contemporary evidence emphasizes that successful vital pulp therapy should be assessed using both clinical and radiographic outcomes rather than symptom resolution alone, particularly in immature permanent teeth in which continued root maturation represents an important treatment objective ^{2,3}.

In the present study, periapical complications were detected in 4 of the 27 treated teeth (14.81%). One of the 13 teeth treated with ProRoot MTA (7.69%) developed periodontitis, whereas complications occurred in 3 of the 14 teeth treated with Trioxident (21.4%). Although the complication rate was numerically higher in the Trioxident group, the difference was statistically insignificant ($p > 0.1$). Accordingly, these findings do not demonstrate a statistically significant difference between the two materials. The numerical difference should be interpreted cautiously because of the small sample size and the limited statistical power of the study.

The absence of a statistically significant difference between the materials is consistent with recent evidence indicating that the clinical performance of contemporary calcium silicate-based materials is generally favorable and that clear superiority of one material over another has not been consistently demonstrated. Sabeti et al. reported a high overall prognosis for vital pulp therapy in permanent dentition, although differences between treatment modalities and materials varied according to follow-up and clinical circumstances ¹. A systematic review and meta-analysis by Xavier et al. similarly reported generally favorable clinical, radiographic, and histological outcomes for calcium silicate-based cements, while highlighting substantial heterogeneity among studies and materials ⁴.

The findings are also supported by the systematic review and meta-analyses of Coll et al., which evaluated vital pulp therapy in permanent teeth using evidence available through June 2024. Their analysis demonstrated high success rates across indirect pulp treatment, direct pulp capping, partial pulpotomy, and full pulpotomy in appropriately selected permanent teeth. Importantly, in teeth diagnosed with symptomatic irreversible pulpitis, partial or full pulpotomy also showed favorable outcomes, and the authors emphasized the importance of adequate pulpal bleeding control in achieving successful treatment ³. This is relevant to the present study because hemostasis was an integral part of the pulpotomy protocol.

Recent evidence specifically addressing calcium silicate materials also supports the present observations. Immich et al. evaluated premixed calcium silicate-based materials in a 2025 systematic review and meta-analysis and reported clinical success rates ranging from 76.6% to 97.1%, with no significant overall differences between premixed calcium silicate materials and comparator materials. The authors concluded that larger clinical studies with longer follow-up were still needed, particularly for permanent teeth, where the certainty of evidence remained low⁷. This supports a cautious interpretation of the present comparison between Trioxident and ProRoot MTA.

The radiographic findings of the present study are particularly important because the treated teeth had incomplete root development before intervention. Continued root formation was manifested by an increase in root length, narrowing of the root canals, and closure of the apical foramen, while complete root formation was reported in 13 cases (57%). These findings are consistent with the biological rationale for vital pulpotomy in immature permanent teeth. Ageel et al., in their systematic review of MTA-assisted apexogenesis, found that different pulpotomy agents generally produced comparable clinical outcomes to MTA in carious or traumatized immature permanent teeth. However, the authors emphasized that the available evidence was insufficient to establish a definitive advantage of one material over another ⁵.

The findings of the present study are also consistent with the most recent evidence comparing vital pulp therapy with root canal treatment in immature permanent teeth. Gu and Yang reported in a 2026 meta-analysis that vital pulp therapy was associated with higher odds of clinical and radiographic success than root canal treatment in immature permanent teeth with pulpal involvement. Their analysis further suggested favorable outcomes for complete or coronal pulpotomy and for follow-up of at least 24 months ⁶.

The two-year follow-up included in the present study therefore provides clinically meaningful evidence of the potential for continued root maturation after vital pulpotomy.

The clinical case of tooth 46 provides an illustrative example of this biological response. The patient presented with nocturnal pain and a deep carious lesion, and the tooth was diagnosed clinically and radiographically with irreversible pulpitis. Following vital pulpotomy with ProRoot MTA, no signs of complications were observed at the two-week follow-up. Subsequent radiographs demonstrated signs of apexogenesis, and complete root formation was observed after two years. Although this individual case cannot be considered comparative

evidence, the sequential radiographic findings provide a clinically clear example of continued root maturation following preservation of the remaining pulp.

The management of symptomatic irreversible pulpitis has undergone a substantial conceptual change in recent years. Historically, irreversible pulpitis was generally considered an indication for complete pulpectomy and root canal treatment. Current evidence, however, suggests that the clinical designation of irreversible pulpitis does not necessarily imply complete loss of the biological capacity for pulp healing. Asgary and Eghbal highlighted this changing concept and argued that contemporary vital pulp therapy may preserve viable pulp tissue in selected cases that would previously have been managed exclusively by root canal treatment¹³. Similarly, Kahler et al. reviewed the biological basis for VPT in permanent teeth diagnosed with irreversible pulpitis and emphasized that appropriate case selection, aseptic treatment, calcium silicate-based materials, and an effective coronal seal are essential to treatment success¹⁴.

The systematic review by Bafail further supports this emerging clinical approach. In teeth with symptomatic irreversible pulpitis treated with hydraulic calcium silicate cements, reported clinical success generally ranged from 78% to 90% at one to five years, while radiographic success ranged from 81% to 90%. Importantly, some studies reported outcomes comparable with nonsurgical root canal treatment¹⁰. Although most of the evidence summarized by Bafail concerns mature permanent posterior teeth, the underlying biological concept is relevant to the present study because the current investigation also treated teeth with clinical features of advanced pulpal inflammation while attempting to preserve viable radicular pulp in immature teeth.

The present findings should also be interpreted in relation to broader evidence regarding pulpotomy. Wang et al. reported in a 2024 systematic review and meta-analysis that pulpotomy using hydraulic calcium silicate cements achieved success rates comparable with root canal treatment in mature permanent teeth with carious pulp exposure. Their analysis also found lower postoperative pain during the first postoperative week following pulpotomy¹¹. Bastos et al. similarly reported favorable clinical and radiographic outcomes for pulpotomy across primary and permanent teeth in their 2024 systematic review and meta-analysis¹². Although these studies predominantly involve mature teeth or mixed dentitions and therefore are not directly equivalent to the present population, they provide additional support for the broader biological and clinical role of contemporary pulpotomy.

A 2025 systematic review and meta-analysis focused specifically on vital pulp treatment in children and adolescents also supports the present therapeutic concept. Asgary et al. analyzed randomized clinical trials involving vital permanent teeth and found that contemporary pulp-preserving approaches, including MTA-based therapy, provided effective outcomes, although uncertainty remained regarding the relative performance of individual treatment protocols and materials¹⁵. The consistency between this evidence and the present clinical observations supports continued investigation of conservative pulp therapy in young permanent teeth.

Another relevant consideration is crown discoloration. In the present study, crown discoloration was observed in 8 of the 14 teeth treated with Trioxident (57.1%). This finding is clinically important because the assessment of treatment success should consider not only pulpal and periapical healing but also clinically relevant changes in tooth appearance. Recent systematic evidence has identified discoloration as a recognized limitation of some calcium silicate-based materials. Coll et al. reported greater discoloration with MTA than with Biodentine in their evidence synthesis, while Immich et al. similarly found a greater discoloration tendency associated with MTA compared with premixed calcium silicate-based materials^{3,7}. However, the present study cannot establish a causal relationship between Trioxident and the observed discoloration because an objective colorimetric assessment was not performed.

The 2026 network meta-analysis by Elmsmari et al. further emphasizes the complexity of comparing bioactive materials. In mature permanent teeth, MTA remained an important reference material, but several newer calcium silicate-based materials demonstrated outcomes that were not significantly different from MTA in the analyzed comparisons⁸. The significance of this evidence for the present study is methodological rather than direct, because the present investigation concerns immature teeth. Nevertheless, it reinforces the need to avoid interpreting numerical differences between individual calcium silicate materials as evidence of superiority without appropriately powered comparative studies.

The 2025 systematic review by Pusa et al. likewise demonstrated favorable overall outcomes for vital pulp therapy in pulp-exposed permanent teeth, although the magnitude of success varied according to treatment modality, follow-up duration, and clinical circumstances⁹. These observations are consistent with the present findings, in which favorable clinical and radiographic responses were observed over follow-up but a statistically significant difference between Trioxident and MTA could not be demonstrated.

A further strength of the present study is the inclusion of longer-term radiographic assessment rather than restricting evaluation to the immediate postoperative period. Continued root elongation, canal narrowing, and apical closure represent clinically meaningful outcomes in immature permanent teeth because they indicate that the tooth retained the capacity for further maturation. The evidence summarized in recent systematic reviews indicates that longer follow-up is particularly important in evaluating VPT, since early clinical success does not necessarily predict long-term biological stability^{3,6,7}.

At the same time, the findings should not be interpreted as establishing equivalence between Trioxident and ProRoot MTA. Trioxident is considerably less extensively studied in the contemporary clinical literature than established MTA-based materials. Most recent evidence syntheses focus on MTA, Biodentine, premixed calcium silicate materials, or other widely investigated hydraulic cements^{4,7-9}. The present study therefore contributes preliminary clinical evidence concerning Trioxident in a specific population of immature permanent teeth, but it does not provide sufficient evidence to establish non-inferiority, equivalence, or superiority. The difference in periapical complication rates observed in the present study may nonetheless be clinically relevant as a hypothesis-generating observation. Complications occurred in 21.4% of Trioxident-treated teeth compared with 7.69% of MTA-treated teeth, but the difference was not statistically significant. Possible explanations for such numerical variation may include the small sample size, differences in the severity of pulpal inflammation, anatomical characteristics of individual teeth, technical factors, and the biological variability of immature pulp tissue. Because these factors were not independently controlled in the present study, attribution of the difference to the material itself would be inappropriate.

The principal scientific contribution of the study is therefore the direct clinical comparison of Trioxident and ProRoot MTA in immature permanent teeth with incomplete root development, with emphasis on both clinical findings and continued physiological root maturation. The study suggests that vital pulpotomy can preserve the developmental potential of immature permanent teeth and provides preliminary evidence supporting further clinical evaluation of Trioxident as a potentially accessible calcium-containing material.

Several limitations should be acknowledged. The sample size was small, comprising 20 patients and 27 treated teeth, which limits statistical power and makes detection of modest between-group differences

difficult. The available study description does not indicate randomized treatment allocation or blinded clinical and radiographic outcome assessment. The follow-up intervals varied according to the stage of root development, and quantitative measurements of root length, dentinal wall thickness, and apical diameter were not reported. Crown discoloration was assessed clinically without standardized colorimetric measurements. These limitations reduce the strength of causal and comparative conclusions.

Future research should therefore include larger prospective multicenter studies and, where ethically and clinically feasible, randomized controlled trials comparing Trioxident with ProRoot MTA and other contemporary calcium silicate-based materials. Standardized diagnostic criteria, predefined treatment protocols, objective radiographic measurements, quantitative assessment of tooth color, and long-term follow-up should be incorporated. Particular attention should be given to immature permanent teeth because the preservation of pulp vitality and continued root development may provide benefits that cannot be captured by conventional short-term measures of endodontic success. Overall, the present findings are in agreement with the growing body of evidence supporting vital pulp therapy as a biologically conservative approach to selected permanent teeth. Within the limitations of the present study, both Trioxident and ProRoot MTA were associated with favorable clinical and radiographic findings, including continued root development. The higher numerical frequency of periapical complications in the Trioxident group was not statistically significant, while crown discoloration occurred in 57.1% of Trioxident-treated teeth. These findings support continued investigation of Trioxident but do not justify a conclusion of superiority or equivalence relative to ProRoot MTA.

DECLARATIONS

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The work was not funded.

Data Sharing

Not applicable

Ethical Approval

“Not applicable”

Ethics approval

This study was conducted in accordance with the ethical principles of the World Medical Association Declaration of Helsinki, as revised in 2024. The study protocol was reviewed and approved by the Ethics Committee of Yerevan State Medical University after Mkhitar Heratsi (YSMU).

Consent for publication

Written informed consent for publication of the clinical case and accompanying clinical and radiographic images

Authors' contributions

All authors contributed to the conception and design of the study, clinical treatment, data collection, interpretation of the findings, and preparation and revision of the manuscript. All authors approved the final version of the manuscript.

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REVIEW ARTICLE

DENTAL IMPLANT DISPLACEMENT INTO THE MAXILLARY SINUS: AN EVIDENCE-INFORMED CLINICAL REVIEW AND ANATOMY-DRIVEN MANAGEMENT ALGORITHM—A NARRATIVE REVIEW

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Abstract

Background: Displacement of a dental implant into the maxillary sinus is uncommon but clinically important. Management is complicated by inconsistent terminology and by the need to distinguish a stable, osseointegrated implant that merely protrudes radiographically beyond the sinus floor from a truly displaced implant that has lost bony support and migrated into the sinus cavity.

Objective: To provide a focused, clinically oriented synthesis of the etiology, risk factors, diagnosis, complications, prevention, and management of dental implant displacement into the maxillary sinus, and to propose an anatomy-driven decision framework integrating implant stability, three-dimensional location, sinus health, oroantral pathology, and surgical accessibility.

Methods: A focused narrative review was performed using PubMed/MEDLINE as the principal database, supplemented by reference-list screening of relevant systematic reviews, consensus statements, cohort studies, case series, and clinically informative case reports. Search concepts included dental implant displacement or migration, maxillary sinus, sinus floor elevation, implant protrusion, CBCT, foreign body removal, endoscopic sinus surgery, transoral retrieval, Caldwell-Luc, and odontogenic sinusitis. Evidence from systematic reviews, larger clinical series, and multidisciplinary consensus statements was prioritized for general recommendations; case reports and small series were used primarily to illustrate unusual locations and technical approaches. No meta-analysis or formal risk-of-bias grading was performed.

Results: Implant displacement is multifactorial. Reduced residual bone height, posterior maxillary atrophy, poor bone quality, inadequate primary stability, inappropriate implant dimensions or trajectory, excessive insertion force, sinus augmentation-related complications, and subsequent loss of osseous support may contribute. CBCT is central when true displacement is suspected because it defines implant location, residual support, sinus anatomy, mucosal disease, and accessibility. A stable implant with preserved osseous support and limited radiographic sinus protrusion should not be equated with a freely displaced implant. For true displacement, retrieval is generally favored, with timing and route individualized according to symptoms, sinus pathology, oroantral communication, implant mobility and location, ostiomeatal drainage, and surgical accessibility. Transoral, transnasal endoscopic, endoscope-assisted, and combined approaches each have appropriate indications.

Conclusion: Treatment should not be determined by radiographic sinus penetration alone. The decisive variables are implant stability, three-dimensional location, sinus health, anatomical accessibility, and associated oroantral or sinonasal disease. Prevention through three-dimensional planning and reliable primary stability remains fundamental. The proposed algorithm is an evidence-informed expert synthesis and requires prospective clinical validation.

Keywords: dental implant; implant displacement; implant migration; maxillary sinus; CBCT; sinusitis; endoscopic surgery; transoral retrieval; oroantral communication; clinical algorithm.

1. INTRODUCTION

Dental implants are an established treatment modality for the rehabilitation of partially and completely edentulous patients. Implant placement in the posterior maxilla, however, remains technically demanding because tooth loss is commonly followed by alveolar ridge resorption and progressive pneumatization of the maxillary sinus. The resulting reduction in residual vertical bone height and the relatively low-density bone frequently encountered in this region can compromise implant anchorage and primary stability.^{1–3}

Sinus floor elevation has substantially expanded the indications for implant rehabilitation in the atrophic posterior maxilla and is generally associated with favorable implant survival.^{1–3} The development of contemporary sinus floor elevation was founded on the pioneering work of Boyne and James, who described grafting of the maxillary sinus floor with autogenous marrow and bone, followed by the development of maxillary and sinus implant reconstruction techniques described by Tatum.^{4,5} Nevertheless, sinus augmentation introduces specific intraoperative and postoperative complications.⁶ Schneiderian membrane perforation is among the most frequently reported intraoperative events, whereas postoperative complications may include infection, graft-related complications, wound problems, and sinus pathology.^{7–9} Changes in the augmented sinus volume may also occur over time and should be considered during long-term treatment assessment.¹⁰

One uncommon but clinically important complication is displacement of a dental implant into the maxillary sinus. Implant displacement may occur during implant insertion, in the early postoperative period, or later following loss of osseous support.^{11–13} Reported contributing factors include insufficient residual bone height, inadequate primary stability, poor bone quality, inappropriate implant dimensions or positioning, excessive insertion forces, complications associated with sinus augmentation, failure of osseointegration, and progressive loss of supporting bone.^{12–16} Implant displacement has also been reported following internal sinus floor elevation and may occur in both grafted and nongrafted maxillary sinuses.^{14,17}

The clinical presentation of displaced implants is heterogeneous. Retrospective studies and clinical reports have demonstrated variability in the timing of displacement, implant position, associated symptoms, and underlying anatomical conditions.^{13,18} Implant displacement may be associated with local or

sinonasal complications and therefore requires individualized clinical assessment.^{15,18}

Treatment of dental implant displacement into the maxillary sinus represents a distinct clinical problem. Published clinical studies have described different therapeutic strategies according to implant location, mobility, sinus condition, and accessibility.^{19–22} Foreign bodies of dental or iatrogenic origin may similarly require surgical retrieval when they remain within the maxillary sinus or produce associated complications.^{20–22}

Accurate imaging is essential for determining the anatomical position of a displaced implant and for selecting an appropriate treatment strategy. Cone-beam computed tomography (CBCT) can provide three-dimensional information regarding the relationship of the implant to the sinus floor, sinus walls, surrounding bone, and adjacent anatomical structures.²³ The radiographic appearance of an implant within or protruding into the maxillary sinus should, however, be interpreted in the context of implant stability and osseous support.

