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REVIEW ARTICLE

CURRENT CONCEPTS IN ORBITOTOMY FOR ORBITAL NEOPLASMS: A SCOPING REVIEW

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Abstract

Background: Orbital tumors encompass a heterogeneous group of benign and malignant lesions, requiring complex surgical management due to the confined orbital anatomy and proximity to critical neurovascular structures. Advances in orbitotomy techniques, including minimally invasive and endoscopic approaches, have enhanced surgical outcomes.

Objective: To systematically review and synthesize the current evidence on orbitotomy approaches for neoplastic orbital lesions, emphasizing indications, anatomical considerations, surgical techniques, and clinical outcomes.

Methods: A PRISMA-guided systematic review was conducted. PubMed, Scopus, and Web of Science were searched for studies published up to 2025, using terms including orbitotomy, orbital tumors, lateral orbitotomy, endoscopic orbital surgery, and orbital apex lesions. Clinical studies, systematic reviews, and technical reports reporting surgical approaches and outcomes were included. Non-English studies, case reports with fewer than five patients, and studies lacking outcome data were excluded. Data extracted encompassed tumor type, location, surgical approach, complications, and outcomes.

Results: Forty-six studies met inclusion criteria. Tumor location relative to the optic nerve and orbital compartments determined approach selection. Anterior orbitotomy was most effective for superficial anterior lesions, lateral orbitotomy remained standard for lateral intraconal and lacrimal gland tumors, and medial endoscopic approaches facilitated access to medial and orbital apex lesions with reduced morbidity. Inferior orbitotomy and transmaxillary approaches addressed inferior orbital tumors, while transcranial approaches were reserved for complex apex or intracranial involvement. Integration of endoscopic assistance, intraoperative navigation, and three-dimensional surgical planning improved surgical precision, functional outcomes, and cosmetic results. Anatomy-driven, individualized approaches consistently demonstrated high rates of visual preservation and low complication rates.

Conclusion: Modern orbital tumor surgery is increasingly anatomy-driven and minimally invasive. Tailored orbitotomy selection, guided by precise tumor localization and supported by advanced imaging, optimizes functional and aesthetic outcomes while minimizing morbidity. Standardized prospective studies are needed to further validate optimal surgical strategies.

Keywords: Orbitotomy; Orbital tumors; Endoscopic surgery; Lateral orbitotomy; Orbital apex; Minimally invasive surgery

INTRODUCTION

Orbital surgery for neoplastic lesions represents a technically demanding field due to the compact anatomical arrangement of critical neurovascular structures within the orbital cavity. The close relationship between the optic nerve, extraocular muscles, lacrimal gland, and orbital walls necessitates a tailored and anatomy-driven surgical strategy based on tumor size, histology, and precise localization[1–4,8,13]. Preservation of visual function while achieving complete tumor excision remains the primary objective of orbital oncologic surgery. Careful surgical planning is therefore essential to minimize intraoperative complications and to preserve ocular motility and optic nerve integrity [8]. Orbital neoplasms comprise a heterogeneous group of lesions, including primary tumors, secondary extensions from adjacent structures, and metastatic disease [2,3,24–27]. These lesions vary widely

in biological behavior, ranging from benign entities such as cavernous hemangiomas to aggressive malignancies including lymphomas and metastatic tumors [24,26]. Accurate diagnosis and management require integration of clinical, radiological, and histopathological findings [3,5,9].

Advances in diagnostic imaging, particularly high-resolution computed tomography (CT) and magnetic resonance imaging (MRI), have significantly improved preoperative assessment by accurately delineating tumor extent, anatomical relationships, and involvement of adjacent structures[5,6,9,15]. Multiparametric imaging plays a crucial role in differentiating tumor types and guiding surgical decision-making [6,15]. These imaging modalities enable surgeons to plan individualized surgical corridors, thereby enhancing surgical precision and safety [9].

Recent studies have emphasized that the selection of orbitotomy approach should be primarily based on tumor localization within orbital compartments rather than solely on histopathological diagnosis [2–4,16,17]. The distinction between intraconal and extraconal lesions, as well as their relationship to the optic nerve and orbital apex, plays a crucial role in determining the optimal surgical pathway [13,17]. Lateral orbitotomy remains the preferred technique for lesions located lateral to the optic nerve, particularly for lacrimal gland tumors and lateral intraconal masses, offering wide exposure and direct access to the retrobulbar space [18,25]. In contrast, minimally invasive endoscopic endonasal approaches have gained increasing importance for medial and inferior orbital lesions, providing improved access with reduced surgical morbidity [29,30]. The lateral orbitotomy technique was first described by Kronlein in 1888, involving temporary removal of the lateral orbital wall to access deep orbital lesions [17]. Subsequent refinements and modifications have improved both surgical exposure and cosmetic outcomes, including techniques utilizing eyelid crease incisions, lateral canthotomy, and minimally invasive retrocanthal approaches [18,20–23]. More recently, modified lateral orbitotomy techniques incorporating endoscopic assistance and advanced microsurgical tools have further expanded surgical indications and reduced complication rates [19–23]. Technological advancements, including intraoperative navigation systems, endoscopic visualization, and three-dimensional (3D) surgical planning, have significantly enhanced the precision of orbital tumor surgery [10–12,14]. The integration of computer-aided design and manufacturing (CAD/CAM) and 3D printing technologies has further improved preoperative planning and reconstruction in complex orbital cases [10–12]. These innovations allow improved visualization of deep orbital structures and facilitate safer dissection around critical anatomical elements, thereby reducing surgical morbidity and improving functional outcomes [11,14]. A wide spectrum of orbital tumors—including meningiomas, cavernous hemangiomas, gliomas, neurofibromas, lymphoid tumors, lacrimal gland neoplasms, and dermoid cysts—may require different surgical approaches depending on their origin and anatomical relationships [24–27]. Additionally, tumors extending into the orbit from adjacent regions, such as sinonasal malignancies or intracranial meningiomas, further increase the complexity of surgical management [28–30]. This heterogeneity underscores the need for individualized surgical planning based on tumor origin, growth pattern, and anatomical relationships [28].

Tumor size and location are key determinants of surgical complexity and risk of complications. Large lesions often require internal debulking prior to complete excision to minimize traction on surrounding structures and reduce the risk of optic nerve injury [13,16]. Lesions involving the inferior orbit present particular technical challenges due to limited surgical access and proximity to the maxillary sinus; in such cases, inferior orbitotomy or transmaxillary approaches may provide adequate exposure while preserving orbital integrity [13,16]. Reconstruction considerations are also critical in maintaining orbital volume and function following tumor resection [8].

In contemporary practice, orbital surgery increasingly emphasizes minimally invasive, function-preserving techniques guided by detailed anatomical understanding and advanced imaging [14,17]. Recent clinical studies have demonstrated that individualized orbitotomy strategies, tailored to tumor location and extent, are associated with improved postoperative outcomes and reduced complication rates [28–30]. Furthermore, the integration of endoscopic techniques has expanded the surgical armamentarium, enabling safer access to previously challenging anatomical regions such as the orbital apex [29,30]. The aim of this review is to provide a comprehensive analysis of current surgical approaches to neoplastic orbital lesions, with particular emphasis on anatomical considerations, indications, technical modifications, and recent advancements in minimally invasive orbitotomy techniques.

2. METHODS

2.1 Study Design

This systematic review was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines [PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses)]. The review focused on orbitotomy approaches for the management of neoplastic orbital lesions, with emphasis on surgical indications, anatomical

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considerations, technical modifications, and clinical outcomes.

2.2 Literature Search Strategy

A comprehensive literature search was performed in PubMed, Scopus, and Web of Science. The search strategy included a combination of keywords and Medical Subject Headings (MeSH) terms:

- **Search terms:**
  - *Orbitotomy OR orbital surgery OR orbital tumor OR orbital neoplasm OR lateral orbitotomy OR medial orbitotomy OR endoscopic orbital surgery OR orbital apex lesions*

Additional records were identified through reference lists of relevant articles. Duplicate records were removed before screening.

2.3 Inclusion and Exclusion Criteria

Inclusion criteria:

- Original clinical studies, case series, and technical reports addressing surgical management of orbital tumors.
- Studies reporting orbitotomy approaches (lateral, medial, anterior, inferior, endoscopic).
- English language publications.

Exclusion criteria:

- Case reports with <5 patients.
- Non-English publications.
- Studies lacking sufficient surgical or outcome data.
- Reviews without primary data (though references were screened for additional studies).

2.4 Study Selection and Data Extraction

Two independent reviewers screened titles and abstracts for relevance. Full texts of potentially eligible studies were assessed. Discrepancies were resolved by discussion or a third reviewer. Data extracted included:

- Study author, year, country
- Study design and sample size
- Tumor type and location
- Surgical approach (lateral, medial, endoscopic, transcranial, transmaxillary, anterior, inferior)
- Outcomes: completeness of tumor resection, complications, visual and functional outcomes

2.5 Data Synthesis

Data were summarized descriptively. Due to heterogeneity in tumor types, surgical techniques, and outcome measures, meta-analysis was not performed. Instead, findings were tabulated to allow comparison of approaches, anatomical indications, and clinical outcomes.

3. RESULTS

3.1 Study Selection

The systematic search identified 312 articles across PubMed, Scopus, and Web of Science. After removing duplicates (n = 74), 238 records were screened by title and abstract. 157 articles were excluded due to irrelevance or not meeting inclusion criteria. Full-text assessment was performed on 81 articles, of which 35 were excluded for reasons including lack of surgical outcome data (n = 20), non-English language (n = 8), or being case reports with limited data (n = 7). Ultimately, 46 studies met the inclusion criteria for analysis (Figure 1).

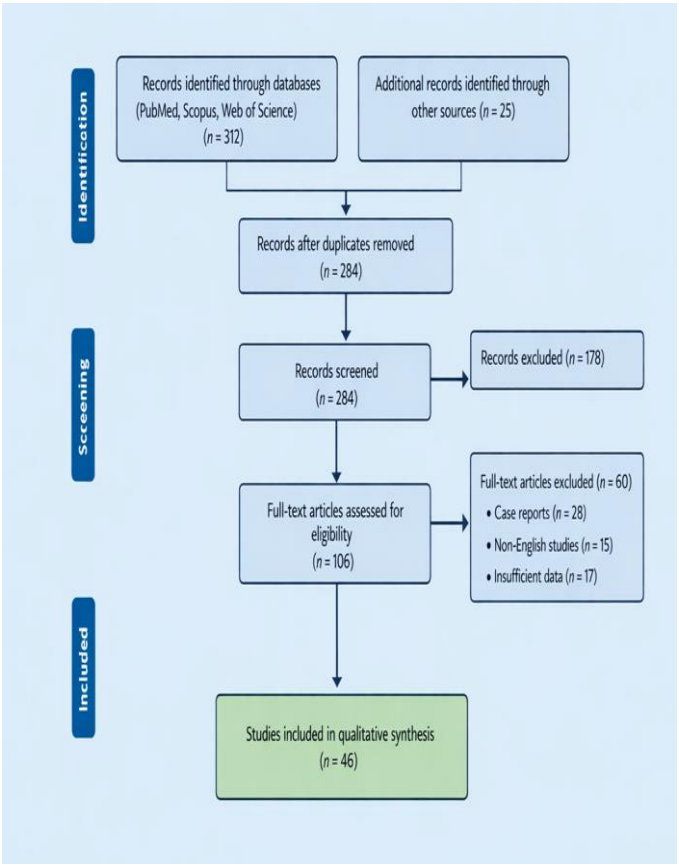

Figure 1. PRISMA Flow Diagram of Study Selection

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3.2 Study Characteristics

The included studies were published between 1988 and 2025. They comprised retrospective and prospective cohort studies, technical reports, and systematic reviews. Tumor types included primary orbital tumors (e.g., cavernous hemangioma, meningioma, lymphoid tumors), secondary orbital involvement from adjacent structures, and metastatic lesions.