Terminology is clinically important because radiographic penetration of an implant into the maxillary sinus does not necessarily represent true displacement. An otherwise stable and osseointegrated implant with limited radiographic protrusion beyond the sinus floor may remain clinically functional and does not automatically require removal.²⁴ In contrast, an implant that has lost osseous support and is mobile or freely located within the sinus cavity represents true displacement and requires a different clinical assessment. The distinction is particularly important because treatment should not be based on radiographic appearance alone but should incorporate implant stability, three-dimensional position, sinus condition, symptoms, and associated oroantral or sinonasal pathology.²⁴

The distinction between radiographic protrusion and true displacement has been specifically addressed by an international multidisciplinary consensus. The consensus emphasized that radiographic protrusion of an osseointegrated implant into the maxillary sinus or nasal fossae should be distinguished from actual displacement and that management should take into account clinical symptoms and associated sinonasal disease.²⁴ This distinction provides an important clinical basis for avoiding unnecessary implant removal while ensuring appropriate treatment when true displacement or sinonasal complications are present.

Several surgical approaches have been described for removal of displaced implants from the maxillary sinus. These include transoral retrieval through the alveolar ridge or lateral sinus wall, Caldwell–Luc-type approaches, transnasal endoscopic removal, endoscope-

assisted transoral techniques, and combined approaches.^{19, 21, 22, 25}

The choice of approach depends on the three-dimensional location of the implant, its mobility, the condition of the sinus, the presence of oroantral communication or infection, the status of the ostiomeatal drainage pathway, and the accessibility of the foreign body.^{20–25}

Endoscope-assisted transoral retrieval has been described as a minimally invasive alternative for selected implants displaced into the maxillary sinus.²⁶ Other reports have documented unusual implant migration and emphasize that implant location may change over time or become difficult to localize clinically.²⁷ Transnasal endoscopic techniques have also been successfully used for retrieval of migrated implants through the nasal cavity and sinus drainage pathway.²⁸ These reports support an individualized, anatomy-driven approach to surgical retrieval.

More recent evidence has further contributed to the development of structured management strategies. A multicenter retrospective cohort study evaluated implant displacement into the maxillary sinus and proposed a management protocol based on the clinical and anatomical characteristics of individual cases.²⁹ Such evidence is particularly relevant to the development of standardized clinical pathways for diagnosis, observation, retrieval, and multidisciplinary treatment.

The condition of the maxillary sinus is another important component of treatment planning. When implant displacement is accompanied by sinus inflammation or other sinonasal disease, collaboration among oral and maxillofacial surgeons, implant clinicians, and otorhinolaryngologists may be appropriate. Current multidisciplinary consensus statements on odontogenic sinusitis emphasize the importance of identifying the dental source, evaluating sinonasal disease, and coordinating treatment when both dental and sinonasal pathology are present.^{30, 31} The European Position Paper on Rhinosinusitis and Nasal Polyps also provides a broader framework for the assessment and management of sinonasal disease and its relevant anatomical and inflammatory features.³²

A displaced implant may remain asymptomatic, particularly when it does not interfere with sinus drainage or produce significant mucosal irritation. However, symptomatic cases may present with facial discomfort, nasal obstruction, malodor, recurrent sinonasal symptoms, maxillary sinusitis, or oroantral communication.^{11, 13, 15, 20–22}

The clinical significance of these findings depends on the implant's exact location, degree of mobility, relationship to the sinus walls and drainage pathway, and the presence of associated sinonasal pathology.^{11, 24, 29}

Three-dimensional imaging, particularly CBCT, therefore plays a central role when implant displacement is suspected. CBCT can establish the precise three-dimensional position of the implant and its relationship to the sinus walls, residual osseous support, sinus floor, and adjacent anatomical structures.^{23, 24} It can also provide information regarding mucosal thickening, opacification, bony defects, and other findings relevant to surgical planning.²³

In patients with suspected odontogenic or implant-related sinus disease, radiographic assessment should be interpreted together with the clinical sinonasal findings because the presence and severity of sinus pathology may influence both treatment timing and the choice of surgical approach.^{30–32}

The available literature remains heterogeneous and consists of systematic reviews, retrospective studies, case series, and case reports, with substantial variation in patient characteristics, mechanisms of displacement, clinical presentation, imaging findings, associated sinus pathology, and treatment strategies.^{11–29}

Although recent consensus statements and multicenter clinical studies provide a more structured evidence base, differences remain in the terminology used to describe implant protrusion and displacement and in the indications for retrieval.^{24, 29}

Despite these contributions, a clinically practical framework that clearly separates stable radiographic protrusion from true displacement and integrates implant stability, three-dimensional anatomy, sinus health, oroantral pathology, and surgical accessibility remains useful. Such a framework may help clinicians avoid unnecessary intervention in stable implants while facilitating timely multidisciplinary management of mobile or displaced implants associated with sinonasal disease.

The aim of this focused narrative review is therefore to synthesize current evidence on the etiology, risk factors, diagnosis, complications, prevention, and management of dental implant displacement into the maxillary sinus, with particular emphasis on (1) distinguishing stable radiographic protrusion from true displacement, (2) defining the role of CBCT and systematic sinonasal assessment, and (3) providing an anatomy-driven approach to observation, retrieval, and multidisciplinary management.

2. METHODS

2.1 Review design and scope

This article was designed as a focused narrative review rather than a systematic review or meta-analysis. The objective was to integrate clinically relevant evidence across implantology, oral and maxillofacial surgery, radiology, and otorhinolaryngology, with particular emphasis on clinical decision-making, diagnostic assessment, prevention, and management rather than quantitative estimation of treatment effects.¹¹⁻²⁴⁻²⁵⁻²⁹

The review focused on dental implants protruding into, displaced into, or migrating within the maxillary sinus. Literature concerning sinus floor elevation, Schneiderian membrane perforation, odontogenic sinusitis, peri-implant disease, and other maxillary sinus foreign bodies was included when it directly informed the mechanisms, diagnosis, complications, prevention, or management of implant displacement or migration.⁶⁻¹⁰⁻¹¹⁻²⁵⁻³⁰⁻³²

2.2 Literature identification

PubMed/MEDLINE was used as the principal bibliographic database. Reference lists of relevant systematic reviews, consensus statements, and previously published reviews were also screened to identify additional clinically important publications.⁷⁻¹¹⁻²¹⁻²⁴⁻²⁹

Search concepts included combinations of the terms *dental implant displacement*, *dental implant migration*, *implant migration into maxillary sinus*, *dental implant displaced into maxillary sinus*, *maxillary sinus*, *sinus floor elevation*, *sinus augmentation*, *implant protrusion*, *foreign body maxillary sinus*, *CBCT*, *endoscopic removal*, *functional endoscopic sinus surgery*, *transoral removal*, *Caldwell-Luc*, and *odontogenic sinusitis*. Boolean operators AND and OR were used where appropriate.

Before submission, the authors should report the final search date and, where available, the complete PubMed search strategy to facilitate reproducibility. If additional bibliographic databases were searched, these should also be explicitly identified.

2.3 Selection and evidence interpretation

Publications were considered relevant when they addressed mechanisms or causes of implant displacement, anatomical or surgical risk factors, sinus floor elevation-related complications, clinical or

sinonasal manifestations, radiographic or CBCT diagnosis, differentiation of sinus protrusion from true displacement, surgical retrieval, endoscopic or transoral management, multidisciplinary treatment, or preventive strategies.¹¹⁻²⁹⁻³⁰⁻³²

Systematic reviews, larger clinical or multicenter studies, and multidisciplinary consensus statements were given greatest weight when formulating general clinical statements.⁷⁻⁸⁻⁹⁻¹¹⁻²¹⁻²⁴⁻²⁹

Case reports and small case series were retained when they provided clinically relevant information about unusual mechanisms, remote migration, uncommon anatomical locations, or specific retrieval techniques.¹²⁻¹⁸⁻²⁶⁻²⁸ Case reports were not used to infer comparative treatment efficacy.

Because this was a narrative review, no formal risk-of-bias assessment, evidence grading system, or meta-analysis was performed. Consequently, recommendations in this article should be interpreted according to the strength and design of the underlying literature. The management algorithm proposed below represents an evidence-informed expert synthesis rather than a formally validated clinical guideline.

3. Evidence Synthesis

3.1 Etiology and risk factors

Dental implant displacement into the maxillary sinus is best understood as a multifactorial complication involving anatomical, biomechanical, implant-related, surgical, sinus augmentation-related, and biological factors. The posterior maxilla is particularly susceptible because alveolar resorption after tooth loss frequently occurs together with progressive sinus pneumatization. Reduced residual bone height can leave insufficient cortical or cancellous bone for predictable implant anchorage.¹⁻³⁻¹¹⁻¹⁵

Bone quality is also relevant. Relatively low-density posterior maxillary bone may provide limited resistance during implant insertion. When an implant is placed in a severely atrophic site with inadequate cortical or cancellous support, primary stability may be insufficient, facilitating immediate displacement or later loss of fixation.¹⁻³⁻¹²⁻¹³

Sinus floor elevation creates an additional context in which displacement can occur. Manipulation of the Schneiderian membrane, limited residual bone, inadequate osteotomy preparation, inappropriate implant trajectory, insufficient primary stability, or postoperative loss of support may contribute.⁶⁻⁹⁻¹⁷⁻¹⁸

Biological failure represents a different pathway: an initially positioned implant may later lose support because of failed osseointegration, peri-implant bone loss, or other progressive loss of fixation.^{14–16}

The principal risk domains and their potential contributions are summarized in Table 1.

Table 1. Principal risk domains associated with implant displacement into the maxillary sinus

Risk domain	Examples	Potential contribution	Typical evidence base
Anatomical	Reduced residual bone height; sinus pneumatization; thin alveolar ridge	Insufficient bony support and reduced anchorage	Systematic reviews; clinical studies
Bone-related	Low-density bone; severe posterior maxillary atrophy	Reduced primary stability	Clinical studies; mechanistic evidence
Implant-related	Inappropriate length/diameter; unfavorable three-dimensional positioning	Loss of fixation or sinus penetration	Retrospective studies; case series
Surgical	Excessive insertion force; inadequate osteotomy; uncontrolled trajectory	Immediate displacement during placement	Case series; case reports
Sinus augmentation-related	Membrane perforation; insufficient residual bone; inappropriate elevation technique	Instability and sinus-related complications	Systematic reviews; clinical studies
Biological	Failure of osseointegration; progressive peri-implant bone loss	Delayed loss of support and possible migration	Clinical studies; case series
Postoperative	Functional loading of an inadequately stabilized implant	Delayed displacement after loss of fixation	Case series; mechanistic evidence

3.2 Mechanisms: immediate displacement and delayed migration

Two broad clinical mechanisms can be distinguished. Immediate displacement usually occurs during implant insertion or shortly thereafter when an implant placed in a severely atrophic posterior maxilla encounters insufficient resistance from the surrounding bone. The implant may penetrate the sinus floor and become partially or completely displaced into the sinus cavity.¹²⁻¹³⁻¹⁷⁻¹⁸

Delayed migration represents a different biological and mechanical process. An implant initially positioned within alveolar bone may subsequently lose support because of inadequate osseointegration, biological complications, progressive peri-implant bone loss, or mechanical failure.^{14–16} Once sufficient support has been lost, the implant may migrate toward or into the sinus. The final position may influence symptoms, associated sinus pathology, and the feasibility of retrieval.¹⁵⁻¹⁶

3.3 Stable sinus protrusion is not synonymous with displacement

A key diagnostic distinction is between radiographic sinus protrusion and true displacement. An implant that extends beyond the radiographic sinus floor but remains osseointegrated and supported by bone should not automatically be classified as migrated. Multidisciplinary consensus has emphasized that the clinical significance of protrusion should be interpreted in relation to implant stability, symptoms, and sinonasal pathology.²⁴

No universally validated dimensional threshold defines an acceptable depth of sinus protrusion. Therefore, management should not be based on millimeters of radiographic penetration alone. Stability, residual support, mucosal and sinonasal status, and longitudinal clinical findings are more relevant than protrusion depth in isolation.²⁴

This subsection is important and should definitely remain. It prevents an overly simplistic conclusion that every implant penetrating the sinus is a displaced implant requiring removal.

3.4 Diagnosis and the role of CBCT

Diagnosis requires integration of clinical history, intraoral examination, conventional radiography, and three-dimensional imaging when true displacement or sinus complications are suspected. The history should establish the timing of implant placement, previous sinus augmentation, onset of symptoms, and any prior attempts at retrieval.^{11–19}

Panoramic or periapical imaging may provide an initial overview, but CBCT is particularly valuable for defining the implant's three-dimensional position and relationship to residual bone, the sinus floor and walls, adjacent teeth, mucosal changes, and potential access routes.^{23,24} Imaging should also assess whether the implant remains partially supported by bone or is freely displaced, and whether sinonasal abnormalities or obstruction of the ostiomeatal drainage pathway are present.^{23,24}

ENT assessment is appropriate when significant sinonasal symptoms, chronic sinus disease, ostiomeatal complex involvement, or the need for endoscopic sinus surgery is suspected.^{30–32} The main components of the diagnostic assessment are summarized in Table 2.

Table 2. Diagnostic assessment of suspected implant displacement

Component	Purpose	Key findings
Clinical history	Define timing and mechanism	Immediate vs delayed event; prior augmentation; onset and duration of symptoms
Intraoral examination	Assess local status	Wound healing; mobility; infection; oroantral communication/fistula
Panoramic/periapical imaging	Initial localization	Gross implant position; relation to sinus floor
CBCT	Three-dimensional assessment	Exact location; residual support; sinus walls; mucosal changes; access route
Sinonasal assessment	Identify associated disease	Mucosal thickening; fluid; opacification; inflammatory changes
Oroantral assessment	Detect communication	Communication between oral cavity and maxillary sinus
ENT evaluation when indicated	Assess sinus function and drainage	Sinusitis; ostiomeatal obstruction; chronic sinonasal disease

3.5 Clinical complications

The clinical consequences of displacement vary substantially. Some displaced implants remain asymptomatic, whereas others are associated with local discomfort, malodor, nasal symptoms, inflammatory changes, recurrent infection, maxillary sinusitis, or oroantral communication.^{11–13 15 20–22}

The presence of a foreign body does not, by itself, establish sinusitis. Clinical and radiological assessment should distinguish an asymptomatic foreign body from established odontogenic sinonasal disease. Conversely, sinus symptoms after implant placement should not automatically be attributed to implant migration, because odontogenic sinusitis and other sinonasal disorders may produce overlapping manifestations.^{30–32}

Published systematic-review data indicate that a substantial proportion of reported patients with true displacement become symptomatic and that sinusitis and/or oroantral communication are common associated findings.¹¹ This supports timely evaluation and, for a freely displaced implant, generally favors retrieval rather than indefinite observation.^{11, 29}

3.6 Prevention

Prevention begins with three-dimensional treatment planning. In patients with substantial posterior maxillary atrophy or an uncertain relationship between the alveolar ridge and maxillary sinus, CBCT should be considered to define residual bone volume, sinus anatomy, and relevant anatomical limitations.^{23, 24}

Implant dimensions and trajectory should be selected according to available bone, anatomical constraints, and prosthetic requirements. When residual bone is insufficient to provide predictable primary stability, sinus floor elevation or another appropriate augmentation strategy may be preferable to placement of an inadequately supported implant.^{1–3, 10} Careful osteotomy preparation, controlled insertion, appropriate management of the Schneiderian membrane during augmentation, and verification of primary stability are central preventive measures.^{7–9} Postoperative radiographic assessment should be obtained when displacement or another complication is suspected.^{11, 23, 24} Key preventive measures and their corresponding clinical objectives are summarized in Table 3.

Table 3. Preventive measures and clinical objectives

Preventive measure	Clinical objective
Preoperative three-dimensional assessment when indicated	Define residual bone volume, sinus anatomy, and limitations
Assessment of residual bone height and quality	Determine feasibility of conventional placement and expected primary stability
Appropriate implant dimensions	Avoid inadequate anchorage or unnecessary sinus penetration
Prosthetically driven three-dimensional planning	Establish appropriate trajectory and final position
Controlled osteotomy and insertion	Maintain planned trajectory and depth; reduce uncontrolled displacement
Careful Schneiderian membrane management	Reduce augmentation-related complications
Verification of primary stability	Identify implants at risk of early loss of fixation
Postoperative imaging when clinically indicated	Detect displacement or associated complications early

4. Clinical Decision-Making and Management

4.1 Is removal always indicated?

Management depends first on whether the implant is stable and supported by bone or has become a freely displaced foreign body. These are not equivalent clinical entities.^{11, 24}

For an osseointegrated implant with preserved support and radiographic sinus protrusion, absence of significant sinonasal disease may justify individualized clinical and radiological follow-up rather than prophylactic removal.²⁴ If sinus symptoms develop, evaluation should involve both the implant provider and an otorhinolaryngologist; treatment should address the sinus disease and the implant should not be removed solely because it protrudes radiographically.²⁴

For a truly displaced, mobile, or freely located implant, the balance is different. The systematic-review literature supports retrieval, in part to prevent infectious complications.¹¹ The urgency and route of retrieval should nevertheless be individualized according to symptoms, sinus pathology, oroantral communication, implant location and mobility, anatomical accessibility, and the experience of the treating team.^{11, 19, 21, 25, 29}

When sinusitis or other odontogenic sinonasal disease is present, dental/maxillofacial and ENT management should be coordinated. Multidisciplinary consensus on odontogenic sinusitis supports shared decision-making between dental and otorhinolaryngology providers, particularly when endoscopic sinus surgery may be required.^{30, 31}

4.2 Selection of the retrieval route

Transoral retrieval provides direct access through the alveolar ridge or lateral wall of the maxillary sinus and is particularly useful when the implant is close to the sinus floor or lateral wall, when an oroantral communication already provides access, or when a limited lateral window can reach the implant predictably.^{25–27}

Caldwell-Luc-type access provides broad exposure but is more invasive and should generally be reserved for situations in which less invasive routes do not provide adequate access.^{21,25}

Transnasal endoscopic removal offers direct visualization of the sinus through a minimally invasive route and is particularly attractive when the implant is accessible through the nasal pathway, when sinonasal disease requires simultaneous treatment, or when the implant lies near the natural drainage pathway.^{19,20,28}

Endoscope-assisted transoral techniques combine direct oral access with enhanced visualization and may be useful when an implant is difficult to visualize or grasp through a conventional transoral window.²⁶ Combined oral and endonasal approaches may be appropriate for complex anatomy, oroantral fistula, significant sinus disease, or migration toward anatomically remote compartments.^{25,29}

The choice of technique should therefore be anatomy-driven rather than based on a universal preference for one surgical route. The principal retrieval approaches, their advantages, limitations, and clinical indications are compared in Table 4.

Table 4. Comparison of principal retrieval approaches

Approach	Main advantages	Limitations	Particularly useful when
Transoral/lateral	Direct access; familiar to oral and maxillofacial surgeons	May require a larger bony window; postoperative morbidity	Implant is near sinus floor/lateral wall or oral access is direct
Caldwell-Luc-type	Broad access to sinus cavity	More invasive; greater morbidity	Foreign body cannot be accessed adequately by less invasive routes
Transnasal endoscopic	Direct visualization; minimally invasive; can treat sinonasal disease	Requires suitable anatomy and endoscopic expertise	Nasal route is favorable or concomitant sinus disease requires treatment
Endoscope-assisted transoral	Direct oral access plus enhanced visualization	Requires equipment and expertise	Implant is difficult to visualize/grasp through conventional oral access
Combined approach	Addresses oral and sinonasal components	More complex procedure	Sinus disease, fistula, difficult anatomy, or remote migration coexist

4.3 Proposed Anatomy-Driven Management Algorithm

Based on the available evidence, we propose an anatomy-driven algorithm for the clinical management of dental implants protruding into or displaced into the maxillary sinus. The initial assessment should integrate the clinical history, intraoral examination, and CBCT to determine implant stability, residual osseous support, exact three-dimensional location, relationship to the sinus floor and walls, sinonasal status, oroantral communication or fistula, and anatomical accessibility.^{23,24} The implant should then be classified as either a stable implant with preserved osseous support and radiographic sinus protrusion or a true displaced implant with loss of osseous support.²⁴ Stable protrusion without significant symptoms or sinonasal pathology may be managed with individualized clinical and radiological follow-up, whereas a freely displaced implant generally favors retrieval.^{11,24}

When sinusitis or other relevant sinonasal pathology is present, implant retrieval should be coordinated with appropriate treatment of the sinus disease.^{29–32} The retrieval route should subsequently be selected according to the three-dimensional location and accessibility of the implant, the presence of sinonasal disease or oroantral communication, and the

experience of the treating team.^{19–29} Transoral/lateral, transnasal endoscopic, endoscope-assisted transoral, Caldwell–Luc-type, or combined approaches may therefore be selected according to the individual anatomical and clinical circumstances.^{19–29} This algorithm emphasizes individualized, anatomy-driven management rather than a universal preference for a single surgical technique **Figure 1**.

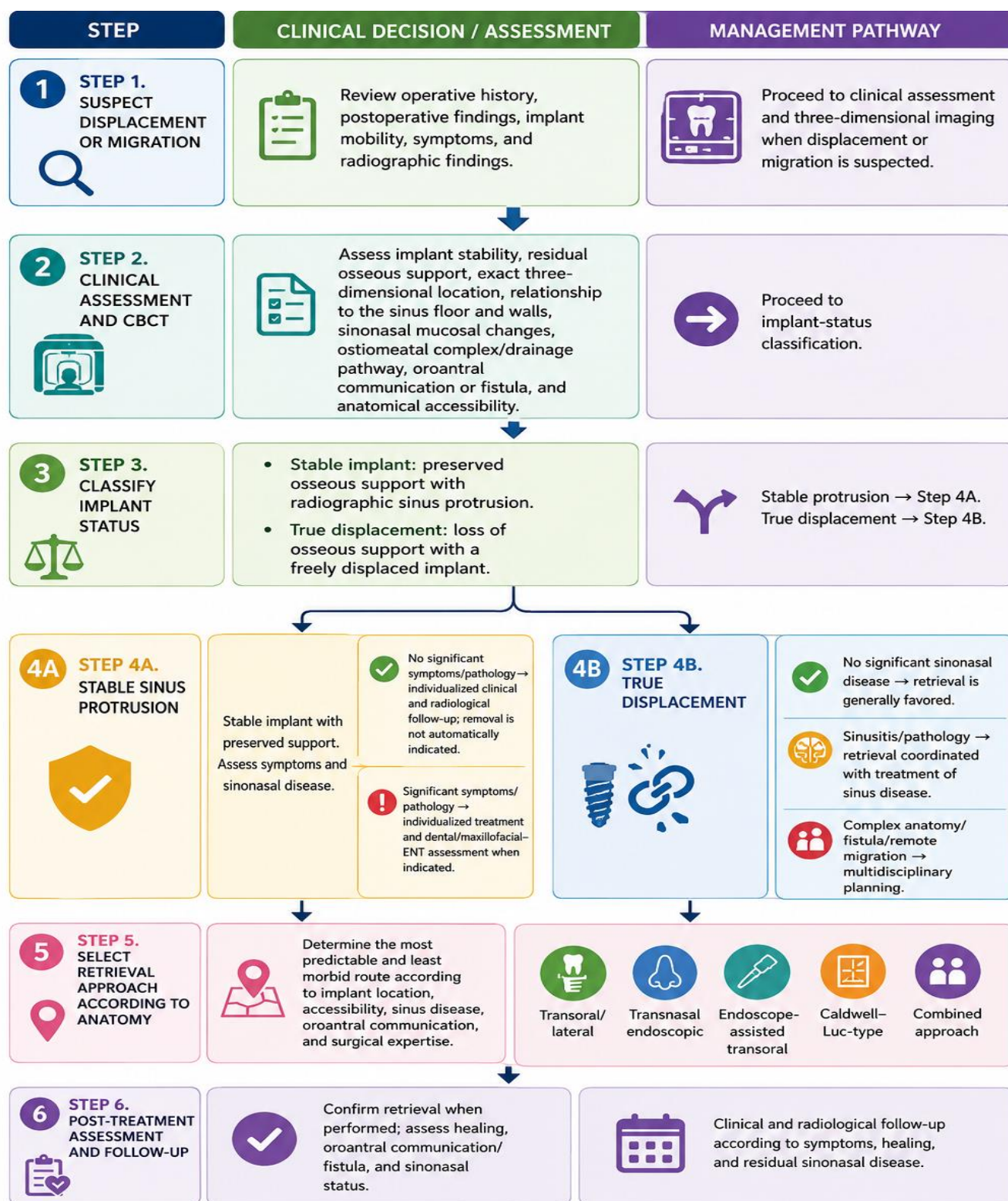


Figure 1. Proposed anatomy-driven clinical management algorithm

Important: This algorithm represents an evidence-informed expert synthesis and has not undergone prospective clinical validation. It should therefore not be interpreted as a formal clinical guideline or as a substitute for individualized clinical judgment.

5. Clinical Illustrations

Clinical illustration of implant displacement into the maxillary sinus The radiological presentation of a dental implant displaced into the maxillary sinus is illustrated in Figure 2. This clinical illustration emphasizes the importance of accurate imaging for confirming implant displacement and guiding individualized management and selection of the appropriate retrieval approach. The CT image was kindly provided by Dr. Karen Grigoryan



Figure 2. Clinical and radiological illustration of dental implant displacement into the maxillary sinus.

The schematic illustrations demonstrate the displacement of the dental implant into the maxillary sinus and its subsequent transoral surgical removal. **Figure 3. Panel A** illustrates the displaced implant within the maxillary sinus. **Panel B** demonstrates the transoral surgical approach and the removal of the displaced implant from the maxillary sinus through the selected access pathway. Together, the schematic illustrations demonstrate the displacement of the implant and its surgical removal.

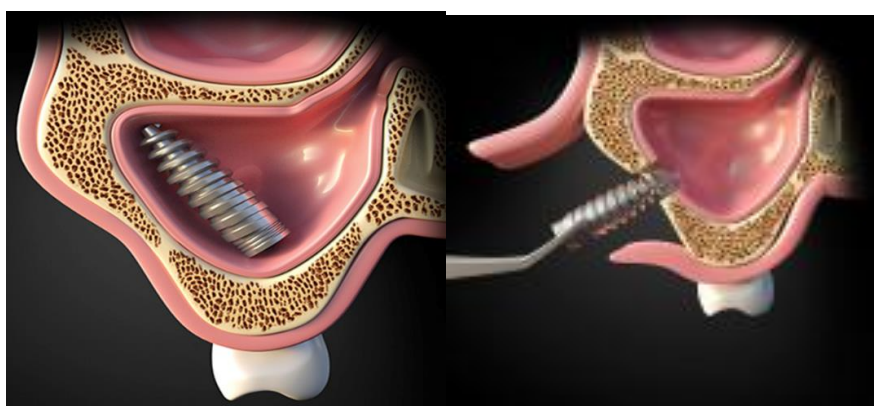


Figure 3. Schematic illustration of dental implant displacement into the maxillary sinus and transoral surgical removal. (A) Displacement of the dental implant into the maxillary sinus. (B) Transoral surgical removal of the displaced implant

6. DISCUSSION

The principal clinical message of this review is that radiographic protrusion of a dental implant beyond the maxillary sinus floor and true implant displacement are distinct clinical entities. This distinction is clinically important because the available literature provides different recommendations depending on implant stability and residual osseous support. A systematic review of displaced implants emphasized appropriate retrieval because of the potential for

infectious complications, whereas the multidisciplinary Delphi consensus on radiographic implant protrusion indicated that stable, osseointegrated implants with preserved support should not be removed solely because of sinus penetration.¹¹⁻²⁴ These findings support the use of implant stability and residual bone support as the initial determinants of management.¹¹⁻²⁴

Implant displacement is multifactorial and may result from the combination of anatomical, biomechanical, surgical, implant-related, and biological factors. The

posterior maxilla is particularly susceptible because alveolar resorption and sinus pneumatization may result in limited residual bone height, while relatively low-density bone can reduce primary stability.^{1,3,4,5,10} Immediate displacement may occur during implant placement, whereas delayed migration may follow failure of osseointegration, progressive peri-implant bone loss, or loss of mechanical fixation.^{12–18} The timing and mechanism of displacement should therefore be considered when interpreting clinical and radiological findings.^{12–18}

The anatomical position of a displaced implant is a major determinant of treatment. Implants located near the sinus floor or lateral wall may be accessible through a transoral or lateral approach, whereas transnasal endoscopy may be preferable when the implant is accessible through the nasal pathway or when associated sinonasal disease requires endoscopic treatment.^{19,20,25,26,28,29} Endoscope-assisted transoral techniques may improve visualization in selected cases, while combined approaches may be necessary for complex anatomy, oroantral fistula, significant sinus disease, or remote migration.^{15,16,25,28,36,38} Consequently, no single retrieval technique can be considered universally superior.^{11,19,21,22,25,29}

CBCT is central to this approach because it provides three-dimensional information that may not be adequately obtained from panoramic or periapical imaging. It allows assessment of implant position, residual osseous support, sinus walls, adjacent structures, mucosal changes, and potential surgical access routes.^{23,24} CBCT-based evaluation is also particularly relevant when a foreign body is suspected within the maxillary sinus or when the precise anatomical relationship between the implant and the sinus structures must be established.²³

However, imaging findings must be interpreted together with clinical symptoms and sinonasal findings. Radiographic sinus penetration or mucosal thickening alone does not establish symptomatic odontogenic sinusitis, and sinonasal symptoms should not automatically be attributed to the displaced implant. When sinonasal disease is present, management may require coordinated dental/maxillofacial and ENT care. Contemporary consensus statements on odontogenic sinusitis emphasize multidisciplinary diagnosis and treatment, particularly when chronic disease or obstruction of the ostiomeatal complex is present.^{30–32} In these situations, successful treatment may require both removal of the dental/foreign-body source and appropriate management of the sinus pathology.^{30,31}

The clinical consequences of displacement should also be interpreted in the context of the broader literature on foreign bodies within the maxillary sinus. Retrospective and systematic-review evidence has documented a range of presentations, including asymptomatic cases, sinus inflammation, infection, and oroantral communication.^{11,20–22} The presence of a foreign body within the sinus does not necessarily produce immediate symptoms, but persistent foreign material may become clinically relevant when associated with sinus obstruction, inflammation, or infection.^{20–22}

The distinction between an implant that merely protrudes into the sinus and an implant that has become freely displaced is therefore fundamental. Radiographic protrusion of an otherwise stable implant with preserved osseous support should not automatically be interpreted as migration.²⁴ Conversely, complete loss of osseous support with free displacement represents a different clinical condition and generally warrants retrieval, particularly when associated with sinonasal pathology.^{11,24} This distinction is consistent with the multidisciplinary consensus concerning radiographic implant protrusion and with systematic-review evidence concerning displaced implants.^{11,24}

Prevention remains preferable to retrieval. Evidence from sinus augmentation literature highlights the importance of adequate case selection, assessment of residual bone, careful Schneiderian membrane management, and control of intraoperative complications.^{1–3,6–10} The development of sinus floor elevation procedures has substantially expanded the indications for implant rehabilitation in the atrophic posterior maxilla, but these procedures also introduce specific technical risks that must be considered during treatment planning.^{4–9}