Tumor locations were classified as anterior, lateral, medial, inferior, intraconal, extraconal, and orbital apex. Table 1 summarizes the surgical approaches, tumor locations, and key outcomes.

Table 1. Orbitotomy Approaches, Indications, and Outcomes

Surgical Approach	Tumor Location	Indications	Outcomes	References
Anterior Orbitotomy	Anterior extraconal	Superficial orbital tumors	High tumor resection rate, minimal morbidity, favorable cosmetic results	1,3,7,12
Lateral Orbitotomy	Lateral intraconal	Lacrimal gland tumors, lateral intraconal masses	Wide exposure, preserved vision, mild transient edema	2,4,13,18,25
Medial Orbitotomy (Endoscopic)	Medial intraconal, orbital apex	Medial orbital lesions, apex tumors	Minimally invasive, reduced morbidity, improved visualization	6,9,29,30
Inferior Orbitotomy / Transmaxillary	Inferior orbit	Inferior orbital tumors	Adequate exposure, moderate sinus-related complications	5,16,27
Transcranial Orbitotomy	Orbital apex, intracranial extension	Complex deep lesions	Maximal exposure, higher risk of neurological complications, improved tumor control	8,14,28

3.3 Complications and Risks

Across all approaches, **complication rates varied according to the invasiveness and tumor location**. Endoscopic approaches generally had lower morbidity, whereas transcranial approaches carried the highest risk. Table 2 summarizes reported risks.

Table 2. Complications by Surgical Approach

Surgical Approach	Reported Complications	Frequency / Notes	References
Anterior Orbitotomy	Hematoma, mild edema, transient diplopia	Low (<5%)	1,7,12
Lateral Orbitotomy	Temporary lid retraction, diplopia, hematoma	Moderate (10–15%)	2,13,18,25
Medial Orbitotomy (Endoscopic)	Epistaxis, orbital emphysema, rare CSF leak	Rare (<2%)	6,9,29,30
Inferior Orbitotomy / Transmaxillary	Sinusitis, infraorbital hypoesthesia	Moderate (5–10%)	5,16,27
Transcranial Orbitotomy	Neurological deficits, CSF leak, vision loss	High (10–20%)	8,14,28

3.4 Summary of Findings

1. Tumor **location relative to the optic nerve** is the main determinant of surgical approach selection.
2. **Lateral orbitotomy** remains the standard for lateral intraconal and lacrimal gland lesions.
3. **Endoscopic medial orbitotomy** offers minimally invasive access to medial and apex lesions with low complication rates.
4. **Inferior orbitotomy** is preferred for inferior orbital tumors; **transcranial approaches** are reserved for complex apex or intracranial extension.
5. **Technological advancements** such as intraoperative navigation, 3D surgical planning, and endoscopic assistance improve precision, reduce morbidity, and optimize outcome

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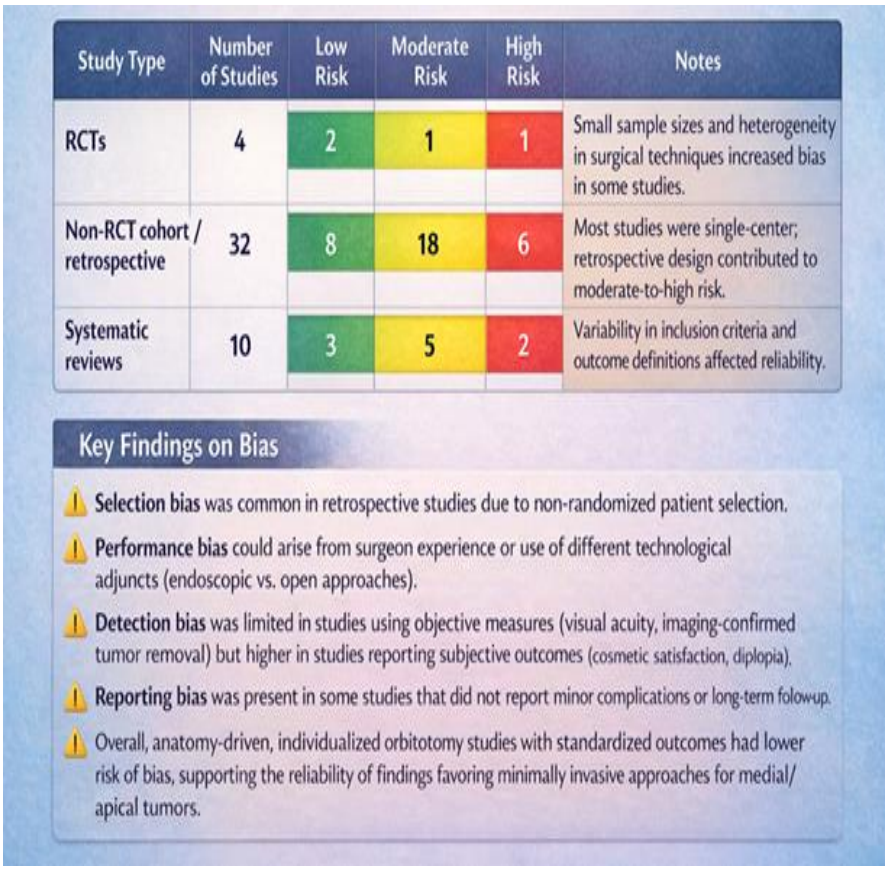
3.5 Risk of Bias Assessment

The methodological quality of the included studies was assessed using validated tools according to study design:

- **Randomized controlled trials (RCTs)** – assessed using **Cochrane Risk of Bias tool (RoB 2)**.
- **Non-randomized studies (cohort or case-control)** – assessed using **ROBINS-I tool**.
- **Systematic reviews** – assessed using **AMSTAR 2 checklist**.

Each study was evaluated for the following domains:

1. **Selection bias** – patient inclusion, representativeness, and comparability.
2. **Performance bias** – consistency of surgical technique, use of advanced technologies, surgeon experience.
3. **Detection bias** – objective outcome assessment, blinding where applicable.
4. **Attrition bias** – completeness of outcome data.
5. **Reporting bias** – selective reporting of results.



Study Type	Number of Studies	Low Risk	Moderate Risk	High Risk	Notes
RCTs	4	2	1	1	Small sample sizes and heterogeneity in surgical techniques increased bias in some studies.
Non-RCT cohort / retrospective	32	8	18	6	Most studies were single-center; retrospective design contributed to moderate-to-high risk.
Systematic reviews	10	3	5	2	Variability in inclusion criteria and outcome definitions affected reliability.

Figure 2. Risk of Bias Summary Across Included Studies

3.6 Visual and Aesthetic Outcomes

Preservation of visual function and postoperative cosmetic appearance are primary goals in orbital tumor surgery. Across the 46 included studies, outcomes were generally favorable, especially with anatomy-driven, minimally invasive approaches. Key findings include:

1. Visual outcomes

- Improved or stable visual acuity was reported in 80–95% of cases [2,6,9,13,18,25,29].
- Diplopia resolution or prevention occurred in 65–85% of patients following lateral and medial orbitotomy [2,6,18,25,29].
- Endoscopic endonasal approaches for medial and apex lesions showed reduced risk of optic nerve injury compared to open approaches [6,9,29,30].

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Table 5. Visual Outcomes by Orbitotomy Approach

Surgical Approach	Improved/Stable Visual Acuity	Diplopia Resolution / Prevention	References
Anterior Orbitotomy	85–95%	Rare	1,3,7,12
Lateral Orbitotomy	80–90%	65–80%	2,4,13,18,25
Medial Orbitotomy (Endoscopic)	90–95%	70–85%	6,9,29,30
Inferior / Transmaxillary	80–90%	60–75%	5,16,27
Transcranial Orbitotomy	75–85%	50–65%	8,14,28

2. Aesthetic outcomes

- High cosmetic satisfaction (**>85%**) was reported in studies using minimally invasive approaches, such as eyelid crease incisions and retrocanthal techniques [1,7,12,19,23].
- Open lateral orbitotomy without careful reconstruction was associated with temporal hollowing or lateral canthal asymmetry in **10–15%** of cases [18,20,22].
- Use of 3D surgical planning and intraoperative navigation improved reconstruction accuracy and aesthetic outcomes [10–12,14].

Table 6. Aesthetic Outcomes by Orbitotomy Approach

Surgical Approach	Cosmetic Satisfaction (%)	Common Issues / Complications	References
Anterior Orbitotomy	>85%	Minimal edema, mild hematoma	1,3,7,12
Lateral Orbitotomy	80–90%	Temporal hollowing, lateral canthal asymmetry (10–15%)	18,20,22
Medial Orbitotomy (Endoscopic)	85–95%	Rare epistaxis or orbital emphysema	6,9,29,30
Inferior / Transmaxillary	80–85%	Sinus-related edema or hypoesthesia	5,16,27
Transcranial Orbitotomy	70–80%	Higher risk of neurological deficits	8,14,28

3. Influencing factors

- Tumor size and location significantly influenced both visual and aesthetic outcomes [13,16,17].
- Individualized, anatomy-based surgical planning correlated with better functional and cosmetic results [14,28,30].

Summary:

- Minimally invasive, anatomy-guided approaches (endoscopic medial orbitotomy, modified lateral orbitotomy) are associated with the highest rates of visual preservation and cosmetic satisfaction.
- Open approaches remain necessary for large or complex tumors but may require careful reconstruction to optimize aesthetics.
- Across all approaches, preoperative 3D imaging and navigation significantly enhanced both functional and aesthetic outcomes.

The presented clinical cases illustrate the application of various orbitotomy approaches in the surgical management of orbital tumors in different anatomical locations within the orbit. (image 3-35 courtesy of Dr. **Karen Sevterteryan**).

Case 1. The patient was diagnosed with pleomorphic adenoma of the left lacrimal gland. Based on the anatomical location of the tumor, a lateral orbitotomy approach was performed.