Three-dimensional planning, appropriate implant dimensions and positioning, controlled osteotomy and insertion, and verification of primary stability should therefore be integrated into the treatment-planning process.^{1–3,10,23} When augmentation is required, appropriate management of the Schneiderian membrane and careful control of the augmentation procedure are particularly important because membrane perforation and other sinus-related complications may influence subsequent treatment.^{7–9,35}

The potential relationship between implant displacement and peri-implant biological complications should also be considered. Peri-implantitis and other peri-implant diseases may result in progressive loss of supporting bone and compromise implant stability, although these conditions represent a different pathological process from the acute displacement of an implant during insertion.^{33,34} In selected cases, delayed migration may therefore reflect

a sequence in which biological loss of support precedes implant mobility and subsequent displacement.^{14_16:33_34}

The literature also demonstrates that implant-related foreign bodies may migrate beyond the maxillary sinus into anatomically remote craniofacial compartments. Reports have described displacement into the orbit, sphenoid sinus, and anterior cranial fossa, illustrating that migration is not invariably confined to the maxillary sinus.^{36_38} These unusual reports reinforce the importance of accurate three-dimensional imaging and anatomy-driven surgical planning when the implant is not located in a readily accessible portion of the maxillary sinus.^{23_36_38}

6.1 Development and clinical relevance of the proposed algorithm

The anatomy-driven management algorithm proposed in this review was developed by the authors through integration of the available literature and their clinical experience. The algorithm is intended to organize the principal clinical variables relevant to decision-making into a sequential framework: implant stability, residual osseous support, three-dimensional location, sinonasal status, oroantral pathology, anatomical accessibility, and surgical expertise.^{11_24_29}

The algorithm deliberately avoids defining a numerical threshold for sinus protrusion because current evidence does not establish a universally validated millimetric cutoff for removal of a stable implant.²⁴ Instead, it prioritizes the clinical distinction between stable sinus protrusion and true displacement, followed by assessment of sinonasal disease and anatomical accessibility.^{24_30_32}

This approach is also consistent with the available evidence concerning sinus augmentation and implant-related complications. The decision to intervene should take into account not only the radiographic position of the implant but also the quality and quantity of residual bone, the status of the sinus, the presence of oroantral communication, and the potential morbidity of the selected retrieval route.^{1_3:7_10_25} The proposed framework should be regarded as an evidence-informed expert synthesis rather than a formal clinical guideline or validated clinical prediction model. Its clinical utility, reproducibility, and safety require prospective and external validation. The heterogeneous nature of the published evidence, including systematic reviews, retrospective studies, case series, and case reports, further supports cautious interpretation of the proposed pathway.^{11_13:19_21_22_29}

6.2 Future research directions

Future research should move beyond isolated case reports toward multicenter prospective registries and standardized retrospective or prospective cohorts. Studies should use consistent terminology distinguishing stable protrusion, partial displacement, and free migration and should report residual bone support, implant position, timing of displacement, mobility, CBCT findings, sinus status, retrieval technique, complications, postoperative outcomes, and patient-reported outcomes.^{11_29}

Three-dimensional digital planning, image-guided surgery, endoscopic navigation, and other minimally invasive technologies may further improve the management of anatomically complex cases.^{23_26_28_36_38} Comparative studies are needed to determine which retrieval approaches provide the best balance between access, morbidity, sinus preservation, and postoperative recovery. Evidence from existing clinical reports and systematic reviews suggests that the choice of approach should remain individualized according to implant location, sinus condition, and anatomical accessibility.^{11_19_21_25_29} Prospective validation of the proposed anatomy-driven algorithm should also be prioritized. Future studies should specifically evaluate whether classification according to implant stability and residual osseous support improves clinical decision-making, reduces unnecessary removal of stable protruding implants, and facilitates timely retrieval of freely displaced implants associated with sinonasal disease.^{24_29}

7. Limitations

The available evidence on dental implant displacement into the maxillary sinus is limited and heterogeneous. Published studies vary considerably in terminology, patient characteristics, timing and mechanism of displacement, imaging protocols, associated sinonasal disease, and surgical techniques. Much of the evidence consists of retrospective studies, case series, and case reports, which are susceptible to selection and publication bias and provide limited comparative evidence.^{11_22_25_29}

This article is a focused narrative review rather than a systematic review or meta-analysis. The literature search was centered on PubMed/MEDLINE with additional reference-list screening, and no formal PRISMA selection process, standardized risk-of-bias assessment, quantitative evidence grading, or meta-analysis was performed. Consequently, the review cannot provide comparative estimates of treatment efficacy. The proposed management algorithm represents an additional limitation. Although it was developed from the available literature and the authors' clinical experience, it has not undergone prospective or external validation. It should therefore be considered an evidence-informed clinical framework rather than a validated guideline. Treatment

decisions should remain individualized, particularly in patients with significant sinonasal disease, oroantral pathology, or anatomically complex migration.^{24,29–32,36–38}

8. CONCLUSION

Dental implant displacement into the maxillary sinus is an uncommon but clinically important complication that requires differentiation between stable sinus protrusion and true displacement. Management should be based on implant stability, residual osseous support, three-dimensional location, sinonasal status, and anatomical accessibility rather than radiographic protrusion alone.

CBCT is essential for accurate localization and treatment planning. When true displacement occurs, retrieval is generally favored, while the surgical approach should be selected according to individual anatomy and clinical circumstances. Transoral, transnasal endoscopic, endoscope-assisted, and combined approaches may each be appropriate in selected cases. Prevention depends on appropriate three-dimensional planning, adequate primary stability, and careful surgical technique. The anatomy-driven algorithm proposed in this review, developed from the available literature and the authors' clinical experience, provides a practical framework for individualized management. Prospective multicenter studies are needed to validate this approach and establish more standardized evidence-based treatment pathways.

DECLARATIONS

Ethical approval

Not applicable to the narrative review. For any identifiable clinical images, confirm that appropriate patient consent for publication has been obtained.

Competing interests

The authors declare no conflict of interest.

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REVIEW ARTICLE

MINIMALLY INVASIVE MANAGEMENT OF ODONTOGENIC CYSTS: A SCOPING REVIEW OF CONSERVATIVE SURGERY, REGENERATIVE TECHNIQUES, AND DIGITAL-ASSISTED APPROACHES

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Abstract

Background: Odontogenic cysts are common jaw lesions that may cause bone destruction, displacement of adjacent teeth, and involvement of critical anatomical structures. Conventional treatment may require extensive surgery and can be associated with postoperative morbidity and loss of healthy tissues. Increasing attention has therefore been directed toward minimally invasive and tissue-preserving approaches.

Objective: To map and synthesize current evidence on minimally invasive management of odontogenic cysts, focusing on conservative surgery, endoscopic techniques, piezoelectric surgery, regenerative procedures, and digital-assisted treatment planning.

Methods: A scoping review was conducted according to the PRISMA-ScR framework. After duplicate removal and title/abstract screening, 42 full-text articles were assessed and all 42 met the predefined eligibility criteria. Data on cyst characteristics, treatment modalities, minimally invasive techniques, regenerative procedures, clinical and radiographic outcomes, complications, and recurrence were descriptively and thematically synthesized.

Results: The evidence demonstrated a shift toward conservative and minimally invasive management. Decompression and marsupialization were associated with reduction in lesion size, preservation of adjacent structures, and progressive bone regeneration. Endoscopic-assisted procedures provided improved visualization through limited access, while piezoelectric surgery enabled precise bone cutting with preservation of surrounding tissues. Regenerative approaches, including guided bone regeneration and platelet concentrates, supported restoration of post-cystic bone defects. CBCT-based planning and digital workflows improved anatomical assessment and individualized surgical planning.

Conclusion: Minimally invasive, regenerative, and digitally assisted approaches represent increasingly important strategies for odontogenic cyst management and may reduce surgical morbidity while preserving anatomical structures. However, heterogeneity in study designs and outcome measures limits definitive comparisons. Further prospective studies with standardized outcomes and long-term follow-up are warranted.

Keywords: Odontogenic cysts; Minimally invasive surgery; Decompression; Marsupialization; Endoscopic surgery; Piezoelectric surgery; Bone regeneration

1.INTRODUCTION

Odontogenic cysts comprise a diverse group of pathological lesions arising from odontogenic epithelial remnants and are among the most frequently encountered cystic lesions of the jaws. Their development is associated with epithelial components involved in tooth formation and, in some cases, with inflammatory processes affecting the periapical and periodontal tissues. The current classification of

odontogenic lesions reflects substantial differences in their histopathological characteristics and biological behavior, which are important considerations when establishing an appropriate treatment strategy.¹⁻⁴

Although most odontogenic cysts are benign, their clinical behavior is not uniform. The rate of growth, lesion size, anatomical location, and relationship with adjacent teeth and vital structures may vary considerably between

individual lesions. Many cysts remain asymptomatic for prolonged periods and are detected incidentally on routine radiographic examination. Once they become larger or secondarily infected, however, they may present with swelling, pain, infection, tooth displacement, or other functional disturbances.^{5–7}

The clinical importance of odontogenic cysts is largely related to their capacity for progressive expansion and destruction of the surrounding jawbone. Large lesions may produce cortical thinning or perforation, displace adjacent teeth, and, in selected cases, compromise structures such as the inferior alveolar canal or the maxillary sinus. These changes may complicate subsequent treatment and can result in substantial osseous defects after removal of the lesion. Consequently, contemporary treatment is directed not only toward elimination of the pathological tissue and prevention of recurrence, but also toward preservation of teeth, surrounding bone, and important anatomical structures.^{6–8}

Surgical enucleation has traditionally been the principal treatment for many odontogenic cysts because removal of the cystic lining permits direct elimination of the pathological tissue. Depending on the biological behavior and extent of the lesion, more extensive procedures may also be required. This is particularly relevant in lesions with extensive growth, cortical perforation, or a substantial risk of recurrence. Although conventional surgery remains an important and effective component of odontogenic cyst management, the extent of surgical intervention must be balanced against the potential loss of healthy tissue and the risk of postoperative complications.^{8–10}

Over the past several decades, the management of odontogenic cysts has gradually moved toward more conservative and tissue-preserving strategies. This change reflects a broader shift in oral and maxillofacial surgery toward limiting unnecessary surgical trauma while maintaining adequate control of the underlying disease. Rather than applying an identical surgical procedure to every lesion, current approaches increasingly take into account cyst type, size, anatomical location, relationship with adjacent structures, recurrence risk, and the patient's future functional requirements.^{9–11}

Decompression and marsupialization are among the most established conservative techniques, particularly for large cystic lesions in which immediate enucleation may result in considerable bone loss or increase the risk of injury to adjacent structures. By reducing intracystic pressure and maintaining controlled drainage, these procedures may permit gradual reduction of cyst volume and progressive bone

regeneration. They have been used for a range of odontogenic lesions, including large developmental and inflammatory cysts, and may allow preservation of adjacent teeth and vital anatomical structures.^{12–14} Nevertheless, conservative treatment generally requires prolonged clinical and radiographic follow-up, patient cooperation, and, in selected cases, subsequent enucleation after sufficient reduction of the lesion.^{11–14}

The development of endoscopic techniques has provided an additional option for lesions situated in anatomically difficult regions. Endoscopic-assisted surgery allows visualization of areas that may be difficult to access through a conventional surgical field and can facilitate controlled removal of pathological tissue through a more limited approach. This has particular relevance for lesions involving the posterior mandible, maxillary sinus, and other regions in close proximity to neurovascular structures. Clinical reports have described endoscopic-assisted enucleation as a feasible tissue-preserving approach in appropriately selected cases, although its use requires specific equipment, surgical experience, and adequate training.^{15–18}

Advances in three-dimensional imaging and digital planning have further influenced the contemporary management of odontogenic cysts. Cone-beam computed tomography (CBCT) provides detailed information about lesion dimensions, cortical bone integrity, root relationships, and the proximity of the lesion to important anatomical structures. Such information can improve preoperative assessment and help determine the most appropriate surgical access and treatment strategy.^{19,20}

Virtual surgical planning and other digital workflows may further support individualized treatment planning, particularly in complex cases in which conventional two-dimensional imaging does not adequately demonstrate the three-dimensional anatomy.²¹

Preservation of the jawbone has become an increasingly important consideration, particularly when large cystic lesions result in substantial residual defects or when subsequent implant rehabilitation is anticipated. Regenerative procedures have therefore been incorporated into the management of selected post-cystic defects. Bone grafting materials and guided bone regeneration techniques can provide structural support and maintain space for new bone formation, while barrier membranes may limit soft-tissue ingrowth and create a more favorable environment for osseous regeneration.^{22–25} The choice of regenerative material and technique depends on the size and morphology of the defect, the availability of residual bony walls, local vascularity, infection control, and the planned functional rehabilitation.^{22–25}

Biological adjuncts have also attracted increasing interest in regenerative treatment. Platelet-rich fibrin (PRF), for example, provides an autologous source of platelets and biologically active mediators that may contribute to angiogenesis, cellular activity, and tissue healing. Although the clinical evidence remains heterogeneous, the use of platelet concentrates in combination with established regenerative techniques represents a potentially useful approach for selected osseous defects.^{26,27}

Another technological development relevant to minimally invasive surgery is the use of piezoelectric devices. These systems employ ultrasonic microvibrations to cut mineralized tissues while providing a degree of protection to adjacent soft tissues. This characteristic can be advantageous when bone removal is required close to nerves, vessels, or sinus membranes. Piezoelectric surgery has consequently become an established adjunct in oral and maxillofacial procedures in which precision and preservation of surrounding structures are important.^{28–30} However, its application may be associated with longer operative times and requires appropriate operator experience; therefore, it should be regarded as a precision-enhancing surgical technology rather than a substitute for sound surgical principles.^{28–30}

Regenerative management also reflects a broader change in the objectives of cyst surgery. Removal of the lesion alone may leave a substantial osseous defect, whereas preservation or reconstruction of the affected bone may be essential for maintaining jaw function and facilitating subsequent implant-supported rehabilitation. Available evidence suggests that bone grafting, barrier membranes, and biological adjuncts can contribute to reconstruction of post-cystic defects, although outcomes remain dependent on the characteristics of the defect, infection control, biomaterial selection, and patient-related factors.^{22–27,31}

Conservative treatment may also include nonsurgical endodontic management in carefully selected inflammatory periapical lesions. Preservation of the involved tooth can be particularly important when a lesion is associated with a treatable root canal infection and adequate endodontic disinfection can be achieved. However, the distinction between inflammatory periapical lesions and true cystic pathology remains clinically important, and large lesions, persistent disease, or extensive bone destruction may still require surgical treatment.^{35–37}

Despite the expanding range of minimally invasive techniques, the available evidence remains

heterogeneous. Differences in cyst type, lesion size, anatomical location, treatment protocols, follow-up duration, and outcome assessment make direct comparison between individual approaches difficult. Evidence is relatively more established for conservative decompression and marsupialization, whereas endoscopic, piezoelectric, regenerative, and digitally assisted approaches have been investigated across a broader range of clinical settings and study designs.^{12–32}

These developments indicate that minimally invasive management should not be regarded as a universal replacement for conventional surgery. Rather, it represents an expanding group of complementary strategies that can be incorporated into an individualized treatment plan according to the biological characteristics of the lesion, its anatomical relationships, the anticipated surgical morbidity, and the patient's functional requirements. The central objective is increasingly to achieve adequate pathological control while preserving healthy tissues and creating favorable conditions for subsequent healing and rehabilitation.^{9,21–27,31,32}

The aim of the present scoping review was therefore to map and synthesize the available evidence on minimally invasive management of odontogenic cysts, with particular emphasis on conservative decompression and marsupialization, endoscopic-assisted surgery, piezoelectric techniques, regenerative procedures, and CBCT-based and digital-assisted treatment planning. By bringing these approaches together, the review seeks to clarify their current clinical applications, potential advantages, limitations, and areas in which further evidence is required.