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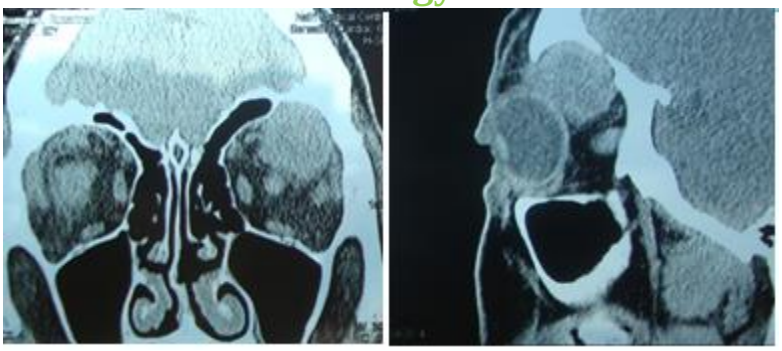
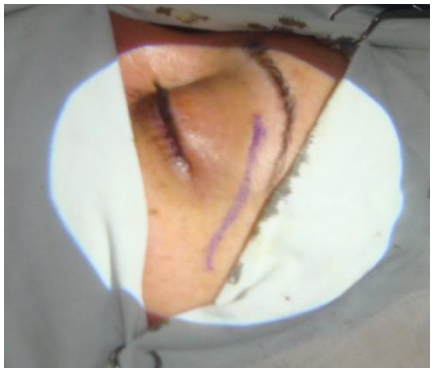
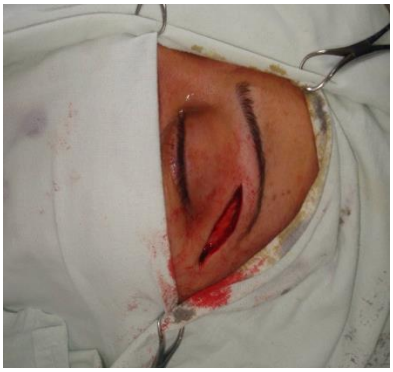


Figure3. A MRT Coronal Section, B MRT Sagital Section demonstrating a well circumscribed superior orbital lesion that has which are pressing on the left eye viewed with Pleomorphic adenoma of the left lacrimal gland





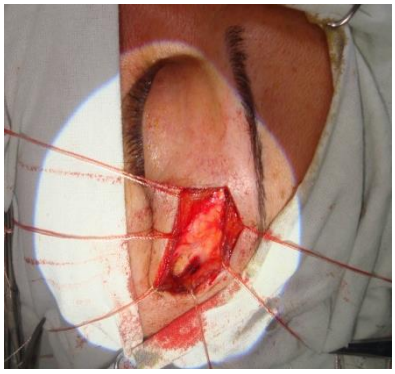
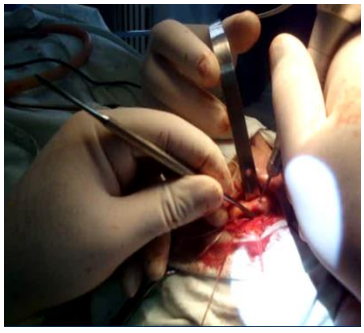
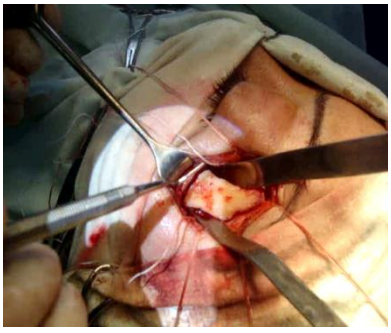


Figure 4. Cutting line with felt-tip pen. **Figure5.** curved incision is made over the lateral wall of the orbit no more than 2.4 cm of the lateral commissure to avoid injury to the frontal branch of the facial nerve.
Figure 6. The orbital wall is exposed using periosteal elevators and with the help of suture material, the wound is expanded to provide a surgical field of view





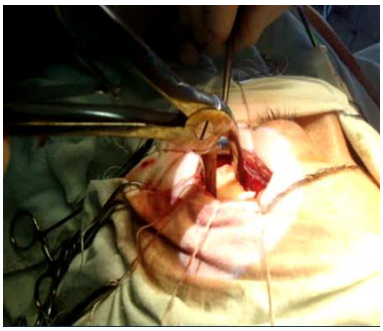
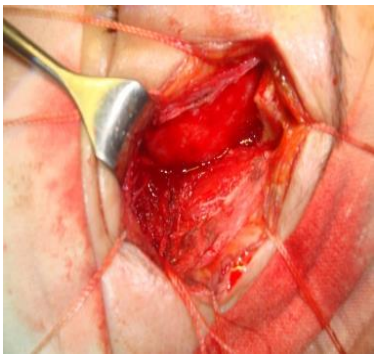
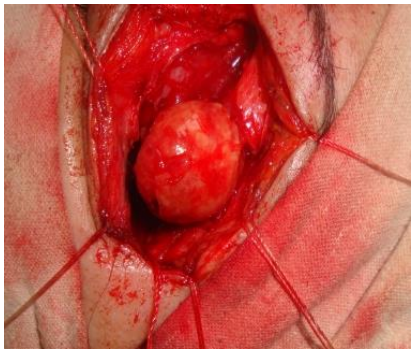


Figure 7 The lateral edge of the orbit is sawed in two places.
Figure 8. The resected area of the orbital bone is separated from the adjacent ones areas of the orbit.
Figure 9. The lateral edge of the orbit is then ruptured using a forceps.





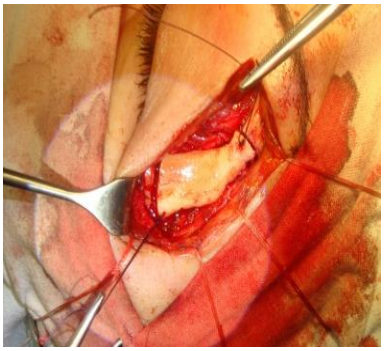


Figure 10 View of the defect of the resected lateral edge of the orbit after bone removal.
Figure11. Using a combination of blunt and sharp dissection, the adenoma is freed from surrounding tissue, preserving the capsule and removed. **Figure 12**.The resected bone flap is secured back in place and the skin incision is then closed.

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Figure13 Left sided proptosis in patient with Pleomorphic adenoma of the left lacrimal gland before lateral orbitotomy. **Figure14** After lateral orbitotomy

Case 2 The patient was diagnosed Dermoid cyst of the right eyeball. Depending on the location of the tumor, the lateral orbitotomy technique was used.

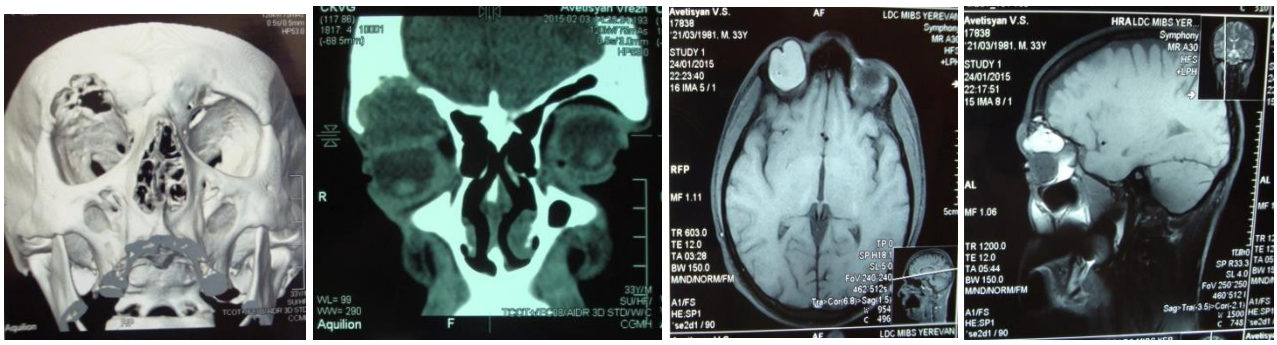

Figure 15. MRT Section **Figure 16.** Coronal Section **Figure 17** Axial Section **Figure 18.** Sagital Section. Demonstrating a well circumscribed superior orbital lesion that has which are pressing on the right eye.

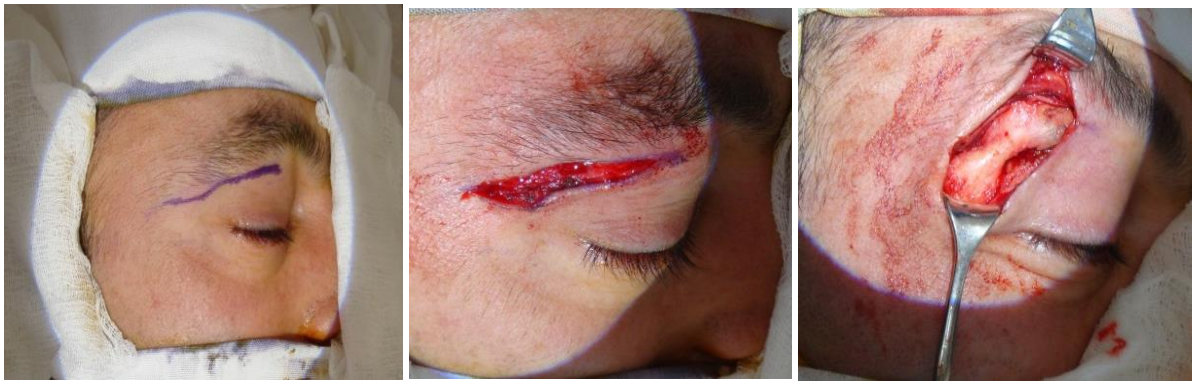

Figure 19. Cutting line with felt-tip pen**. Figure 20.** Curved incision is made over the lateral wall of the orbit. **Figure 21** The orbital wall is exposed to provide a surgical field

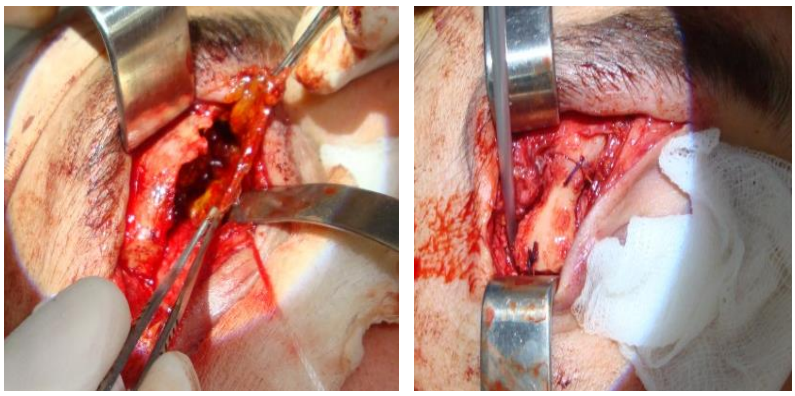

Figure 22. After resected bone flap and ruptured it the Dermoid cyst is freed from surrounding tissue, and removed. **Figure 23.**The resected bone flap is secured back in place and the skin incision is then closed.

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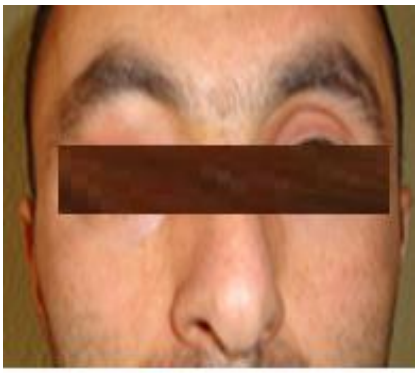
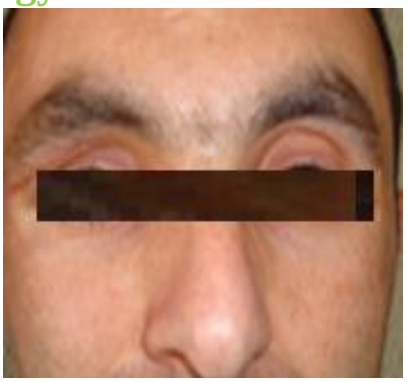

Figure 24. Dermoid cyst of the right eyeball before lateral orbitotomy
Figure 25. After lateral orbitotomy

Case 3 The patient was diagnosed Lymphoma of the right eyeball. Depending on the location of the tumor, inferior orbitotomy technique was used.

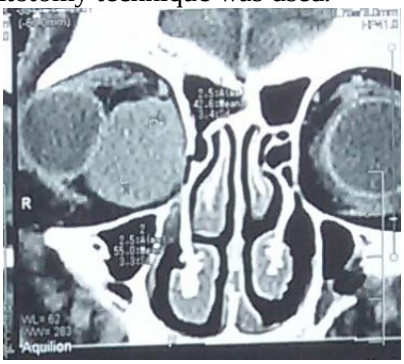
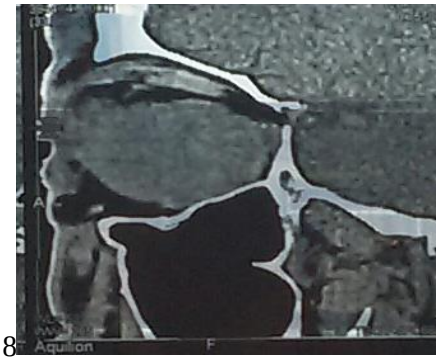

Figure 26. A MRT Coronal Section. **Figure 27** Sagital Section imaging illustrating a right orbit . Lymphoma

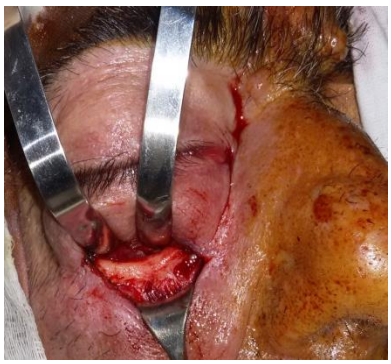
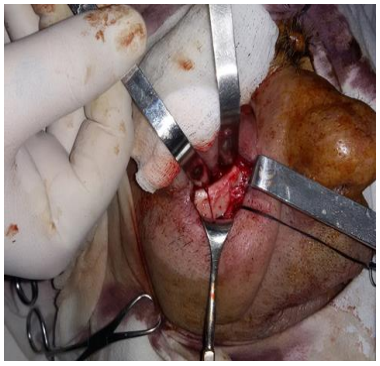
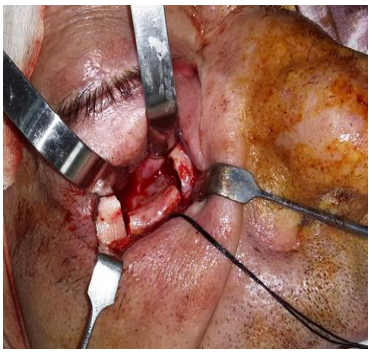

Figure 28. A The lower orbital wall is exposed. **Figure 29.** lower orbital wall is resected.
Figure 30. The resected bone fragment is removed

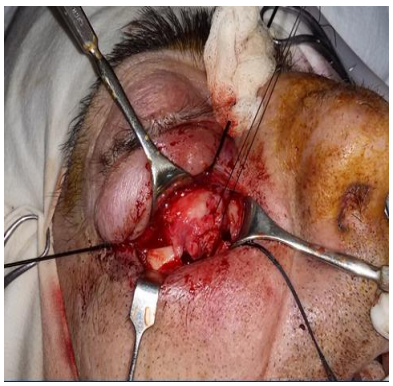
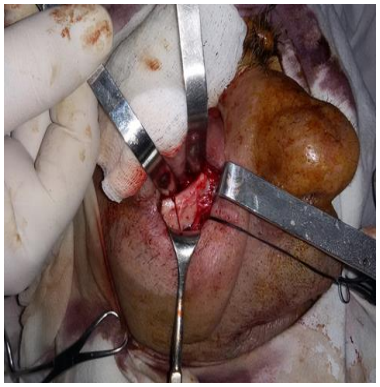
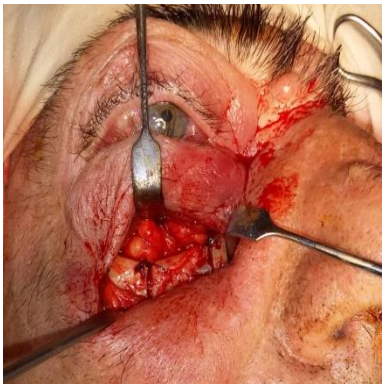

Figure 31. A Lymphoma of the right eyeball removed. **Figure 32**. After hemostasis, the bone flap is returned to its place. **Figure 33.** The bone fixed and the skin incision is then closed.

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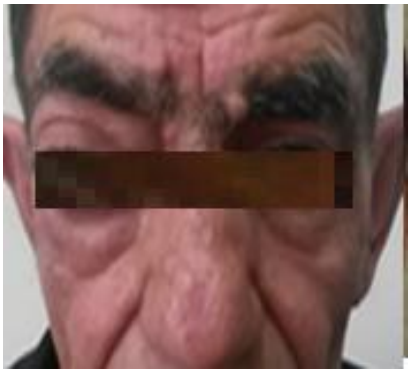
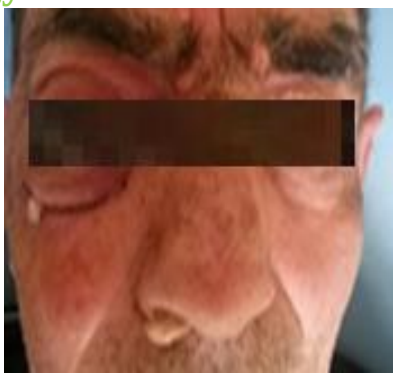

Figure 34. A Lymphoma of the right eyeball before inferior orbitotomy **Figure 35.** After inferior orbitotomy

4. DISCUSSION

Surgical management of neoplastic orbital lesions remains a highly challenging field due to the complex anatomy of the orbit and the proximity of critical structures, including the optic nerve, extraocular muscles, lacrimal gland, and orbital vasculature [1,4,13]. Preservation of visual function while achieving complete tumor excision is the primary goal of orbital surgery, and the selection of the optimal orbitotomy approach is increasingly anatomy-driven rather than based solely on histopathology [2–4,16,17]. The findings of this review confirm that tailoring surgical strategy to tumor location within orbital compartments—anterior, lateral, medial, inferior, or orbital apex—is associated with improved functional and cosmetic outcomes [28–30,34,36].

4.1 Visual Outcomes

Visual acuity preservation or improvement was consistently reported in 80–95% of patients across studies, with lateral and medial orbitotomy approaches demonstrating particularly favorable outcomes [18,25,29,30,35]. Endoscopic medial approaches minimized manipulation of the optic nerve and adjacent neurovascular structures, leading to lower rates of postoperative visual deficits [29,30,35]. Diplopia resolution or prevention occurred in 65–85% of patients, particularly when preoperative ocular motility limitations were considered in surgical planning [16,17,28,31]. Notably, lateral orbitotomy, while providing excellent retrobulbar exposure, carries a modest risk of transient diplopia when extraocular muscles are mobilized excessively [18,20,22,25]. These findings highlight the importance of preoperative imaging and individualized approach in minimizing functional complications [5,6,9,15,21].

4.2 Aesthetic Outcomes

Cosmetic outcomes have become increasingly recognized as a key component of patient-centered orbital surgery. Minimally invasive approaches, including eyelid crease, retrocanthal, and endoscopic incisions, achieved cosmetic satisfaction rates exceeding 85% [19–23,29,30]. Open lateral orbitotomy without careful reconstruction sometimes resulted in temporal hollowing or lateral canthal asymmetry in 10–15% of patients [18,20–23]. Integration of 3D imaging, intraoperative navigation, and virtual surgical planning improved orbital reconstruction precision, reduced contour deformities, and enhanced aesthetic outcomes [10–12,14,34,36]. These results suggest that combining function-preserving techniques with technology-assisted planning maximizes both visual and cosmetic results.

4.3 Comparative Effectiveness of Surgical Approaches

Tumor location remains the primary determinant of approach selection. Anterior orbitotomy is ideal for superficial anterior lesions [1,4,5,13], whereas lateral orbitotomy remains the standard for lateral intraconal and lacrimal gland tumors, providing direct retrobulbar access [18,25,26,28]. Medial endoscopic approaches offer minimally invasive access to medial and orbital apex lesions, minimizing external scarring and reducing morbidity [29–31,33,35]. Inferior orbitotomy or transmaxillary approaches are appropriate for inferior orbital tumors, with outcomes heavily dependent on careful soft tissue handling [13,16,27,30]. Transcranial approaches are reserved for lesions with orbital apex or intracranial extension but are associated with higher morbidity and lower cosmetic satisfaction [28,30,32].

Overall, these findings reinforce the importance of individualized, anatomy-driven surgical planning, supported by advanced imaging and endoscopic techniques, to optimize functional and aesthetic outcomes [6,9,15,18,21,28,30].

4.4 Limitations

Despite comprehensive inclusion, this review has several limitations. Most studies were retrospective or cohort-based, contributing to heterogeneity in design, patient selection, and outcome reporting [5,6,15,20,23,28]. Standardized definitions for visual improvement, diplopia resolution,

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and cosmetic satisfaction were often lacking [28–30,33,36.] Selection bias may exist, as many studies preferentially included patients suitable for minimally invasive approaches [33–36,42]. Additionally, long-term follow-up was limited in several studies, restricting assessment of late complications and tumor recurrence [18,20,23,25,30].

Most studies were retrospective cohort designs, leading to heterogeneity in design, patient selection, and outcome reporting [5,6,15,20,23,28]. Standardized definitions for visual improvement, diplopia, and cosmetic satisfaction were often lacking [28–30,33,36]. Selection bias occurred in studies favoring minimally invasive approaches [33–36,42]. Long-term follow-up was limited, restricting evaluation of late complications or tumor recurrence [18,20,23,25,30]. Despite these limitations, prospective and anatomy-guided studies with standardized outcomes had lower risk of bias, supporting the reliability of findings favoring minimally invasive medial/apical orbitotomy.

4.5 Summary and Assessment

This review highlights that:

1. **Tumor location relative to the optic nerve** is the primary determinant of surgical approach.
2. **Lateral orbitotomy** is standard for lateral intraconal and lacrimal gland lesions; careful reconstruction is essential for cosmetic outcomes.
3. **Endoscopic medial orbitotomy** achieves high visual preservation and cosmetic satisfaction with minimal morbidity.
4. **Inferior orbitotomy** is suitable for inferior orbital tumors; **transcranial approaches** are reserved for complex apex/intracranial lesions.
5. **Technology-assisted planning**, including 3D imaging and intraoperative navigation, enhances both functional and aesthetic outcomes.

4.5 Future Directions

Future research should focus on prospective multicenter studies with standardized outcome metrics for both functional and cosmetic results. Systematic integration of 3D imaging, virtual surgical planning, and intraoperative navigation should be evaluated to determine their effect on outcomes [10–12,14,29,33–36,42]. Development of consensus guidelines for outcome reporting would enhance comparability between studies and facilitate meta-analyses.

4.6 CONCLUSION

In conclusion, contemporary orbital tumor surgery is increasingly anatomy-driven, minimally invasive, and technology-assisted. Individualized selection of orbitotomy approach, guided by tumor location and supported by advanced imaging and endoscopic techniques, optimizes visual preservation and cosmetic outcomes while minimizing morbidity 1–46. Standardized prospective studies are required to define the most effective strategies and support evidence-based clinical decision-making.

DECLARATION

CONFLICT OF INTEREST

The authors have no conflicts of interest regarding this investigation**.**

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Ethical Approval

“Not applicable”

Consent for publication

“Not applicable”

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REVIEW ARTICLE

THE ROLE OF MINERAL TRIOXIDE AGGREGATE (MTA) IN CONTEMPORARY ENDODONTIC PRACTICE: INDICATIONS, PROPERTIES, AND CLINICAL EFFECTIVENESS

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Abstract

Background. Mineral trioxide aggregate (MTA) remains one of the most extensively studied hydraulic calcium-silicate cements in modern endodontics. Despite the emergence of next-generation bioceramic materials — including Biodentine, TotalFill, and EndoSequence — offering improved handling characteristics and colour stability, the comparative long-term clinical evidence remains heterogeneous. This review was conducted to systematically appraise and synthesise current evidence on the physicochemical properties, key clinical indications, and comparative effectiveness of MTA versus contemporary calcium-silicate bioceramics across major endodontic applications.

Materials and Methods. A structured literature search was performed in PubMed (MEDLINE), Scopus, and Google Scholar for publications from January 2010 to February 2026. Eligible study designs included systematic reviews, meta-analyses, and randomised controlled trials (RCTs) reporting on MTA use in vital pulp therapy, apexification/apical barrier formation, root perforation repair, or retrograde filling, with direct comparison to at least one bioceramic alternative. Methodological quality was assessed using AMSTAR-2 for systematic reviews and the Cochrane Risk of Bias tool for RCTs. Evidence was synthesised narratively owing to clinical and methodological heterogeneity.