2. MATERIALS AND METHODS

2.1. Study Design and Reporting Framework

The present study was designed as a scoping review to map and synthesize the available clinical evidence concerning minimally invasive management of odontogenic cysts. The review was conducted in accordance with the methodological framework recommended by the Joanna Briggs Institute (JBI) for scoping reviews and was reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR).^{33,34}

A scoping review design was selected because the literature concerning minimally invasive treatment of odontogenic cysts is broad and heterogeneous, encompassing different cyst types, conservative surgical techniques, endoscopic procedures, piezoelectric surgery, regenerative interventions, imaging modalities, and digital treatment-planning approaches. The purpose was

therefore to map the range of available evidence, characterize the clinical applications of the different approaches, summarize reported outcomes, and identify limitations and gaps in the current evidence base rather than to estimate a single pooled treatment effect.

The review focused on minimally invasive, conservative, tissue-preserving, regenerative, and technology-assisted strategies used in the management of odontogenic cystic lesions. The principal approaches of interest were decompression and marsupialization, conservative enucleation, endoscopic-assisted surgery, piezoelectric surgery, regenerative procedures, platelet concentrates, and CBCT-based or digitally assisted treatment planning. Selected nonsurgical endodontic and laser-assisted approaches were also considered when they were directly relevant to conservative or minimally invasive management of odontogenic cystic lesions.

The methodological framework, eligibility criteria, information sources, search strategy, study-selection process, and data-charting procedures were established before the final evidence synthesis.

2.2. Review Question and Objectives

The review was developed around the following primary research question:

What is the current evidence regarding minimally invasive approaches for the treatment of odontogenic cysts, and what clinical outcomes, advantages, limitations, and regenerative implications have been reported with these approaches?

The specific objectives were:

1. To identify and characterize minimally invasive treatment modalities reported in the literature for the management of odontogenic cysts.
2. To describe the clinical indications and applications of conservative, endoscopic-assisted, piezoelectric, regenerative, and digitally assisted approaches.
3. To summarize reported outcomes, including cyst reduction or resolution, radiographic bone regeneration, preservation of adjacent anatomical structures, postoperative morbidity, recurrence, and subsequent rehabilitation.
4. To identify the role of regenerative procedures, including bone grafting, guided bone regeneration, barrier membranes, and platelet-rich fibrin.

5. To examine the contribution of CBCT and digital technologies to diagnosis, anatomical assessment, surgical planning, and management of anatomically complex lesions.
6. To identify limitations and gaps in the current evidence and areas requiring further clinical investigation.

2.3. Eligibility Criteria

Eligibility criteria were established according to the Population–Concept–Context (PCC) framework recommended by the JBI for scoping reviews.³⁴ The criteria were applied consistently during title and abstract screening and subsequent full-text assessment.

Population

The population consisted of patients diagnosed with odontogenic cystic lesions. Eligible lesions included inflammatory and developmental odontogenic cysts, including radicular cysts, dentigerous cysts, odontogenic keratocysts, and other clinically relevant odontogenic cystic lesions described in the literature.

Concept

The concept of interest was minimally invasive, conservative, tissue-preserving, regenerative, endoscopic, piezoelectric, or technology-assisted management of odontogenic cysts.

The interventions and treatment-related approaches of interest included:

- decompression;
- marsupialization;
- conservative or limited-access enucleation;
- endoscopic-assisted cyst surgery;
- piezoelectric surgery;
- bone grafting;
- guided bone regeneration;
- barrier membrane techniques;
- platelet concentrates, particularly platelet-rich fibrin;
- CBCT-based anatomical assessment and treatment planning;
- virtual surgical planning and other digital-assisted approaches.

Selected nonsurgical endodontic approaches were also considered when they were used for the management of inflammatory periapical lesions with cyst-like characteristics and were directly relevant to tooth preservation and avoidance of surgical intervention.

Context

Studies conducted in oral surgery, oral and maxillofacial surgery, endodontics, implant dentistry, and related dental specialties were considered eligible when the reported approach was clinically applicable to the management of odontogenic cystic lesions.

Inclusion Criteria

Studies were included when they:

- 1. addressed odontogenic cystic lesions;
- 2. evaluated or described a minimally invasive, conservative, regenerative, endoscopic, piezoelectric, or digitally assisted treatment or treatment-planning approach;
- 3. provided clinical, radiographic, surgical, or treatment-related outcome information;
- 4. were published in English;
- 5. were published between January 1, 1996, and August 31, 2026;

- 6. contained sufficient methodological or clinical information to permit extraction of relevant data.

Exclusion Criteria

Studies were excluded when they:

- 1. focused exclusively on non-odontogenic cysts or unrelated maxillofacial lesions;
- 2. described purely experimental or laboratory investigations without clinically applicable information;
- 3. were conference abstracts without sufficient clinical or methodological information;
- 4. did not provide a meaningful description of the treatment procedure or treatment-planning approach;
- 5. were unrelated to minimally invasive, conservative, tissue-preserving, regenerative, or technology-assisted management;
- 6. contained insufficient information for evaluation of the reported clinical approach or outcome.

The eligibility framework is summarized in Table 1.

Table 1. Population–Concept–Context Framework and Eligibility Criteria

PCC component	Definition in the present review
Population	Patients with odontogenic cystic lesions, including radicular cysts, dentigerous cysts, odontogenic keratocysts, and other developmental or inflammatory odontogenic cysts
Concept	Minimally invasive, conservative, tissue-preserving, regenerative, endoscopic, piezoelectric, and digital-assisted treatment or treatment-planning approaches
Interventions of interest	Decompression, marsupialization, conservative or limited-access enucleation, endoscopic-assisted surgery, piezoelectric surgery, bone grafting, guided bone regeneration, barrier membranes, platelet-rich fibrin, CBCT-based planning, and digital workflows
Context	Oral surgery, oral and maxillofacial surgery, endodontics, implant dentistry, and related dental specialties
Publication period	January 1, 1996–August 31, 2026
Language	English
Eligible evidence	Clinical studies, prospective and retrospective observational studies, comparative clinical studies, case series, and clinically relevant technical reports
Required information	Description of the treatment or treatment-planning approach and clinical, radiographic, surgical, or outcome-related information
Main exclusions	Non-odontogenic lesions, non-clinical laboratory studies, conference abstracts without sufficient information, insufficiently described procedures, and studies unrelated to minimally invasive or tissue-preserving management

2.4. Information Sources

A comprehensive literature search was performed using major biomedical and multidisciplinary electronic databases selected to provide broad coverage of oral and maxillofacial surgery, dentistry, endodontics, regenerative medicine, biomaterials, and minimally invasive surgical techniques. The following databases were searched:

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- PubMed/MEDLINE
- Scopus
- Web of Science Core Collection
- ScienceDirect
- Cochrane Library

The literature search covered publications from January 1, 1996, to August 31, 2026. This time frame was selected to capture both established conservative approaches and subsequent developments in minimally invasive surgery, regenerative procedures, piezoelectric technology, CBCT-based assessment, and digital-assisted treatment planning. The principal information sources and their intended contribution to the literature search are presented in Table 2.

Table 2. Electronic Information Sources Used in the Review

Database	Main purpose in the literature search
PubMed/MEDLINE	Identification of biomedical, dental, oral surgery, endodontic, and maxillofacial literature
Scopus	Broad multidisciplinary coverage and identification of clinical and surgical publications
Web of Science Core Collection	Identification of indexed scientific literature and multidisciplinary studies
ScienceDirect	Retrieval of relevant dental, surgical, regenerative, biomaterials, and clinical literature
Cochrane Library	Identification of systematic reviews and controlled clinical evidence relevant to conservative and surgical treatment

2.5. Search Strategy

The search strategy was developed using combinations of controlled vocabulary and free-text terms related to odontogenic cysts and minimally invasive, conservative, regenerative, and technology-assisted management. The search was intentionally broad to reduce the risk of excluding relevant studies that used different terminology to describe similar clinical approaches. Where database-specific syntax permitted, controlled vocabulary and field-specific searching were used to improve retrieval of relevant records. The complete database-specific search strategies should be retained as supplementary search documentation. The main search terms included combinations of the following concepts:

Table 3. Main Search Concepts and Keywords

Search concept	Principal terms
Odontogenic pathology	“odontogenic cyst”, “odontogenic cysts”, “jaw cyst”, “radicular cyst”, “periapical cyst”, “residual cyst”, “dentigerous cyst”, “follicular cyst”, “odontogenic keratocyst”, “keratocystic odontogenic tumor”
Conservative management	“conservative treatment”, “conservative management”, “decompression”, “marsupialization”, “marsupialisation”, “conservative enucleation”, “limited-access enucleation”
Minimally invasive surgery	“minimally invasive surgery”, “endoscopic surgery”, “endoscopic-assisted surgery”, “endoscopic enucleation”
Precision surgery	“piezoelectric surgery”, “piezosurgery”, “ultrasonic bone surgery”
Regeneration	“guided bone regeneration”, “bone graft”, “bone grafting”, “bone regeneration”, “collagen membrane”, “barrier membrane”, “platelet-rich fibrin”, “PRF”, “platelet concentrate”
Digital imaging technology	and “CBCT”, “cone-beam computed tomography”, “three-dimensional imaging”, “digital planning”, “virtual surgical planning”, “computer-assisted surgery”, “navigation”
Adjunctive approaches	“endodontic treatment”, “root canal treatment”, “intracanal medicament”, “laser-assisted”, “laser surgery”
Boolean combination	Odontogenic cyst terms AND minimally invasive/conservative/regenerative/endoscopic/piezoelectric/digital treatment terms

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2.6. Study Selection Process

All records identified through the electronic database searches were collected and imported into reference-management software. Duplicate records were identified and removed before the screening process.

Following duplicate removal, the remaining records were independently screened by two reviewers in two sequential stages.

During the first stage, titles and abstracts were evaluated against the predefined eligibility criteria. Records that were clearly unrelated to odontogenic cysts, did not address minimally invasive, conservative, regenerative, or clinically relevant technology-assisted management, or did not contain sufficient clinical information were excluded at this stage.

Potentially eligible articles were subsequently retrieved for full-text assessment. The full texts were examined against all predefined inclusion and exclusion criteria.

Any disagreement between the reviewers was discussed and resolved by consensus. The final study-selection process was documented in accordance with PRISMA-ScR recommendations.³³

The study-selection pathway is presented in the PRISMA-ScR flow diagram (Figure 1).

Table 4. Study Selection Process

Selection stage	Number of records/studies
Records identified through database searching	123
Records remaining after removal of duplicates	96
Records excluded during title/abstract screening	54
Full-text articles assessed for eligibility	42
Full-text articles excluded	0
Studies included in the final scoping review	42

Thus, 42 full-text articles fulfilled the predefined eligibility criteria and were included in the final evidence synthesis.

2.7. Data Extraction and Charting

Data were charted using a standardized data-charting form developed for the purposes of the present review and informed by the recommendations of the JBI scoping review methodology.³⁴

The data-charting process was designed to capture both the clinical characteristics of the included studies and the specific features of the minimally invasive, regenerative, and technology-assisted approaches investigated.

For each included article, the following information was recorded:

- first author and year of publication;
- country in which the study was conducted;
- study design;
- number and characteristics of patients;
- type of odontogenic cyst;
- anatomical location of the lesion;
- lesion size, when reported;
- relationship with adjacent teeth and anatomical structures;
- treatment modality;
- conservative or minimally invasive component of treatment;
- use of decompression or marsupialization;
- use of endoscopic assistance;

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- use of piezoelectric surgery;
- use of regenerative materials or procedures;
- use of platelet concentrates such as PRF;
- use of CBCT or digital treatment planning;
- duration of follow-up;
- clinical outcomes;
- radiographic outcomes;
- evidence of cyst reduction or resolution;
- bone regeneration or reconstruction;
- postoperative complications;
- recurrence, when reported;
- preservation of adjacent teeth or anatomical structures;
- feasibility of subsequent implant rehabilitation, when reported.

Table 5. Data-Charting Variables

Domain	Variables extracted
Bibliographic information	Author, year, country
Study characteristics	Study design, sample size, clinical setting
Lesion characteristics	Cyst type, anatomical location, lesion size, relationship to adjacent structures
Primary treatment	Decompression, marsupialization, enucleation, endoscopic surgery, piezoelectric surgery, endodontic treatment
Regenerative treatment	Bone grafts, guided bone regeneration, collagen or barrier membranes, PRF, and other biological adjuncts
Digital and imaging technology	CBCT, three-dimensional imaging, virtual planning, computer-assisted planning, or navigation
Clinical outcomes	Cyst resolution or reduction, symptoms, preservation of teeth, postoperative morbidity
Radiographic outcomes	Bone regeneration, defect reduction, cortical healing, lesion dimensions
Safety outcomes	Complications, sensory disturbance, infection, membrane-related complications
Long-term outcomes	Recurrence, additional surgery, functional rehabilitation, implant rehabilitation
Follow-up	Duration and timing of clinical and radiographic evaluation

2.8. Organization of the Evidence

After data charting, the included studies were grouped according to the principal treatment strategy investigated. Because the available literature comprised heterogeneous study designs, patient populations, cyst types, treatment protocols, and outcome measures, the evidence was organized thematically rather than subjected to statistical pooling.

Five principal evidence categories were established:

1. Conservative decompression and marsupialization
2. Endoscopic-assisted surgery
3. Piezoelectric surgery
4. Regenerative approaches
5. Digital-assisted and CBCT-based treatment planning

Selected studies addressing conservative endodontic treatment and laser-assisted approaches were considered as adjunctive strategies when they were directly relevant to minimally invasive or tissue-preserving management of odontogenic cystic lesions.

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Table 6. Evidence Categories Used for the Thematic Synthesis

Evidence category	Principal approaches	Main outcomes considered
Conservative treatment	Decompression, marsupialization, conservative or limited-access enucleation	Lesion reduction, bone regeneration, preservation of adjacent structures, need for secondary surgery
Endoscopic-assisted surgery	Endoscopic-assisted enucleation and cyst removal	Surgical access, visualization, tissue preservation, postoperative morbidity
Piezoelectric surgery	Ultrasonic bone cutting and precision osteotomy	Surgical precision, preservation of surrounding soft tissues, operative morbidity
Regenerative treatment	Bone grafts, guided bone regeneration, barrier membranes, PRF	Bone-volume restoration, healing, reconstruction, implant-site preparation
Digital-assisted and CBCT-based treatment planning	CBCT, three-dimensional imaging, virtual planning, navigation, computer-assisted workflows	Anatomical assessment, treatment planning, surgical precision, preservation of anatomical structures
Adjunctive approaches	Conservative endodontic treatment and laser-assisted procedures	Tooth preservation, periapical healing, tissue preservation, healing, avoidance or reduction of surgical intervention

2.9. Outcome Assessment

The principal outcomes considered in the review were selected to reflect the clinical objectives of minimally invasive management of odontogenic cysts.

Primary Outcomes

The primary outcomes included:

- reduction or resolution of the cystic lesion;
- radiographic evidence of bone regeneration;
- preservation of adjacent teeth and important anatomical structures;
- successful pathological control;
- recurrence, when reported.

Secondary Outcomes

Secondary outcomes included:

- postoperative pain and swelling;
- sensory disturbances;
- infection and other postoperative complications;
- duration of treatment;
- need for secondary surgical intervention;
- quality and predictability of surgical access;
- restoration of jawbone volume;
- feasibility of subsequent implant rehabilitation;
- reported advantages and limitations of each approach.

Because the included studies used different definitions, follow-up periods, imaging methods, and outcome-assessment protocols, outcomes were not converted into a single standardized effect measure.

2.10. Data Synthesis

The extracted information was synthesized descriptively and thematically. The purpose of the synthesis was to identify

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patterns across the available literature and characterize the clinical applications, potential benefits, limitations, and reported outcomes of the different minimally invasive approaches.

The findings were organized according to the principal evidence categories and compared with respect to:

- clinical indication;
- biological rationale;
- degree of tissue preservation;
- reported treatment effectiveness;
- bone-healing and regenerative potential;
- preservation of adjacent structures;
- recurrence;
- postoperative complications;
- treatment duration;
- technical requirements;
- limitations of the available evidence.

Where studies reported different follow-up periods or outcome definitions, the findings were retained in their original context rather than directly compared as equivalent measures.

The evidence was subsequently summarized in comparative tables to facilitate interpretation of the clinical characteristics and reported outcomes of the different minimally invasive approaches.

No quantitative meta-analysis was performed because of substantial heterogeneity in study designs, cyst types, treatment protocols, outcome definitions, and follow-up periods.