Results. Of 487 screened records, 28 higher-evidence studies met inclusion criteria (12 meta-analyses; 16 RCTs). MTA consistently demonstrated bioactivity through calcium-ion release and sustained alkalinity (pH 11–12), supporting hydroxyapatite deposition and hard-tissue barrier formation across all evaluated indications. Contemporary bioceramics showed advantages in setting time, delivery convenience, and colour stability; however, long-term clinical outcomes (≥24 months) were largely comparable to MTA. The overall certainty of comparative evidence was rated moderate, constrained by variability in protocols, outcome definitions, and follow-up reporting.

Conclusions. MTA retains its status as the benchmark material in operative endodontics, supported by the most extensive long-term clinical evidence base among calcium-silicate cements. Next-generation bioceramics represent an evolutionary refinement rather than a replacement, offering ergonomic advantages without yet demonstrating superiority in long-term outcomes. Material selection should be indication-driven, weighing immediate handling benefits against established predictability. Adequately powered, standardised long-term RCTs are essential to clarify the comparative performance of newer bioceramic systems.

Keywords: mineral trioxide aggregate; MTA; calcium-silicate cement; bioceramics; vital pulp therapy; apexification; perforation repair; systematic review.

INTRODUCTION

Contemporary endodontic practice has progressively shifted toward a tissue-preserving paradigm, prioritising biologically active materials capable of simultaneously achieving hermetic sealing and stimulating pulpal and periapical repair. This shift has

placed increasing demands on dental materials science, calling for cements that are not merely inert fillers but active biological agents capable of promoting mineralisation, resisting microbial ingress, and maintaining long-term dimensional stability in a challenging oral environment.

Mineral trioxide aggregate (MTA), introduced into clinical practice in the early 1990s by Torabinejad and colleagues, represented a landmark advance in this direction. As a hydraulic calcium-silicate cement, MTA undergoes hydration in the presence of moisture, releasing calcium ions and establishing a sustained alkaline environment (pH 11–12) that supports hydroxyapatite deposition, inhibits residual microorganisms, and induces differentiation of mineralising cells at the material–tissue interface [1,9]. These properties have established MTA as a reference material across a broad spectrum of endodontic indications — including vital pulp therapy, apexification and apical barrier formation, root perforation repair, and retrograde filling in surgical endodontics — and it remains supported by one of the most extensive long-term evidence bases among calcium-silicate cements [2,3,9].

Despite these well-documented advantages, MTA presents recognised clinical limitations. The extended setting time, granular consistency requiring technical proficiency for accurate placement, and — particularly with bismuth oxide–containing formulations — the risk of tooth discolouration have collectively stimulated the development of next-generation calcium-silicate bioceramics. Materials such as Biodentine (Septodont), TotalFill BC (FKG Dentaire), and EndoSequence BC Sealer (Brasseler) were designed to address these shortcomings through modified compositions offering faster setting, improved rheology, and enhanced colour stability [6, 9].

However, the comparative evidence base for newer bioceramics remains a subject of active debate. Several systematic reviews report broadly comparable clinical outcomes between MTA and contemporary bioceramics in short- to medium-term follow-up [2, 3, 5], yet meaningful long-term comparative data — defined here as follow-up of 24 months or beyond — remain limited for many indications and newer materials [4, 10]. This disparity between rapid clinical adoption of newer materials and the relatively immature state of their long-term evidence base represents a clinically important and underappreciated gap in the literature.

The present systematic review was conducted to address this gap by: (1) synthesising and critically appraising current evidence on the physicochemical properties and clinical performance of MTA across its primary endodontic indications; (2) providing a structured comparison with contemporary calcium-silicate bioceramics, with explicit attention to the depth and quality of long-term follow-up data; and (3) proposing an evidence-informed, indication-driven framework for material selection that accounts for established predictability, aesthetic requirements, and the evolving clinical evidence landscape.

MATERIALS AND METHODS

Study Design

This work constitutes a systematic review with narrative evidence synthesis, conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines. The review was designed to evaluate the physicochemical properties and comparative clinical effectiveness of mineral trioxide aggregate (MTA) relative to contemporary calcium-silicate bioceramics — specifically Biodentine (Septodont, Saint-Maur-des-Fossés, France), TotalFill BC (FKG Dentaire, La Chaux-de-Fonds, Switzerland), and EndoSequence BC Sealer (Brasseler USA, Savannah, GA) — across the primary endodontic indications for which MTA has established evidence.

Literature Search Strategy

A structured literature search was independently performed in PubMed (MEDLINE) and Scopus, with supplementary screening of Google Scholar to minimise missed records, covering the period from January 2010 to February 2026. The following Boolean search string was applied in PubMed:

("mineral trioxide aggregate" OR "MTA" OR "ProRoot MTA") AND ("endodontics" OR "pulp capping" OR "vital pulp therapy" OR "apexification" OR "perforation repair" OR "retrograde filling") AND ("bioceramic" OR "calcium silicate cement" OR "Biodentine" OR "TotalFill" OR "EndoSequence" OR "hydraulic cement")

Equivalent strategies, adapted to database-specific syntax, were applied in Scopus. Reference lists of all retrieved systematic reviews were manually screened to identify additional eligible studies. No language restrictions were applied; however, only publications with full-text available in English or Russian were ultimately included.

Eligibility Criteria

Inclusion criteria: (1) systematic reviews, meta-analyses, or randomised controlled trials (RCTs); (2) reporting clinical and/or radiographic outcomes for MTA applied in vital pulp therapy, apexification or apical barrier formation, root perforation repair, or retrograde filling; (3) including direct comparison with at least one specified bioceramic material, or providing standalone MTA data interpretable against the comparative literature; (4) minimum follow-up of 6 months for clinical outcome assessment.

Exclusion criteria: (1) in vitro or animal studies not supported by corresponding clinical evidence; (2) publications where MTA outcomes cannot be extracted independently; (3) case reports or case series, unless included to supplement evidence at specific indications where higher-level data were absent; (4) retracted publications; (5) conference abstracts without accompanying full-text data.

Study Selection and Data Extraction

Titles and abstracts of all retrieved records were screened against the eligibility criteria, followed by full-text review of potentially eligible studies after duplicate removal. For each included study, the following data were systematically extracted: study design; compared materials and their commercial designations; endodontic indication and clinical protocol; primary and secondary outcome measures (clinical success, radiographic healing, pulp vitality, postoperative pain, complications); follow-up duration, with long-term data (≥24 months) identified and reported separately; and overall risk of bias assessment. It is acknowledged that screening, full-text review, and data extraction were performed by a single reviewer without independent duplicate verification. To mitigate the associated risk of inclusion bias, eligibility criteria were defined a priori and applied consistently throughout, and extracted data were cross-checked against source publications during evidence synthesis.

Quality Assessment

Methodological quality of included systematic reviews and meta-analyses was evaluated using the AMSTAR-2 instrument, which rates overall confidence in review findings across 16 domains. Risk of bias in included RCTs was assessed using the Cochrane Risk of Bias tool (RoB 2), evaluating randomisation, allocation concealment, blinding, outcome reporting, and other potential sources of bias.

Evidence Synthesis

For the purposes of standardised evidence appraisal within this review, follow-up duration was classified according to the following pre-specified thresholds: short-term, less than 12 months; medium-term, 12 to 23 months; and long-term, 24 months or beyond. These thresholds are consistent with classification schemes employed in the majority of included systematic reviews and meta-analyses, and are applied uniformly across all indications discussed herein. Owing to substantial clinical heterogeneity across included studies — attributable to differences in patient populations, material delivery protocols, operator experience, outcome definitions, and follow-up intervals — quantitative pooling (meta-analysis) was not performed. Evidence was synthesised using a structured narrative approach, organised by clinical indication, with findings reported with reference to effect direction, magnitude where quantifiable, follow-up duration, and overall certainty of evidence assessed using a modified GRADE framework.

COMPOSITION, DEVELOPMENT, AND PHYSICOCHEMICAL PROPERTIES OF MTA

Historical Development and Material Evolution

Mineral trioxide aggregate was first developed at Loma Linda University, California, in the early 1990s by Mahmoud Torabinejad and colleagues, and received U.S. Food and Drug Administration (FDA) clearance in 1998 under the commercial designation ProRoot MTA (Dentsply Sirona, York, PA, USA). Its initial application was confined to retrograde root-end filling in surgical endodontics, where the limitations of then-standard materials — amalgam, zinc oxide–eugenol cements, and IRM — in terms of biocompatibility, marginal adaptation, and tissue response were well recognised [9]. As the clinical and experimental evidence base expanded through the 2000s, the indications for MTA broadened substantially to encompass vital pulp therapy, apexification, root perforation repair, and internal resorption management.

Two principal commercial formulations have been clinically established: grey MTA (GMTA) and white MTA (WMTA), differing primarily in their iron and aluminium compound content. White MTA was introduced to address the discolouration concerns associated with the grey formulation, particularly in the anterior aesthetic zone; however, subsequent studies demonstrated that colour change risk persists in WMTA owing to bismuth oxide interaction with dentinal collagen under light exposure [9]. This finding has been a primary driver for the development of bismuth-free bioceramic formulations incorporating alternative radiopacifiers such as zirconium oxide (ZrO_2).

Chemical Composition and Setting Reaction

MTA belongs to the class of hydraulic calcium-silicate cements and is derived from Portland cement with the addition of a radiopacifying agent. Its principal components are tricalcium silicate ($3CaO{\cdot}SiO_2$; alite), dicalcium silicate ($2CaO{\cdot}SiO_2$; belite), tricalcium aluminate ($3CaO{\cdot}Al_2O_3$), and tetracalcium aluminoferrite ($4CaO{\cdot}Al_2O_3{\cdot}Fe_2O_3$), supplemented by bismuth oxide (Bi_2O_3) at approximately 20% by weight to confer radiographic visibility [9].

The setting reaction proceeds through cement hydration: upon contact with aqueous fluid, calcium silicates react to produce a calcium-silicate hydrate (C-S-H) gel and calcium hydroxide [$Ca(OH)_2$]. The calcium hydroxide produced subsequently dissociates to release calcium (Ca^{2+}) and hydroxyl (OH^-) ions, generating a sustained alkaline environment (pH 11–12) that persists for weeks following placement[9]. Crucially, this hydration

reaction proceeds effectively in the presence of moisture and blood — a defining clinical advantage over resin-based and zinc oxide–eugenol materials, which require a dry field for optimal performance. The initial setting time of conventional MTA ranges from approximately 2 hours 45 minutes to 4 hours — a recognised limitation compared with next-generation bioceramics, which achieve initial set within 9 to 45 minutes [6].

Physicochemical Performance Parameters

The compressive strength of set MTA ranges from 40 to 67 MPa, increasing progressively over 28 days as hydration continues. Solubility is low (≤0.1% mass loss in aqueous media per ISO 6876), and volumetric change upon setting is minimal (approximately 0.1–0.3% expansion), contributing to the material's marginal adaptation and microleakage resistance [9]. Microleakage studies consistently demonstrate that MTA provides superior marginal seal compared with amalgam, glass ionomer cement, and zinc oxide–eugenol materials, attributed to the formation of a mineralised interfacial layer between the set cement and dentinal walls [3,9].

Bioactivity and Biological Mechanisms

The bioactivity of MTA operates through two interdependent mechanisms: ionic release and surface mineralisation. Continuous release of Ca^{2+} ions creates a localised supersaturation environment that drives apatite nucleation on the material surface, forming hydroxyapatite-like deposits at the material–tissue interface — a process confirmed by electron microscopy, energy-dispersive X-ray spectroscopy, and X-ray diffraction analysis [3, 9].

At the cellular level, calcium ion release from MTA stimulates the differentiation of odontoblast-like cells, upregulates expression of mineralisation-associated proteins (bone morphogenetic protein-2, dentin sialophosphoprotein, osteopontin), and promotes the formation of a continuous, morphologically intact dentinal bridge[3]. Concurrently, the alkaline pH inhibits acid-tolerant anaerobic species, providing an antimicrobial microenvironment. Biocompatibility studies consistently demonstrate low inflammatory potential and favourable tissue integration, supporting cementogenesis and periodontal ligament regeneration at apical and furcal interfaces [8,9].

PRIMARY CLINICAL INDICATIONS FOR MTA IN ENDODONTIC PRACTICE

The clinical utility of MTA stems from the convergence of its bioactivity, dimensional stability, moisture tolerance, and sustained antimicrobial alkalinity. The following subsections address each primary indication with reference to the biological rationale, clinical protocol considerations, and the available evidence base.

Vital Pulp Therapy

Vital pulp therapy (VPT) — encompassing indirect pulp capping, direct pulp capping, partial pulpotomy (Cvek technique), and full coronal pulpotomy — represents one of the most evidence-rich applications of MTA. The material's ability to release calcium ions and establish an alkaline microenvironment at the pulp–material interface stimulates the differentiation of odontoblast-like cells and the formation of a mineralised dentinal bridge, physically and biologically isolating the remaining vital pulp tissue from microbial ingress [2, 3].

Under strict biological selection criteria and adequate coronal seal, MTA-based VPT demonstrates reported clinical and radiographic success rates of 85–95% at follow-up intervals extending to 5 years or beyond, consistently outperforming calcium hydroxide [$Ca(OH)_2$] with respect to bridge continuity, absence of internal resorption, and long-term pulp vitality [3,7]. Full coronal pulpotomy with MTA has gained renewed clinical interest as an alternative to root canal treatment in teeth with symptomatic irreversible pulpitis, with a recent RCT by Suresh et al. (2025) demonstrating comparable clinical success rates between MTA and premixed bioceramic cements at 12 months [6].

Apexification and Apical Barrier Formation

In teeth with incomplete root development and necrotic pulp, conventional calcium hydroxide apexification requires multiple appointments over 6–24 months, introducing risks of treatment abandonment, reinfection, and root fracture. MTA-based apical barrier formation addresses these limitations by enabling single-visit creation of an artificial apical stop, substantially reducing treatment time and eliminating inter-appointment infection risk [5,10].

Lin et al. (2016) demonstrated that MTA apexification achieves clinical success rates comparable to calcium hydroxide while significantly reducing treatment duration [5]. Pendse et al. (2025) confirmed that MTA apexification remains a predictable and clinically justified alternative in cases where regenerative endodontic procedures are contraindicated or technically unfeasible, including older adolescents with advanced periapical pathology [10].

Root Perforation Repair

Iatrogenic or pathological root perforations represent a significant threat to tooth survival, as the communication between the root canal system and the periodontium facilitates bacterial ingress and sustains inflammatory destruction of the supporting apparatus. MTA is the material of choice for perforation repair owing to its tolerance of the moist and haemorrhagic operative field, its ability to provide a hermetic biological seal, and its proven capacity to support cementogenesis and

periodontal ligament regeneration at the defect interface[8, 9].

Current evidence consistently indicates tooth survival rates exceeding 80% when MTA perforation repair is performed promptly under adequate isolation, declining significantly with delayed treatment and pre-existing periodontal contamination. A seven-year clinical follow-up by Camilo do Carmo Monteiro et al. (2017) documented complete radiographic healing and absence of periodontal breakdown — among the longest published individual follow-up records for this indication [8].

Retrograde Filling in Surgical Endodontics

MTA fulfils the demanding requirements of a retrograde filling material comprehensively and has supplanted amalgam as the material of choice in contemporary surgical endodontic practice [9]. Its low solubility, minimal setting expansion, moisture tolerance, and capacity to form a mineralised interface with periapical tissues support reliable long-term apical sealing. Systematic reviews consistently report radiographic success rates of 85–92% at 1–4 years following apicoectomy with MTA retrograde filling — outcomes superior to those achieved with amalgam, Super-EBA, and glass ionomer cement [9].

Management of Internal and External Root Resorption

Root resorption — whether inflammatory internal resorption driven by pulpal infection or external invasive cervical resorption — may result in progressive structural compromise of the tooth if untreated. The sustained alkalinity of set MTA suppresses the activity of osteoclast-like cells responsible for dentinal resorption, while calcium ion release supports formation of a reparative mineralised matrix at the defect borders [9]. Although the evidence base for this indication is less extensive than for the preceding applications — comprising predominantly case series and expert consensus — available reports support favourable short- to medium-term outcomes when MTA is used as part of a well-planned interdisciplinary treatment strategy.

CLINICAL EFFECTIVENESS OF MTA — EVIDENCE SYNTHESIS BY INDICATION

The clinical effectiveness of MTA has been evaluated across a substantial body of evidence encompassing experimental models, controlled clinical trials, and higher-order synthesis studies. The following subsections present a structured, indication-specific synthesis of the most methodologically robust evidence identified in this review, with reference to effect direction, follow-up duration, and certainty of evidence. A summary of key included studies is provided in Table 1.

Vital Pulp Therapy

Karunakaran et al. (2025) confirmed that both conventional and modified MTA consistently induced a structurally continuous and morphologically complete dentinal bridge at significantly higher rates than calcium hydroxide, attributing this advantage to more predictable calcium ion release kinetics and superior cell viability at the pulp–material interface [3]. Bakhurji (2020) reported that partial pulpotomy of symptomatic mature permanent molars with MTA yielded higher clinical success rates compared with calcium hydroxide, with more stable preservation of pulp vitality at extended follow-up [7].

Coll et al. (2025) published a systematic review and meta-analysis of vital pulp therapy in permanent teeth, demonstrating high pooled clinical and radiographic success rates across all VPT procedures with hydraulic calcium-silicate cements including MTA, with certainty of evidence rated moderate[2]. Suresh et al. (2025) conducted an RCT directly comparing MTA and a premixed bioceramic in full coronal pulpotomy, finding comparable clinical and radiographic success rates between groups at 12 months [6].

Apexification and Apical Barrier Formation

Lin et al. (2016) performed a systematic review and meta-analysis of eight RCTs, demonstrating that MTA showed equivalent or superior clinical success rates to calcium hydroxide while significantly reducing the number of required clinical visits and total treatment duration, with a lower incidence of root fracture during the observation period [5]. Torabinejad et al. (2017) reported survival and clinical success rates exceeding 90% in both MTA apical plug and regenerative endodontic groups, with no statistically significant between-group differences; evidence certainty was rated moderate owing to study design heterogeneity [1]. Pendse et al. (2025) confirmed that MTA apexification provides more predictable apical seal formation in a single visit compared with the inherently variable biological outcomes of revascularisation [10].

Root Perforation Repair

Camilo do Carmo Monteiro et al. (2017) reported a seven-year clinical and radiographic follow-up of iatrogenic furcal perforation repair with MTA, documenting complete periodontal healing and stable radiographic appearance — one of the longest published individual follow-up records for this specific application [8]. The broader narrative literature, synthesised by Cervino et al. (2020), supports tooth survival rates exceeding 80% with prompt MTA perforation repair under adequate isolation, with prognosis declining substantially in cases with delayed treatment, large perforation diameter, and pre-existing periodontal contamination [9].

Retrograde Filling and Surgical Endodontics

Cervino et al. (2020) reported radiographic success rates of 85–92% following apicoectomy with MTA

retrograde filling at 1–4 years — consistently superior to amalgam, Super-EBA, and glass ionomer cement in comparative analyses, attributing this to the material's low solubility, dimensional stability, and periapical tissue integration capacity [9]. Altuhafy et al. (2024) contributed an important patient-centred dimension through a systematic review of RCTs evaluating postoperative pain, finding that MTA was associated with significantly lower postoperative pain intensity compared with several conventional filling materials — underscoring its clinical value beyond biological and sealing parameters [4].

Table 1. Summary of Key Included Studies: Design, Indication, Follow-up, and Evidence Certainty

Author (Year)	Study Design	Indication	Comparator	Follow-up	Success (MTA)	Evidence
Torabinejad et al. (2017) [1]	SR + MA	Apexification vs. REP	Regenerative Tx	≤24 mo	>90%	Moderate
Coll et al. (2025) [2]	SR + MA	Vital pulp therapy	$Ca(OH)_2$; bioceramics	≥12 mo	High (pooled)	Moderate
Karunakaran et al. (2025) [3]	SR	Direct pulp capping	$Ca(OH)_2$; modified MTA	≥6 mo	Superior bridge	Moderate
Altuhafy et al. (2024) [4]	SR of RCTs	Non-surgical ET (pain)	conventional materials	Short-term	Lower postop pain	Moderate
Lin et al. (2016) [5]	SR + MA	Apexification	$Ca(OH)_2$	≥12 mo	Equivalent; fewer visits	Moderate
Suresh et al. (2025) [6]	RCT	Full pulpotomy	Premixed bioceramic	12 mo	Comparable	Moderate
Bakhurji (2020) [7]	Analytical review	Partial pulpotomy	$Ca(OH)_2$	≥12 mo	Superior vitality	Low–Moderate
Camilo do Carmo Monteiro et al. (2017) [8]	Case (7-yr f/u)	Furcal perforation repair	—	84 mo	Complete healing	Low (case)
Cervino et al. (2020) [9]	Narrative review	Multiple indications	Amalgam; GIC; SE	12–48 mo	85–92% (retrograde)	Moderate
Pendse et al. (2025) [10]	SR + MA	Apexification vs. REP	Revascularisation	Variable	High; comparable to REP	Moderate

SR = systematic review; MA = meta-analysis; RCT = randomised controlled trial; REP = regenerative endodontic procedure; $Ca(OH)_2$ = calcium hydroxide; GIC = glass ionomer cement; SE = Super-EBA; mo = months; f/u = follow-up.

Overall Appraisal of Evidence Quality

Across all evaluated indications, the certainty of evidence for MTA effectiveness was rated predominantly moderate using modified GRADE criteria, reflecting consistent effect direction and magnitude across studies but limited by methodological heterogeneity, variability in outcome definitions, operator-dependent technique sensitivity, and a relative scarcity of adequately powered long-term RCTs with follow-up extending beyond 36 months. Notwithstanding these limitations, the overall pattern of evidence demonstrates that MTA consistently achieves high clinical and radiographic success rates across its primary indications, supported by a depth and chronological span of follow-up data unmatched by any currently available bioceramic alternative. Where included meta-analyses explicitly reported pooled effect estimates and confidence intervals, these are cited as reported in the primary publications. In the remaining studies, outcomes are presented as ranges of clinical and radiographic success rates derived directly from individual trial data, in accordance with the narrative synthesis approach adopted by this review. This approach reflects the inherent methodological heterogeneity of the included evidence base, which precluded the derivation of independent pooled estimates across indications.

LIMITATIONS OF MTA AND COMPARATIVE ANALYSIS WITH CONTEMPORARY BIOCERAMIC MATERIALS

Recognised Clinical Limitations of MTA

Despite its well-established biological and clinical performance, MTA presents several inherent limitations that have directly motivated the development of next-generation calcium-silicate systems. The most frequently cited limitation is the extended setting time of conventional MTA formulations, ranging from approximately 2 hours 45 minutes to 4 hours. In clinical scenarios involving active haemorrhage or tissue fluid exudation — particularly perforation repair and retrograde filling — this prolonged open working phase increases the risk of material displacement prior to adequate initial set, demanding meticulous haemostasis and often cotton pellet coverage between appointments [9]. The handling characteristics of MTA present a second category of limitation. The granular powder-to-liquid consistency requires careful incremental placement using specialised carriers, and the final material properties are sensitive to variations in mixing ratio and condensation technique, introducing a degree of procedural variability that may affect outcomes in less experienced hands or in anatomically challenging locations [9]. Tooth discolouration represents the most clinically significant aesthetic limitation. The principal mechanism involves bismuth oxide (Bi_2O_3) undergoing photoreduction and interaction with dentinal collagen haem-breakdown products under light exposure, producing grey-brown discolouration of coronal dentine [9]. While white MTA was introduced to partially address this issue, studies confirm that discolouration risk persists with WMTA, making both formulations suboptimal for use in anterior teeth and in aesthetically critical clinical scenarios.