2.11. Methodological Considerations

In accordance with the purpose of a scoping review, a formal risk-of-bias or methodological quality assessment was not performed.^{33,34} The primary objective of the review was to map the existing evidence, identify the range of minimally invasive approaches used in odontogenic cyst management, characterize reported outcomes, and identify areas in which evidence remains limited.

The included literature comprised retrospective clinical studies, prospective observational studies, comparative clinical investigations, case series, and clinically relevant technical reports. The studies differed substantially in patient populations, cyst types, anatomical locations, treatment protocols, follow-up periods, and outcome definitions. Consequently, the evidence was synthesized descriptively and thematically rather than through a pooled effectiveness analysis.

The absence of formal methodological quality appraisal should therefore be considered when interpreting the findings, particularly when comparing outcomes reported across different study designs.

2.12. Ethical Considerations

As this study was a scoping review based exclusively on previously published literature and did not involve direct recruitment of human participants or access to identifiable patient-level data, institutional ethical approval was not required for the review itself.

3. RESULTS

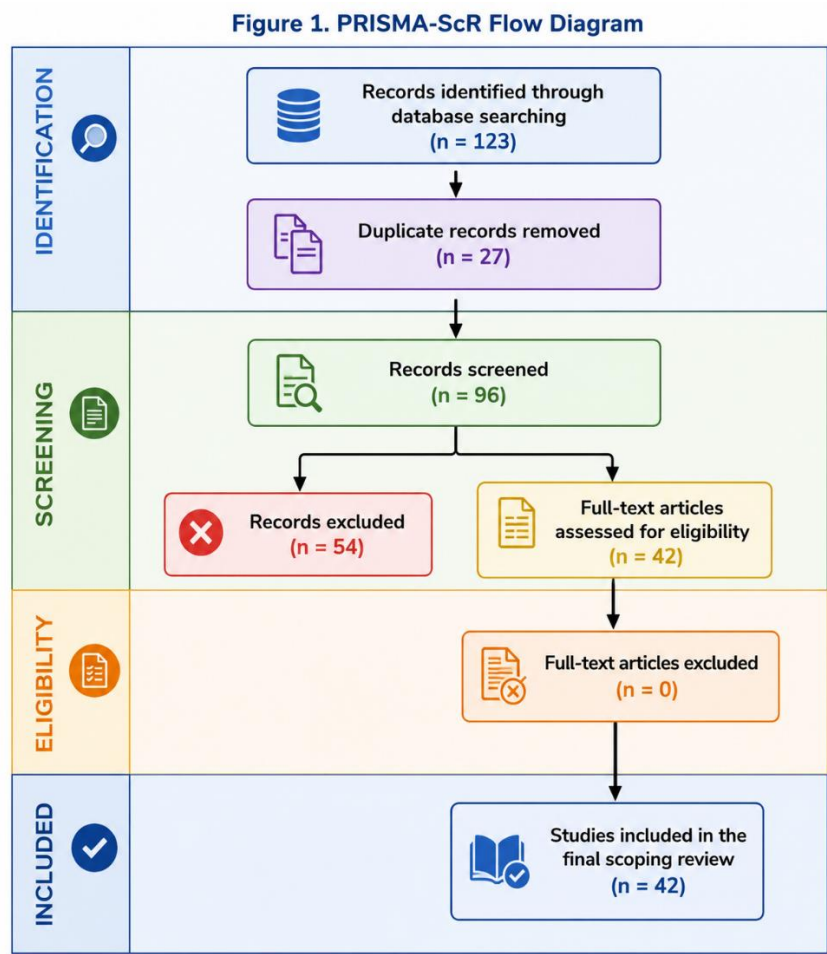
3.1. Study Selection Process

The initial literature search identified 123 records from the selected electronic databases. After removal of duplicate records, 96 unique records remained for title and abstract screening. During this stage, 54 records were excluded because they did not address minimally invasive or tissue-preserving management of odontogenic cysts, focused exclusively on conventional surgical treatment, represented non-clinical investigations, or did not provide sufficient clinical information

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relevant to the review question.

A total of 42 articles were subsequently assessed in full text. Following detailed evaluation against the predefined eligibility criteria, no additional studies were excluded. Therefore, all 42 full-text articles fulfilled the inclusion criteria and were incorporated into the final scoping review synthesis. The study-selection process is presented in the PRISMA-ScR flow diagram (Figure 1).



The final evidence base consisted of 42 publications addressing different aspects of minimally invasive management of odontogenic cysts. The included literature covered conservative decompression and marsupialization, endoscopic-assisted surgery, piezoelectric surgery, regenerative reconstruction, CBCT-based and digital-assisted planning, and selected nonsurgical endodontic and laser-assisted approaches.

Table 7. Study Selection Process

Selection stage	Number of records
Records identified through database searching	123
Records remaining after removal of duplicates	96
Records excluded during title/abstract screening	54
Full-text articles assessed for eligibility	42
Full-text articles excluded	0
Studies included in the final synthesis	42

3.2. Characteristics of the Included Studies

The 42 included studies were published between 1996 and August 2026 and reflected the gradual development of

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conservative, tissue-preserving, regenerative, and technology-assisted approaches to odontogenic cyst management. The evidence base was heterogeneous and included retrospective clinical studies, prospective observational investigations, comparative clinical studies, case series, and technical or clinically oriented reports describing minimally invasive surgical procedures.

The majority of the included studies addressed inflammatory and developmental odontogenic cysts, particularly radicular cysts, dentigerous cysts, and odontogenic keratocysts. A substantial proportion of the reported clinical experience involved lesions of the posterior mandible, posterior maxilla, and maxillary sinus region, where preservation of the inferior alveolar nerve, adjacent teeth, cortical bone, and sinus structures was an important consideration.

The clinical characteristics of the included studies varied considerably. Lesions ranged from relatively small periapical cystic lesions to extensive cystic cavities associated with substantial bone destruction. In many reports, treatment selection was determined by lesion size, anatomical location, proximity to important structures, relationship with teeth, cortical bone involvement, and the possibility of future implant rehabilitation.

The outcomes most frequently reported across the included literature were reduction in cyst size, radiographic evidence of bone regeneration, preservation of adjacent teeth and anatomical structures, postoperative pain and swelling, surgical morbidity, recurrence, and the feasibility of subsequent reconstructive or implant treatment. Follow-up periods were variable, ranging from several months to more than five years, which limited direct comparison of long-term outcomes among treatment modalities.

Table 8. General Characteristics of the 42 Included Studies

Characteristic	Findings across the included evidence
Number of included studies	42
Main study designs	Retrospective clinical studies, prospective observational studies, comparative clinical investigations, case series, and technical/clinical reports
Main cyst types	Radicular cysts, dentigerous cysts, odontogenic keratocysts, and other developmental or inflammatory odontogenic cysts
Common anatomical sites	Posterior mandible, posterior maxilla, maxillary sinus region, and periapical areas
Main treatment approaches	Decompression, marsupialization, conservative or limited-access enucleation, endoscopic-assisted surgery, piezoelectric surgery, regenerative procedures, and CBCT/digital planning
Additional approaches	Selected nonsurgical endodontic treatment and laser-assisted procedures
Main clinical outcomes	Lesion reduction, preservation of anatomical structures, postoperative morbidity, healing, recurrence, and subsequent rehabilitation
Main radiographic outcomes	Reduction in lesion dimensions and progressive bone regeneration
Follow-up	Variable; several months to more than five years in individual reports
Overall evidence pattern	Increasing emphasis on tissue preservation, conservative treatment, regeneration, and digitally assisted planning

3.3. Classification of Minimally Invasive Treatment Approaches

Analysis of the 42 included studies demonstrated that minimally invasive management of odontogenic cysts could be organized into five principal treatment categories: conservative decompression and marsupialization, endoscopic-assisted surgery, piezoelectric surgery, regenerative approaches, and digital-assisted treatment planning. Selected nonsurgical endodontic and laser-assisted techniques were also identified as complementary approaches in specific clinical situations.

The different modalities were not interchangeable. Their clinical application depended primarily on cyst type, lesion

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size, anatomical location, biological behavior, relationship to adjacent teeth and vital structures, and the anticipated need for reconstruction. Overall, the evidence showed a movement away from extensive surgical removal alone toward treatment strategies designed to control the pathological lesion while preserving healthy bone and surrounding anatomical structures.

Table 9. Main Minimally Invasive Approaches Identified in the Included Studies

Treatment category	Main biological or technical principle	Principal indications	clinical	Main advantages	Main limitations
Decompression	Reduction of intracystic pressure and stimulation of gradual lesion reduction and bone remodeling	Large particularly close to structures	cysts, those and vital	Preservation of bone and adjacent structures; reduced surgical trauma	Prolonged treatment and need for patient compliance
Marsupialization	Creation of a permanent drainage pathway and reduction of intracystic pressure	Large cystic lesions requiring reduction before definitive treatment	reduction definitive	Simple and conservative; facilitates gradual reduction of lesion volume	Secondary surgery may be required
Endoscopic-assisted surgery	Magnified visualization through limited surgical access	Cysts in the maxillary sinus, posterior regions, anatomically complex areas	posterior and	Improved visualization and surgical precision; reduced tissue disruption	Specialized equipment, training, and technical expertise required
Piezoelectric surgery	Selective ultrasonic cutting of mineralized tissue	Lesions close to nerves, vessels, sinus structures	to or	Precise bone removal and improved protection of adjacent soft tissues	Longer operative time and equipment requirements
Guided bone regeneration and bone grafting	Space maintenance and guided regeneration of residual osseous defects	Large post-cystic bone defects		Restoration of bone volume and support for subsequent implant rehabilitation	Technique-sensitive; outcome depends on defect characteristics and surgical execution
Collagen membrane-assisted regeneration	Barrier function and exclusion of soft tissue from the bone defect	Contained or partially contained defects		Supports bone regeneration and defect stability	Risk of membrane exposure and need for careful soft-tissue management
PRF/i-PRF	Release of platelet-derived growth factors and modulation of healing	Adjunctive postoperative and soft-tissue healing	bone	Autologous biological adjunct with potential healing benefit	Independent effect on definitive bone regeneration remains uncertain
CBCT-based digital planning	Three-dimensional assessment and surgical simulation	Complex lesions requiring precise anatomical planning		Improved anatomical assessment and treatment predictability	Does not itself constitute a treatment modality and depends on the surgical procedure
Digital-assisted surgery	Three-dimensional visualization, planning, and individualized surgical guidance	Complex cyst anatomy and difficult surgical access		Improved planning accuracy and potentially more controlled access	Availability, cost, and limited clinical evidence for some applications

3.3.1. Decompression and Marsupialization

Decompression and marsupialization were among the most frequently represented conservative treatment strategies in

the included literature. They were predominantly used for large odontogenic cysts in which immediate complete enucleation could result in extensive bone removal or increase the risk of damage to adjacent anatomical structures.

The principal biological rationale of decompression is reduction of intracystic pressure through creation of a controlled communication between the cystic cavity and the oral environment. Reduction of intracystic pressure may lead to gradual shrinkage of the lesion and progressive remodeling of the surrounding bone. Marsupialization follows a closely related principle, with the cystic cavity being converted into an open pouch that permits continuous drainage and gradual reduction in size.

The reviewed studies described favorable clinical effects in large radicular and dentigerous cysts and in lesions located near the inferior alveolar nerve, maxillary sinus, or other structures where aggressive immediate surgery could produce substantial morbidity. Reported benefits included preservation of adjacent teeth, reduction of the risk of neurological injury, limitation of bone removal, and progressive restoration of the osseous defect.

However, conservative decompression and marsupialization were not associated with rapid resolution. Treatment frequently required prolonged follow-up, maintenance of the decompression device or surgical opening, patient cooperation with local care, and repeated radiographic assessment. In selected cases, a second surgical procedure was necessary after sufficient reduction of the cystic cavity. Thus, the evidence supported these techniques primarily as individualized conservative strategies for appropriately selected large lesions rather than universal substitutes for enucleation.

3.3.2. Endoscopic-Assisted Management

Endoscopic-assisted surgery represented one of the more technologically advanced approaches identified in the included evidence. The principal advantage of endoscopic assistance was improved visualization of the operative field through a relatively limited surgical access.

The technique was particularly relevant for lesions located in anatomically difficult areas, including the maxillary sinus, posterior maxilla, posterior mandible, and regions adjacent to neurovascular structures. Magnified visualization facilitated identification of the cystic cavity and its boundaries and allowed the surgeon to work with greater visual control while limiting unnecessary manipulation of surrounding tissues.

The available clinical reports suggested several potential benefits compared with conventional open approaches, including reduced surgical exposure, improved visualization, more precise removal of pathological tissue, and potentially lower postoperative swelling and discomfort. Endoscopic approaches were therefore most useful when adequate conventional visualization would require a substantially larger surgical access.

The main limitations were the requirement for specialized equipment, operator training, technical experience, and familiarity with three-dimensional orientation. The available studies also remained relatively limited in number and heterogeneous in design, making it difficult to establish standardized indications or definitive long-term superiority over conventional techniques.

3.3.3. Piezoelectric Surgery

Piezoelectric surgery was identified primarily as an adjunctive precision technology rather than an independent treatment for odontogenic cysts. Its principal clinical value was related to controlled bone removal in areas where important anatomical structures were located close to the surgical field.

Piezoelectric devices use ultrasonic microvibrations that permit selective cutting of mineralized tissue. This characteristic may reduce unintended injury to adjacent soft tissues and provide greater control during osteotomy. The included evidence particularly supported its use when lesions were located close to nerves, vessels, or the maxillary sinus.

The reported advantages included controlled bone removal, improved operative precision, preservation of surrounding tissues, and potentially safer surgical access in anatomically sensitive regions. These characteristics were consistent with the broader objective of minimally invasive cyst surgery, namely achieving adequate pathological control while

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minimizing unnecessary removal of healthy tissue.

The principal disadvantages were increased operative time compared with some conventional instruments, equipment requirements, and the need for adequate operator experience. Consequently, piezoelectric surgery was best interpreted as a tissue-preserving adjunct that may improve the safety and precision of cyst surgery rather than as a replacement for appropriate surgical principles.

3.3.4. Regenerative Approaches Following Cyst Removal

Regenerative treatment represented an important component of the evidence identified in the 42 included studies. In large cystic lesions, removal of the pathological tissue may leave a substantial osseous defect. The reviewed literature therefore increasingly considered management of the residual bone defect as an integral part of treatment rather than a separate secondary procedure.

The regenerative approaches identified included guided bone regeneration, particulate bone grafting, collagen barrier membranes, platelet-rich fibrin and related platelet concentrates, and selected combinations of these materials.

Bone graft materials were used primarily to provide an osteoconductive scaffold and to maintain the volume of the residual defect during healing. Xenogeneic materials, allogeneic materials, and synthetic substitutes were represented in the literature. Autogenous bone remained biologically important because of its osteogenic, osteoinductive, and osteoconductive properties, although donor-site morbidity and the requirement for an additional surgical procedure limited its routine use in some situations. Guided bone regeneration was particularly relevant to large or poorly contained defects. Barrier membranes were used to limit soft-tissue invasion and maintain a regenerative space for bone formation. Resorbable collagen membranes were frequently favored because they avoid the need for a second removal procedure, whereas non-resorbable membranes may provide greater mechanical stability in selected large or complex defects.

PRF and i-PRF were identified as biological adjuncts intended to support angiogenesis, growth-factor release, and early tissue healing. The available evidence suggested a potentially beneficial effect on postoperative healing, but the independent contribution of platelet concentrates to definitive bone regeneration remained less clearly established than the role of the primary surgical procedure and grafting strategy.

Overall, regenerative techniques were particularly relevant in patients in whom preservation or restoration of alveolar bone was important for subsequent implant-supported rehabilitation. However, the final regenerative outcome depended on defect size and morphology, residual bony walls, vascular supply, infection control, biomaterial selection, surgical technique, and patient-related factors.

Table 10. Biological Basis of Regenerative and Tissue-Preserving Approaches

Technique	Primary mechanism	Potential clinical or biological effect
Decompression	Reduction of intracystic pressure	Progressive lesion reduction and secondary bone regeneration
Marsupialization	Continuous drainage and decompression	Reduction of inflammatory stimulation and facilitation of healing
PRF/i-PRF	Release of platelet-derived growth factors	Enhanced angiogenic response and cellular activity
Guided bone regeneration	Barrier function and space maintenance	Selective regeneration of bone within the defect
Bone grafts	Osteoconductive scaffold formation	Support of new bone deposition and maintenance of defect volume
Bioceramic materials	Bioactive ion release and mineralization support	Potential stimulation of mineralized tissue formation
Collagen membranes	Exclusion of rapidly proliferating soft tissue	Maintenance of a favorable environment for bone regeneration

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3.3.5. Clinical Reconstruction of Post-Cystic Bone Defects

The included evidence demonstrated that regenerative reconstruction could be integrated directly into the surgical management of odontogenic cysts. In cases with substantial residual bone defects, the treatment sequence generally involved removal of the pathological tissue followed by assessment of the remaining defect and selection of an appropriate regenerative strategy.

The clinical reports emphasized the importance of preserving the surrounding bone architecture during cyst removal whenever possible. Following enucleation, regenerative materials could be used to maintain the contour and volume of the alveolar bone and to provide a favorable environment for subsequent bone formation.

This approach was particularly relevant when future implant rehabilitation was anticipated. Restoration of adequate bone volume after cyst removal may facilitate later implant placement and reduce the need for more extensive secondary reconstructive surgery.

The clinical sequence illustrated in Figure 2 demonstrates the concept of combining cyst removal with reconstruction of the resulting osseous defect rather than considering pathological removal as the sole endpoint of treatment.

3.3.6. Digital-Assisted Planning and CBCT-Based Surgery

Digital technologies represented an emerging component of minimally invasive odontogenic cyst management. CBCT was consistently identified as an important diagnostic and planning tool because it provides three-dimensional information about lesion dimensions, cortical bone integrity, tooth and root relationships, and proximity to critical anatomical structures.

The included literature indicated that digital planning could assist clinicians in evaluating lesion morphology before surgery, selecting an appropriate surgical access, anticipating the relationship of the cyst to nerves and sinus structures, and developing an individualized treatment strategy. Digital workflows also allowed more detailed preoperative visualization and surgical simulation. In complex lesions, this may contribute to more predictable access and reduce unnecessary manipulation of healthy tissues. However, the clinical evidence for advanced digital-assisted workflows remained less mature than the evidence for established conservative techniques such as decompression and marsupialization.

The available evidence therefore supported CBCT-based planning as an important component of contemporary treatment planning, particularly for anatomically complex lesions, while recognizing that imaging and digital technologies function primarily as planning and guidance tools rather than independent therapeutic interventions.

Table 11. Role of Digital Technologies in Minimally Invasive Cyst Surgery

Digital technology	Main application	Clinical contribution	Current evidence
CBCT	Three-dimensional anatomical assessment	Defines lesion size, cortical involvement, tooth relationships, and proximity to vital structures	Established and clinically useful
Digital reconstruction	3D Visualization of lesion morphology	Improves spatial understanding of complex lesions	Increasing clinical use
Digital surgical simulation	Preoperative planning	Allows evaluation of surgical access and treatment options	Promising
Computer-assisted planning	Individualized treatment planning	May improve procedural predictability	Emerging
Digital-assisted surgical guidance	Intraoperative orientation	May facilitate precise access and tissue preservation	Limited clinical validation
AI-assisted segmentation and planning	Automated image analysis and treatment planning	Potential for improved efficiency and individualized planning	Early-stage evidence

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3.3.7. Selected Nonsurgical Endodontic Management

A smaller component of the included evidence addressed nonsurgical endodontic management of selected cyst-like periapical lesions, particularly inflammatory radicular lesions associated with non-vital but restorable teeth.

The underlying principle was elimination of the intracanal source of infection through adequate root canal disinfection, thereby reducing the inflammatory stimulus responsible for periapical pathology. Intracanal medicaments, particularly calcium hydroxide-based preparations, were discussed in relation to their antimicrobial effects and their potential to support periapical healing.

The available evidence indicated that selected small and well-contained periapical lesions may resolve following appropriate nonsurgical endodontic treatment. This approach offers the important advantage of preserving the affected tooth and avoiding surgical access to the cystic cavity.

However, accurate diagnosis and case selection remained critical. Large true cysts, lesions with extensive cortical destruction, persistent infection, or lesions that fail to respond to appropriate endodontic therapy may still require surgical treatment. Therefore, nonsurgical endodontic treatment was identified as a selective conservative option rather than a universal replacement for surgical management.

3.3.8. Laser-Assisted Approaches

Laser-assisted treatment represented an emerging and relatively less established component of the reviewed evidence. Er laser applications were described primarily as adjunctive techniques in selected cyst enucleation and periapical surgical procedures.

The potential advantages included precise tissue interaction, limited thermal damage when appropriate parameters are used, improved control of the surgical field, and possible reduction of microbial contamination. Some reports also suggested favorable effects on postoperative tissue healing.

Nevertheless, the clinical evidence supporting routine laser-assisted cyst management remained limited. The available studies did not justify considering laser therapy as a replacement for established conservative or surgical approaches. Instead, it was best regarded as an adjunctive technology requiring further prospective clinical evaluation.

3.4. Comparative Clinical Outcomes

The 42 included studies demonstrated that minimally invasive management can achieve favorable clinical outcomes, but the evidence was heterogeneous and direct comparison between treatment modalities was difficult. Differences in cyst type, lesion size, anatomical location, treatment protocol, follow-up duration, and outcome assessment methods prevented reliable quantitative comparison or pooled analysis. The strongest and most consistent clinical pattern was observed with decompression and marsupialization in appropriately selected large lesions. These approaches were associated with gradual reduction in cyst size and progressive bone regeneration while allowing preservation of adjacent anatomical structures. Their principal disadvantages were prolonged treatment duration, the need for regular monitoring, and dependence on patient compliance.

Endoscopic-assisted surgery demonstrated particular value in anatomically complex regions where conventional access could require greater tissue disruption. The principal benefit was improved visualization and precision through limited access. Piezoelectric surgery was mainly beneficial as an adjunct for precise bone removal near critical anatomical structures. Its clinical value was related to tissue preservation and controlled osteotomy rather than independent cyst treatment. Regenerative approaches showed particular importance for residual post-cystic defects. Bone grafting and guided bone regeneration were used to restore lost bone volume, preserve alveolar architecture, and improve conditions for subsequent implant rehabilitation. PRF and related platelet concentrates were generally reported as adjunctive biological measures rather than independent regenerative treatments.

CBCT-based planning improved anatomical assessment and treatment planning, especially for lesions with complex relationships to teeth, nerves, cortical bone, or the maxillary sinus. However, the clinical evidence for advanced digital workflows remained less extensive than that for established conservative surgical approaches.

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Table 12. Comparative Clinical Outcomes of Minimally Invasive Approaches

Minimally invasive approach	Main clinical indication	Treatment effectiveness	Recurrence considerations	Postoperative complication risk	Approximate healing pattern	Bone regeneration potential
Decompression	Large cysts close to vital anatomical structures	High in appropriately selected cases	Low–moderate with adequate long-term follow-up	Low	Soft-tissue healing approximately 2–4 weeks; radiographic bone regeneration commonly assessed over 6–24 months	High
Marsupialization	Large lesions requiring reduction before definitive treatment	Moderate–high	Moderate; depends on lesion biology and definitive treatment	Low–moderate	Approximately 2–6 weeks for soft-tissue healing; bone remodeling may continue for 6–24 months	Moderate–high
Nonsurgical endodontic treatment	Selected inflammatory radicular lesions associated with treatable teeth	Moderate–high selected lesions	Low–moderate in appropriately selected cases	Very low	Approximately 1–3 weeks for early soft-tissue recovery; radiographic healing generally assessed over 6–12 months	Moderate
Endoscopic-assisted surgery	Lesions in anatomically difficult regions	High in selected cases	Low when complete pathological removal is achieved	Low	Approximately 1–3 weeks; bone healing depends on defect and regenerative protocol	Moderate–high
Piezoelectric surgery	Lesions close to nerves, vessels, sinus structures	High as adjunctive technique	Low when combined complete removal	Low	Approximately 1–3 weeks; bone regeneration commonly assessed over 6–18 months	Moderate–high
Er laser-assisted surgery	Selected enucleation and periapical surgical procedures	Moderate–high as adjunct	Low complete pathological removal achieved when appropriate parameters are used	Low when appropriate parameters are used	Approximately 1–3 weeks; radiographic evidence generally assessed over 6–12 months	Potentially favorable, but clinical evidence remains limited
GBR with bone grafting	Large residual osseous defects	High defect reconstruction	Primarily related to completeness of cyst removal	Moderate	Approximately 2–6 weeks for soft-tissue healing; bone maturation generally assessed over 6–	Excellent

Collagen membrane-assisted regeneration	Contained or partially contained defects	High	Low–moderate	Low–moderate, particularly with membrane exposure	12 months or longer Approximately 2–6 weeks; bone regeneration commonly assessed over 6–12 months	High
	Adjunctive postoperative healing and regeneration	Promising adjunctive effect	Not independently established	Very low	May support early soft-tissue healing; definitive bone regeneration depends on the primary treatment	Moderate–high as a biological adjunct
	Complex lesions requiring precise planning	Improves treatment predictability	Not directly applicable	Low as a planning intervention	Depends on the surgical procedure	Depends on the definitive treatment

The comparative evidence therefore supports an individualized treatment strategy rather than a fixed hierarchy of minimally invasive techniques. The choice of treatment should take into account lesion type, size, anatomical location, relationship to vital structures, tooth vitality and restorability, biological behavior, and the anticipated need for bone reconstruction or future rehabilitation^{1,5,9,32}. Following the comparative evaluation of the available treatment modalities, the evidence identified in this review was integrated into the clinical decision-making algorithm presented in Figure 2. The algorithm is intended as a synthesis of the treatment principles identified in the literature rather than as a validated clinical guideline. It illustrates how lesion characteristics and anatomical considerations may be used to guide selection among conservative, surgical, regenerative, and digital-assisted approaches.

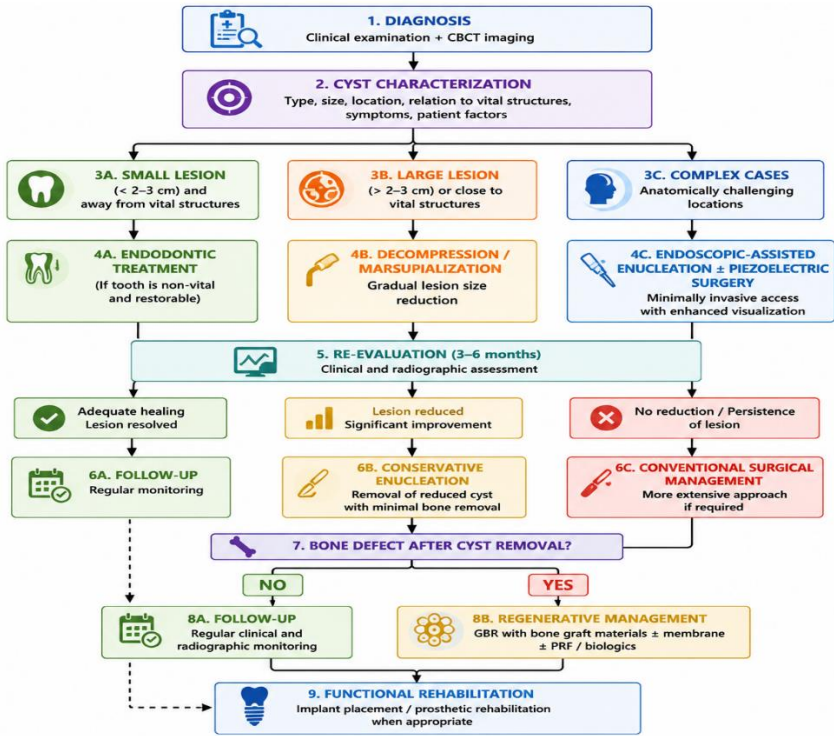


Figure 2. Treatment Algorithm for Minimally Invasive Management of Odontogenic Cysts.

The proposed algorithm begins with clinical examination and appropriate radiographic, including CBCT-based, assessment. Treatment selection is subsequently guided by lesion size, anatomical location, relationship to adjacent vital structures, tooth vitality and restorability, and the anticipated need for definitive pathological control. Selected inflammatory periapical lesions associated with treatable teeth may initially be considered for nonsurgical endodontic management. Larger lesions in which preservation of adjacent structures is a major concern may be considered for decompression or marsupialization, followed when indicated by definitive surgical management. Lesions in anatomically difficult regions may be managed with endoscopic-assisted or piezoelectric techniques when these approaches provide a clinically appropriate advantage. Following lesion removal, residual osseous defects may be evaluated for regenerative reconstruction using bone-graft materials, guided bone regeneration, collagen membranes, and selected biological adjuncts. Long-term clinical and radiographic follow-up remains necessary to evaluate lesion resolution, bone regeneration, and the need for further treatment.

3.5 Overall Evidence Pattern

Taken together, the 42 included studies demonstrated a consistent change in the clinical philosophy of odontogenic cyst management. Rather than focusing exclusively on complete surgical removal through the most extensive possible access, contemporary approaches increasingly emphasized preservation of healthy bone, teeth, nerves, sinus structures, and other adjacent tissues.

The evidence was strongest for established conservative approaches, particularly decompression and marsupialization in appropriately selected large lesions. Endoscopic and piezoelectric technologies provided additional means of improving surgical access and precision in anatomically difficult cases. Regenerative techniques extended the concept of minimally invasive treatment beyond removal of the cyst itself by addressing the residual osseous defect and preparing the site for future functional rehabilitation.

Digital technologies, particularly CBCT-based planning, increasingly supported individualized treatment selection and surgical planning. However, the evidence for advanced digital and emerging technologies remained less mature than that for conventional conservative approaches.

Across the included literature, treatment success was strongly dependent on appropriate case selection. Cyst size, anatomical location, biological behavior, relationship to adjacent teeth and vital structures, cortical involvement, infection control, and the patient's future restorative requirements all influenced the choice of treatment. No single minimally invasive technique was appropriate for all odontogenic cysts.

The comparative evidence therefore supports an individualized treatment pathway in which conservative decompression or marsupialization may be selected for large lesions, endoscopic or piezoelectric techniques may be used when precise access is required, regenerative procedures may be added when significant osseous defects remain, and CBCT-based digital planning may guide the overall surgical strategy. The evidence also demonstrated that minimally invasive treatment should not be interpreted as synonymous with avoiding surgery altogether. In many cases, the minimally invasive concept refers instead to reducing the extent of surgical trauma while maintaining adequate pathological control. The final treatment objective remains complete and appropriate management of the cystic lesion together with preservation or restoration of the surrounding anatomical and functional structures. Overall, the 42 included publications support a contemporary treatment model combining conservative surgery, precision-enhancing technologies, biological regeneration, and digital planning. At the same time, substantial heterogeneity in study designs, patient populations, treatment protocols, definitions of healing, and duration of follow-up limits definitive comparisons between modalities. This heterogeneity also indicates the need for prospective comparative studies using standardized clinical and radiographic outcome measures and sufficiently long follow-up periods.

3.3.5. Clinical Reconstruction of Post-Cystic Osseous Defects

The management of large odontogenic cysts does not end with removal of the pathological lesion. In extensive defects, preservation and reconstruction of the remaining osseous architecture are important components of minimally invasive and tissue-preserving treatment, particularly when subsequent functional rehabilitation or dental implant placement is anticipated. The literature therefore describes the use of bone grafting, barrier membranes, and guided bone regeneration as adjunctive procedures following cyst removal^{22-25,41}. Within this scoping review, a clinical illustration is included to demonstrate the treatment sequence described in the literature, rather than to present a new clinical case or to provide

case-report evidence. The purpose of the illustration is to translate the principal regenerative concepts identified during evidence mapping into a clinically understandable sequence. As illustrated in Figure , management may involve surgical exposure and removal of the cystic lesion, preparation of the residual osseous cavity, placement of bone-graft material, application of a barrier membrane, primary soft-tissue closure, and subsequent radiographic assessment of bone regeneration^{22-25,41}. This type of clinical illustration is particularly relevant to a scoping review because the review maps different treatment modalities and describes how they are applied across the available literature. It does not constitute additional evidence and is not intended to demonstrate treatment efficacy in an individual patient. Instead, it provides a visual representation of the regenerative treatment pathway identified from the reviewed literature, thereby linking the evidence on bone grafting and guided bone regeneration with their potential clinical application.