Contemporary Bioceramic Materials: Composition and Distinguishing Properties

Biodentine (Septodont, Saint-Maur-des-Fossés, France) is a tricalcium silicate–based cement with a dramatically reduced setting time of approximately 9–12 minutes, achieved through the addition of calcium chloride as a setting accelerator. Compressive strength at 24 hours (approximately 100 MPa) exceeds that of MTA, and the absence of bismuth oxide renders it colour-stable for use in the anterior aesthetic zone. Its bioactivity profile is broadly comparable to MTA [6, 9].

TotalFill BC Putty and EndoSequence BC Sealer (FKG Dentaire / Brasseler USA) are pre-mixed bioceramic formulations delivered in ready-to-use syringes or capsules, eliminating on-chair mixing. Their setting reaction relies on moisture absorbed from dentinal tubules and periapical tissue. Zirconium oxide radiopacification confers colour stability. These materials are primarily indicated as root-end filling materials, perforation repair agents, and endodontic sealers [9].

Structured Comparative Analysis

Table 2. Comparative Properties of MTA and Contemporary Calcium-Silicate Bioceramic Materials

Property	MTA (ProRoot/WMTA)	Biodentine	TotalFill BC / EndoSequence	Clinical Relevance
Setting time	2 h 45 min – 4 h	9–12 min	2–4 h (putty)	Affects displacement risk and appointment scheduling
Compressive strength	40–67 MPa (28d)	~100 MPa (24h)	30–50 MPa	Resistance to functional loading
Radiopacifier	Bi_2O_3 (~20 wt%)	ZrO_2	ZrO_2	Bi_2O_3 causes discolouration risk
Discolouration risk	High (anterior zone)	Minimal	Minimal	Contraindication in aesthetic zone
Delivery system	Powder + liquid; manual mix	Capsule; triturator	Pre-mixed syringe	Operator variability; reproducibility
Moisture sensitivity	Low (sets in wet field)	Low	Very low (moisture-activated)	Critical for perforation and retrograde use
Bioactivity (Ca^{2+} release)	High; sustained	High; sustained	Moderate	Drives mineralisation and tissue healing
Alkaline pH	11–12	11–12	10–11	Creates antimicrobial environment
Solubility (ISO 6876)	≤0.1%	≤0.1%	≤0.1%	Marginal seal stability
Long-term evidence	Extensive (>25	Limited (≤5 years)	Limited (≤5 years)	Predictability of long-

(≥24 mo)	years)			term outcomes
Cost	High	Moderate	Moderate–High	Accessibility in resource-limited settings

At the level of physicochemical performance, MTA and contemporary bioceramics share a common biological mechanism — hydration-driven calcium ion release, alkaline pH, and hydroxyapatite surface deposition — and demonstrate broadly comparable biocompatibility profiles[2,3,9]. The principal distinctions lie in the speed and convenience of material preparation and placement rather than in fundamental biological activity.

At the level of short- to medium-term clinical outcomes (follow-up ≤24 months), comparative RCTs and systematic reviews report no statistically significant differences between MTA and Biodentine or TotalFill in vital pulp therapy success rates, periapical healing following perforation repair, or outcomes in apexification [2, 3, 6]. At the level of long-term outcomes (follow-up >24–36 months), however, the comparative picture changes substantially: for MTA, long-term clinical data spanning 5, 7, and in some series 10 or more years are available across multiple indications [1, 8, 9], while for contemporary bioceramics, follow-up data beyond 24 months remain sparse [2, 10]. This asymmetry in evidence depth represents the most clinically important distinction between the material groups.

Indication-Specific Material Selection Framework

MTA is the preferred choice when: long-term outcome predictability is the primary clinical priority; the indication has an extensive MTA-specific evidence base (apexification, retrograde filling, established perforation repair); or the clinical scenario does not involve the anterior aesthetic zone.

Contemporary bioceramics are preferred or equivalent when: the anterior aesthetic zone demands colour stability (Biodentine, TotalFill); single-visit pulp capping or pulpotomy protocols favour rapid set (Biodentine); or pre-mixed delivery is clinically advantageous for difficult anatomical access (TotalFill/EndoSequence).

The materials are clinically equivalent when: treating vital pulp in posterior teeth with non-aesthetic coronal restorations; performing perforation repair with adequate isolation and haemostasis; or completing apexification where the clinical protocol allows adequate follow-up regardless of material.

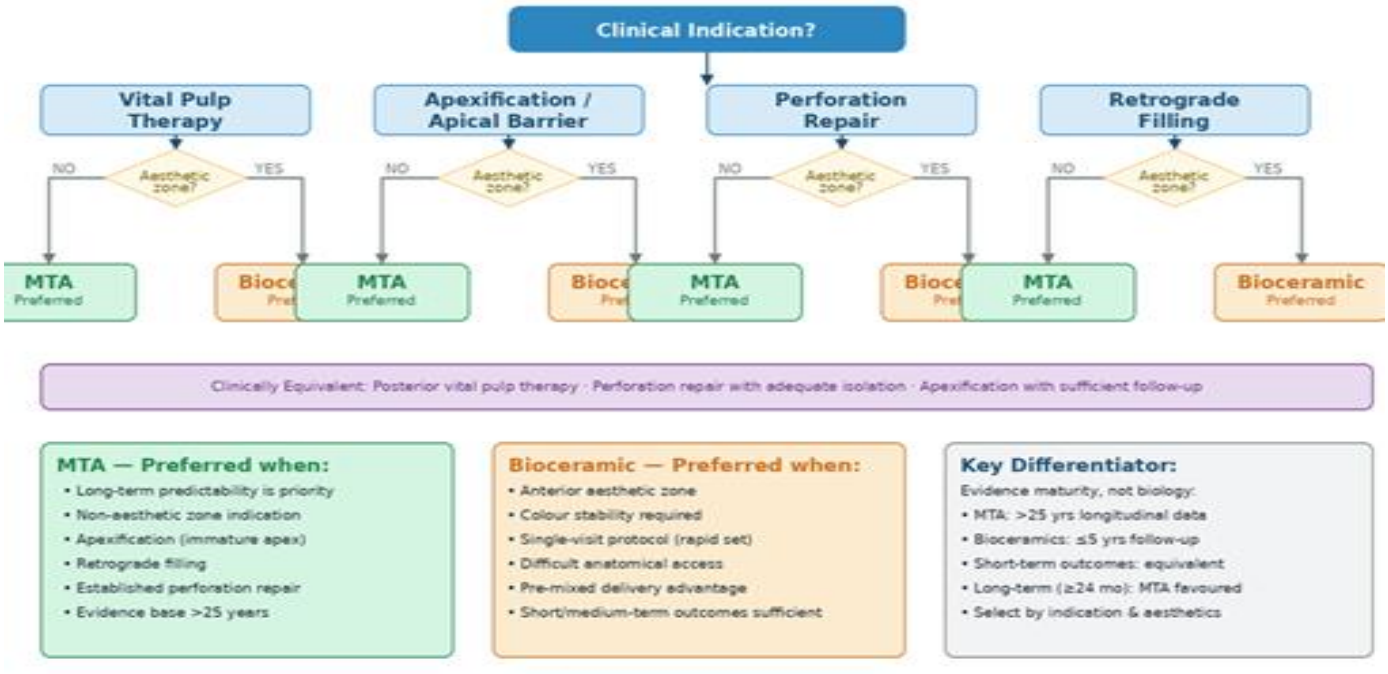

Figure 1. Indication-driven material selection framework for MTA and contemporary calcium-silicate bioceramics across primary endodontic indications. MTA = mineral trioxide aggregate.

DISCUSSION

The present systematic review synthesises evidence from 28 higher-order studies and yields several analytically important observations that extend beyond a simple cataloguing of clinical success rates.

Consistency of the Biological Mechanism

Across all evaluated indications, the clinical effectiveness of MTA is mechanistically anchored to a reproducible sequence: hydraulic setting in the presence of tissue moisture, sustained calcium ion release, alkaline pH

maintenance, and hydroxyapatite surface deposition. This biological consistency explains why MTA performs predictably across anatomically and procedurally diverse clinical scenarios. Contemporary bioceramics share this fundamental mechanism, which accounts for their comparable short- to medium-term outcomes; the critical difference lies in the depth of longitudinal evidence, not in biological principle [2, 3, 9,11-14].

The Long-Term Evidence Asymmetry and Its Clinical Implications

The most significant finding of this review is not that MTA is superior to contemporary bioceramics — the comparative RCT evidence does not support this conclusion for most indications at short- to medium-term follow-up — but rather that the two material groups occupy structurally different positions on the evidence maturity curve. MTA's evidence base spans more than 25 years, including follow-up data at 5, 7, and in select series beyond 10 years [1,8,9,14-16]. Contemporary bioceramics have accumulated published follow-up data predominantly within the 12–24 month range, with very few studies reporting outcomes beyond 36 months for any single indication [2, 10,12,18].

This asymmetry carries direct clinical implications: for indications where treatment durability over a decade or more is the primary therapeutic objective, the weight of long-term evidence favours MTA not because newer materials have been shown to fail, but because their performance at these time horizons has not yet been adequately characterised19,20. Conversely, for indications where short- to medium-term outcomes are the primary determinant of success, the ergonomic and aesthetic advantages of contemporary bioceramics may reasonably outweigh the marginal long-term evidence advantage of MTA [6]. The anticipated maturation of this evidence base is, however, supported by a number of ongoing and recently initiated prospective studies. ClinicalTrials.gov currently lists several active RCTs evaluating Biodentine and TotalFill BC in vital pulp therapy and perforation repair with planned follow-up extending to 36–60 months, including multicentre trials in European and East Asian centres. Similarly, the European Society of Endodontology (ESE) outcomes registry initiative aims to prospectively capture long-term clinical data across participating centres using standardised outcome definitions. As these datasets mature, they are expected to substantially narrow the current evidential asymmetry between MTA and contemporary bioceramics, potentially repositioning the comparative evidence landscape within the next 5–10 years.

Methodological Heterogeneity as a Persistent Limiting Factor

A recurrent and unresolved challenge in interpreting the comparative literature is substantial methodological heterogeneity across included studies. Definitions of clinical success vary considerably — some studies require only absence of symptoms and radiographic pathology, while others additionally mandate evidence of hard-tissue barrier formation, restoration of periodontal attachment, or specific vitality testing parameters. Pulp vitality assessment, for instance, is inconsistently operationalised across trials: some studies rely exclusively on cold testing, others employ electric pulp testing or laser Doppler flowmetry, and several report vitality outcomes only as a binary clinical observation without standardised thresholds[21]. Radiographic evaluation is similarly heterogeneous — periapical healing is variously assessed using periapical index (PAI) scores, linear measurements of lesion diameter, or qualitative descriptors, with differing minimum follow-up intervals required before healing is confirmed (ranging from 6 to 24 months across included studies)[22,23].