G. Hakobyan specifically described bone-grafting procedures for reconstruction of osseous defects associated with dental implants, including defects remaining after removal of cystic lesions. This work provides a clinically relevant example of the reconstructive principle addressed in this section and supports the inclusion of bone grafting as a component of post-cystic defect management⁴¹.

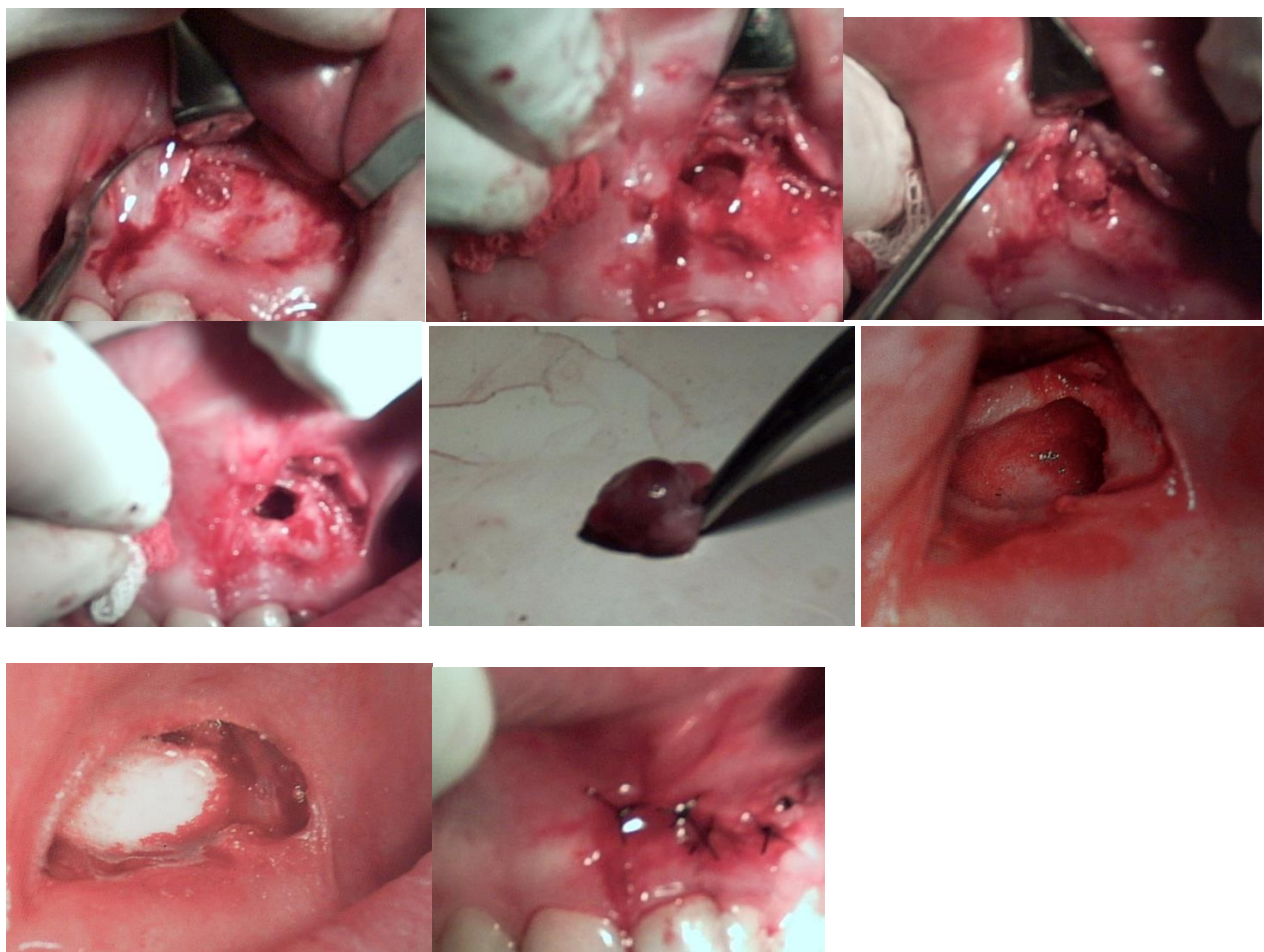




Figure 3. Clinical sequence illustrating regenerative reconstruction of a post-cystic osseous defect. (A) Preoperative clinical and radiographic assessment of the cyst-associated osseous defect. (B) Surgical exposure of the affected region. (C) Removal of the cystic lesion and meticulous preparation of the residual osseous cavity. (D) Preparation of the defect for regenerative reconstruction. (E) Placement of bone-graft material within the residual defect. (F) Coverage of the grafted area with a barrier membrane to support guided bone regeneration. (G) Primary closure of the surgical site. (H) Postoperative radiographic assessment demonstrating progressive reconstruction of the osseous defect. The sequence is presented as a representative clinical illustration of regenerative principles described in the literature and is not intended to represent an independent case report ⁴¹.

4. DISCUSSION

The present scoping review maps the available evidence concerning minimally invasive management of odontogenic cysts and demonstrates a gradual expansion of treatment concepts beyond conventional extensive surgical removal. The literature includes established conservative approaches, such as decompression and marsupialization, as well as endoscopic and piezoelectric surgical techniques, regenerative procedures, nonsurgical endodontic treatment, and digital-assisted planning. The evidence does not support the replacement of conventional surgery by a single minimally invasive technique. Instead, it supports the use of different approaches according to lesion characteristics and the clinical objectives of treatment ^{1,5,9,32}.

Conventional enucleation and other surgical procedures remain important methods for definitive management of odontogenic cysts. Their principal advantage is direct removal of the pathological lesion. Nevertheless, extensive surgical access may require removal of surrounding bone and may increase the risk of injury to adjacent anatomical structures in large or anatomically complex lesions. These considerations have contributed to the development of treatment strategies designed to reduce surgical morbidity while maintaining adequate pathological control ^{8,10,32}.

Decompression and marsupialization represent the most established conservative strategies identified in this review. Their principal biological effect is reduction of intracystic pressure and gradual reduction of the lesion. The systematic review by Berretta et al. supports the use of these procedures for reduction of

cystic jaw lesions, while clinical studies have demonstrated their application in large lesions, including lesions in children and lesions for which preservation of surrounding structures is clinically important ^{9,11-14}. The principal limitations are the prolonged treatment period, the need for regular follow-up, patient compliance, and the possibility that a second surgical procedure may ultimately be necessary.

The endoscopic literature demonstrates another way in which surgical morbidity may be reduced. Endoscopic-assisted enucleation allows direct visualization through a more limited access and has been described for large mandibular cysts and lesions involving difficult anatomical regions ¹⁵⁻¹⁸. Navigation-based endoscopic enucleation represents a further development of this concept by combining endoscopic visualization with navigation technology ¹⁶. These procedures are technically demanding, however, and their wider use depends on equipment availability and surgical expertise. The current evidence is therefore more appropriately interpreted as supporting selected applications rather than routine use for all odontogenic cysts.

Piezoelectric surgery has similarly been incorporated into contemporary oral and maxillofacial surgery as a method of controlled bone manipulation. The selective cutting properties of ultrasonic devices may be useful when access is required near anatomical structures that should be preserved. The literature included in this review supports the use of piezoelectric surgery as an adjunctive technique, but it does not establish it as a distinct treatment for the underlying cystic pathology ²⁸⁻³⁰. Its principal value lies in the manner in which the surgical access or bony component of treatment is performed.

Regenerative treatment represents an important extension of minimally invasive cyst management. Once a cyst has been removed, a large residual osseous cavity may remain. The management of this defect becomes particularly important when the patient is expected to undergo subsequent implant-supported rehabilitation. Bone-graft materials can provide structural support and an osteoconductive environment, while barrier membranes can help maintain a protected space for bone formation²²⁻²⁵. The literature therefore supports considering reconstruction as an integral part of treatment planning in selected extensive defects rather than as a separate procedure unrelated to cyst management.

The clinical importance of regeneration is also illustrated by the literature describing reconstruction of large odontogenic cystic defects and by the work of Hakobyan, which specifically addressed bone-grafting procedures for osseous defects associated with dental implants, including defects arising after removal of cystic lesions^{22-25,31,41}. In the context of this scoping review, such evidence is relevant because it demonstrates how preservation of the residual anatomical architecture and subsequent restoration of bone volume can be incorporated into a broader treatment pathway. The purpose is not to present an individual clinical case as evidence, but to identify the reconstructive principle represented in the literature.

Platelet-rich fibrin has received increasing attention as a biological adjunct to regenerative treatment. Its proposed effects include provision of a fibrin matrix, release of biologically active mediators, and support of angiogenic and tissue-healing processes^{26,27}. Nevertheless, the evidence mapped in this review does not justify treating PRF as an independent substitute for adequate surgical treatment or established regenerative principles. Its role is better understood as an adjunct whose potential contribution may depend on the defect, the primary reconstructive procedure, and other patient-related factors.

Nonsurgical endodontic management provides another example of treatment aimed at preserving rather than removing anatomical structures. In selected inflammatory periapical lesions, successful control of intracanal infection may allow resolution of the associated periapical pathology while preserving the tooth^{35,36}. Calcium hydroxide and contemporary bioceramic materials have favorable biological properties that support their use in endodontic treatment³⁵⁻³⁷. However, the distinction between a clinically diagnosed cyst-like lesion and a histologically confirmed true cyst is essential. The available evidence does not support the conclusion that nonsurgical endodontic treatment is an

appropriate substitute for surgery in all true odontogenic cysts.

Digital-assisted planning has a different but increasingly relevant role. CBCT provides three-dimensional information that can improve understanding of lesion anatomy and its relationship to adjacent structures^{19,20}. Virtual surgical planning and three-dimensional printing may further support individualized operative preparation in selected complex cases²¹. At present, these technologies should be regarded principally as diagnostic and planning tools. The evidence does not support assigning them an independent therapeutic effect on cyst recurrence or bone healing.

Laser-assisted procedures, including Er applications, represent a further emerging area. The systematic review included in the reference set concerns laser application in oral periodontal therapy rather than providing direct evidence for routine treatment of odontogenic cysts⁴⁰. Therefore, the role of laser-assisted surgery in this review should be interpreted cautiously. Potential biological and technical advantages have been proposed in oral surgical applications, but the available evidence is insufficient to establish laser treatment as a standard modality for odontogenic cyst management⁴⁰.

Overall, the evidence mapped in this scoping review indicates that minimally invasive treatment should be understood as a treatment philosophy rather than as a single operative technique. The central principles are reduction of unnecessary tissue injury, preservation of teeth and surrounding anatomical structures when clinically appropriate, control of the pathological process, and restoration of function and tissue volume when required. The most appropriate treatment therefore depends on the individual lesion rather than on the theoretical superiority of one minimally invasive technique.

The available literature also demonstrates important differences in the maturity of the evidence base. Decompression and marsupialization have a comparatively established clinical literature, whereas endoscopic surgery, advanced digital workflows, and laser-assisted procedures remain supported by smaller or more heterogeneous bodies of evidence. Regenerative procedures have a broader biological and reconstructive literature, but their specific application after odontogenic cyst removal also varies substantially between studies^{9,15-18,22-31}. These differences should be considered when interpreting the findings of the present scoping review.

The principal research gap is the absence of standardized comparative studies that evaluate different minimally invasive approaches using common definitions of treatment success, recurrence, bone regeneration,

complications, and long-term functional outcomes. Future studies should therefore use clearly defined diagnostic criteria, standardized radiographic assessment, consistent follow-up intervals, and clinically meaningful outcome measures. Particular attention should also be directed toward prospective evaluation of digital planning and emerging technologies before they become incorporated into routine clinical algorithms.

This scoping review has several limitations that should be considered when interpreting its findings. First, the available literature is heterogeneous with respect to study design, diagnostic criteria, cyst classification, lesion size, anatomical location, treatment protocols, follow-up duration, and outcome definitions. This heterogeneity prevents direct comparison of all treatment modalities and limits the possibility of identifying a single superior minimally invasive approach.

Second, the evidence base includes retrospective clinical studies, case series, observational investigations, technical reports, and other non-randomized forms of evidence. Such studies are valuable for mapping the available clinical literature and identifying treatment trends, but they provide different levels of certainty regarding treatment effectiveness and long-term outcomes. In accordance with the purpose of a scoping review, the present study mapped this evidence rather than undertaking a formal pooled assessment of intervention effectiveness.

Third, the interpretation of cyst resolution is complicated by differences in diagnostic methodology. In particular, periapical lesions described clinically as cysts are not necessarily equivalent to histologically confirmed radicular cysts. This issue is particularly relevant when interpreting reports of nonsurgical endodontic treatment and should be considered when comparing endodontic and surgical treatment outcomes.

Another limitation is the variation in radiographic methods used to assess lesion reduction and bone regeneration. Conventional radiography, CBCT, and other imaging approaches may provide different levels of anatomical information, while criteria for defining radiographic healing are not uniform across studies. Standardized three-dimensional imaging and clearly defined radiographic endpoints would improve the comparability of future research. The evidence for several emerging technologies is also limited. Endoscopic-assisted surgery, digital surgical planning, three-dimensional printing, artificial intelligence-assisted workflows, and laser-assisted procedures are not supported by the same volume of cyst-specific

clinical evidence as decompression and marsupialization. Their potential advantages should therefore be interpreted as emerging findings rather than established clinical standards.

Finally, the literature includes studies addressing different objectives within the same treatment pathway. Some investigations focus on cyst reduction, others on surgical access, bone regeneration, preservation of teeth, or subsequent implant rehabilitation. These different endpoints make direct quantitative comparison difficult. The findings of this scoping review should consequently be interpreted as an evidence map describing the range of available approaches and their reported clinical applications rather than as a ranking of treatment effectiveness.

CONCLUSION

The present scoping review demonstrates that the management of odontogenic cysts is increasingly characterized by conservative, tissue-preserving, regenerative, and technology-assisted treatment concepts. The available literature does not indicate that minimally invasive treatment should replace conventional surgery in all patients. Rather, it demonstrates that different minimally invasive approaches may be incorporated selectively according to lesion characteristics, anatomical relationships, treatment objectives, and the requirements for subsequent rehabilitation. Decompression and marsupialization remain important conservative approaches, particularly for large lesions in which immediate extensive surgery may place adjacent teeth, nerves, sinus structures, or other anatomical tissues at risk. Their principal advantages are reduction of lesion size and preservation of surrounding structures, although prolonged treatment and the possibility of subsequent surgery remain important considerations. Nonsurgical endodontic treatment provides a tooth-preserving option for selected inflammatory periapical lesions when adequate control of the intracanal infection can be achieved. Calcium hydroxide and contemporary bioceramic materials have established biological applications in endodontic treatment, but nonsurgical management should not be considered a universal alternative to surgical treatment of histologically confirmed or persistent odontogenic cysts. Endoscopic-assisted and piezoelectric techniques provide additional methods for reducing surgical access and improving operative control in selected anatomically difficult cases. Their value is principally related to visualization, precision, and tissue preservation rather than to independent biological treatment of the cyst. Regenerative procedures, including bone-graft materials, guided bone regeneration, collagen membranes, and platelet-rich fibrin, have expanded the objectives of cyst management beyond elimination of pathology toward

restoration of the residual osseous defect. These approaches are particularly relevant when preservation or reconstruction of alveolar bone is important for subsequent functional or implant-supported rehabilitation. CBCT and digital planning contribute primarily to diagnosis, anatomical assessment, and individualized preoperative planning. Virtual surgical planning and three-dimensional printing represent further developments in this field, while artificial intelligence-assisted workflows remain at an early stage of clinical validation. These technologies should therefore be regarded as adjuncts to clinical decision-making rather than independent treatment modalities. Overall, minimally invasive management of odontogenic cysts represents a shift from a purely lesion-removal model toward a broader treatment philosophy that seeks to control the pathological process while preserving teeth, bone, and surrounding anatomical structures and, when necessary, restoring lost tissue. The appropriate approach remains dependent on the individual lesion and patient. Future prospective studies using standardized diagnostic criteria, treatment protocols, radiographic assessment, and long-term clinical outcomes are required to establish more predictable evidence-based treatment pathways.

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Ethical Approval

Ethical approval was not required because this study was a scoping review of previously published literature and did not involve the collection or analysis of new patient data.

Conflict of Interest

The authors declare no conflict of interest related to this manuscript.

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