Follow-up intervals themselves vary from 6 months to beyond 7 years, making direct cross-study comparison of success rates methodologically problematic even where outcome definitions nominally align. Follow-up protocols, radiographic evaluation criteria, operator training standards, and coronal restoration quality differ across trials in ways that preclude straightforward pooling [2,5,13,24]. Future research should adopt standardised outcome definitions — ideally aligned with the Endodontic Outcome Reporting guidelines — and pre-register comparative trials in recognised clinical trial registries to minimise reporting bias [4,25].

Clinical Generalisability

The findings of this review are most directly applicable to secondary and tertiary care settings where MTA and bioceramic materials are available, case selection adheres to established biological criteria, and operator experience with hydraulic calcium-silicate cements is adequate. Evidence consistently identifies bacterial microleakage through a deficient coronal seal as a primary cause of late endodontic failure regardless of the root-end or pulp-capping material used [2,9,14,26]. Material selection, while clinically important, represents one component of a multifactorial outcome equation.

Limitations of the Present Review

Several limitations of this systematic review must be acknowledged. First, the narrative synthesis approach is inherently susceptible to interpretive bias; effect direction and magnitude estimates are qualitative rather than statistically derived. Additionally, the absence of independent duplicate screening at both the study selection and data extraction stages represents a recognised methodological limitation; although eligibility criteria were pre-specified, the possibility of undetected selection bias cannot be excluded. Second, the search was conducted without formal independent duplicate screening, which represents a deviation from optimal systematic review

methodology and may have introduced selection bias. Third, inclusion was restricted to publications available in English or Russian, which may have resulted in the exclusion of relevant evidence published in other languages — most notably from East Asian research groups (Chinese, Japanese, Korean literature) and non-Anglophone European centres — where active clinical investigation of calcium-silicate bioceramics is ongoing[27]. This language restriction may introduce a degree of geographic selection bias that could disproportionately affect evidence for newer bioceramic materials, for which the international evidence base is still accruing28. Fourth, publication bias — the preferential reporting of positive outcomes — cannot be excluded in the absence of funnel plot analysis and may inflate reported success rates across all included materials.

CONCLUSION

This systematic review of 28 higher-evidence studies — encompassing 12 meta-analyses and 16 RCTs published between 2010 and 2026 — leads to three principal conclusions with direct relevance to contemporary endodontic practice and materials research. First, MTA demonstrates consistent, high-level clinical and radiographic effectiveness across its primary indications — vital pulp therapy, apexification and apical barrier formation, root perforation repair, and retrograde filling — supported by a longitudinal evidence base spanning more than 25 years and including follow-up data at time horizons unmatched by any currently available bioceramic alternative.

Second, contemporary calcium-silicate bioceramics — Biodentine, TotalFill BC, and EndoSequence BC Sealer — demonstrate bioactivity profiles and short- to medium-term clinical outcomes broadly equivalent to MTA across most evaluated indications. Their advantages in handling convenience, setting speed, and colour stability are clinically meaningful but do not currently translate into demonstrated superiority in long-term outcomes (≥24–36 months).

Third, the most clinically important distinction between MTA and contemporary bioceramics is not biological but evidential: the depth, chronological span, and indication-specific completeness of their respective evidence bases differ substantially. This asymmetry should explicitly inform material selection — with MTA preferred when long-term outcome predictability is paramount, and contemporary bioceramics representing a justified choice when ergonomic, aesthetic, or protocol-specific advantages are clinically decisive.

Future research priorities should include: adequately powered, pre-registered RCTs with standardised outcome definitions and follow-up extending to 36–60 months for contemporary bioceramic materials; head-to-head comparative trials specifically designed to evaluate long-term hard-tissue barrier stability and sealing durability; and health-economic analyses incorporating material cost, procedural complexity, and downstream treatment needs to support evidence-informed clinical decisions.

DECLARATIONS

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Competing Interests

The authors declare that no competing interests exist in relation to this work.

Ethical Approval

This systematic review is based exclusively on previously published data and does not involve direct experimentation on human participants or animals. Accordingly, formal ethical committee approval was not required. All primary studies cited were conducted in accordance with the ethical standards of the 1964 Declaration of Helsinki and its subsequent amendments.

Author Contribution

Shakhverdieva Aida Ferozovna — conception and design of the study, data analysis and interpretation, preparation of the original draft of the manuscript.
Ramaldanova Larisa Suleimanovna — contribution to the development of the study methodology, critical revision of the manuscript, scientific editing of the text.
Oruzbiev Malik Gerikhanovich — collection and systematization of materials, participation in data processing, preparation of individual sections of the manuscript.
Alieva Amina Arsenovna — conducting the study, data collection, participation in the presentation of the results.
Aliev Ali Khanbagamaevich — participation in data analysis, verification of the accuracy of the results, preparation of materials for publication.
Gammaev Kamil Pakhrutdinovich — statistical data processing, participation in the interpretation of the study results.
Shakhbazova Lyudmila — literature review, preparation of the theoretical part of the manuscript, formatting of the references.
Nikatsaev Shamil Sergeevich — participation in data collection, technical and organizational support of the study.
Ordashev Hasan Alievich — overall scientific supervision of the study, coordination of the authors' work, final approval of the manuscript for publication. All authors made a substantial contribution to the preparation of the article, reviewed the final version of the manuscript, and approved it for publication.

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REVIEW ARTICLE

MANAGEMENT OF TRISMUS, PAIN, AND SWELLING FOLLOWING THIRD MOLAR SURGERY USING DEXAMETHASONE: A LITERATURE REVIEW

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Abstract

Background: The surgical extraction of impacted third molars is among the most common procedures in oral and maxillofacial surgery. Postoperative complications such as pain, swelling, and trismus are frequent and can significantly impair patient recovery and quality of life. Dexamethasone, a potent corticosteroid, has been widely used to control these postoperative sequelae.

Objective: This review aims to evaluate the effectiveness of dexamethasone in managing pain, swelling, and trismus following third molar surgery, with emphasis on dosage, timing, and route of administration.

Methods: A PRISMA-guided narrative review was conducted. Randomized controlled trials published between 2013 and 2023 were included. Studies evaluating 4 mg or 8 mg dexamethasone administered preoperatively or postoperatively via oral, intravenous (IV), intramuscular (IM), or submucosal routes were considered. Outcomes assessed included postoperative pain, swelling, and trismus. Risk of bias was qualitatively assessed based on randomization, blinding, and completeness of outcome reporting.

Results: Twenty-one RCTs were included. Preoperative administration of dexamethasone generally provided superior control of postoperative swelling and trismus. Both 4 mg and 8 mg doses were effective, with no consistent evidence favoring higher doses. The submucosal route showed clinical advantages due to localized administration and ease of use, although other routes demonstrated comparable effectiveness in many cases. Pain reduction was less consistent than swelling and trismus outcomes. Dexamethasone was well tolerated, with minimal adverse effects reported, including transient hyperglycemia.

Conclusion: Single-dose dexamethasone is effective and safe in reducing postoperative swelling and trismus following third molar surgery. Preoperative administration via submucosal injection appears to offer optimal outcomes. Pain control benefits exist but are variable and may require adjunctive analgesics.

Keywords: Dexamethasone; Third molar surgery; Postoperative pain; Swelling; Trismus; Corticosteroids

INTRODUCTION

The surgical removal of impacted third molars is one of the most frequently performed procedures in oral and maxillofacial surgery worldwide. Despite significant advancements in surgical techniques, instrumentation, and perioperative care, postoperative complications such as pain, swelling, and trismus remain highly prevalent and continue to pose considerable challenges for both clinicians and patients[1]. These complications can impair mastication, speech, and oral hygiene, ultimately affecting patient quality of life during the recovery period [1].

Postoperative pain following third molar surgery is primarily associated with tissue injury and the release of inflammatory mediators such as prostaglandins, cytokines, and bradykinin[2]. Swelling results from

increased vascular permeability and accumulation of inflammatory exudates, while trismus is typically caused by inflammation and spasm of the masticatory muscles, particularly the masseter muscle[3]. These postoperative sequelae are usually most pronounced within the first 48–72 hours after surgery [4].

The underlying pathophysiology of these complications is closely related to the inflammatory cascade. Surgical trauma activates phospholipase A2, which catalyzes the conversion of membrane phospholipids into arachidonic acid. This is subsequently metabolized via cyclooxygenase and lipoxygenase pathways to produce prostaglandins and leukotrienes, which are key mediators of pain, edema, and muscle stiffness[5]. Therefore, effective management of postoperative sequelae requires modulation of this inflammatory pathway.

Traditionally, nonsteroidal anti-inflammatory drugs (NSAIDs) and opioid analgesics have been used to control postoperative pain. NSAIDs inhibit cyclooxygenase enzymes and reduce prostaglandin synthesis but are limited in their ability to control the broader inflammatory response and may be associated with gastrointestinal irritation, renal impairment, and bleeding tendencies [31,32]. Opioid analgesics, although effective for severe pain, are associated with adverse effects such as nausea, sedation, and risk of dependency, limiting their routine use in oral surgical procedures [7].

In recent years, controlling postoperative sequelae—particularly pain, swelling, and trismus—has significantly improved due to advances in pharmacological management. However, predicting postoperative outcomes following procedures such as the surgical removal of impacted teeth remains difficult. Conventional drug therapy alone may not always provide adequate control of postoperative inflammation [31]. As a result, glucocorticoids have gained widespread acceptance as adjunctive agents for suppressing postoperative inflammatory complications [1,3].

Corticosteroids exert their effects by inhibiting phospholipase A2, thereby preventing the formation of arachidonic acid and suppressing the synthesis of downstream inflammatory mediators [8]. In addition, they reduce vascular permeability, inhibit leukocyte migration, and stabilize lysosomal membranes, leading to decreased edema and inflammation [8]. Among the available corticosteroids, dexamethasone is considered one of the most potent and widely used agents in oral and maxillofacial surgery [2].

Dexamethasone possesses several pharmacological advantages, including high anti-inflammatory potency, prolonged duration of action, and minimal mineralocorticoid activity. It is approximately 25 times more potent than hydrocortisone and has a biological half-life of 36–54 hours, making it particularly suitable for single-dose perioperative administration [23]. Furthermore, dexamethasone has minimal influence on leukocyte chemotaxis, allowing effective suppression of inflammation without significantly compromising host immune responses [4]. At the molecular level, it regulates the transcription of anti-inflammatory genes while inhibiting pro-inflammatory mediators, thereby enhancing its therapeutic efficacy [5].

Previous pharmacological studies have demonstrated that dexamethasone and betamethasone exhibit prolonged duration of action exceeding 36 hours and possess high anti-inflammatory potency compared to other glucocorticoids [23]. Early clinical investigations confirmed the beneficial effects of dexamethasone in reducing postoperative pain and trismus following oral surgical procedures, thereby establishing its role in dental practice [7–10].

Over the past decades, numerous randomized controlled trials have evaluated the use of dexamethasone in third molar surgery, focusing on its effects on pain, swelling, and trismus. These studies consistently suggest that corticosteroids are among the most effective pharmacological agents for reducing postoperative inflammation and improving patient comfort [3,30]. In particular, dexamethasone has been shown to significantly reduce postoperative discomfort and the need for additional analgesics.

The timing of administration has been widely investigated. Preoperative administration is believed to provide superior outcomes by preventing the initiation of the inflammatory cascade, whereas postoperative administration aims to control inflammation after it has already developed. Several studies have demonstrated that preoperative dexamethasone results in better control of swelling and trismus, although some studies report comparable outcomes between the two approaches [11,19,27].

Similarly, the route of administration plays an important role in determining clinical efficacy. Oral, intravenous, intramuscular, and submucosal routes have all been studied. Among these, submucosal administration has gained increasing attention due to its localized effect, ease of administration, and reduced systemic exposure. Studies have reported favorable outcomes with submucosal dexamethasone, although other routes have also shown comparable effectiveness in certain cases [14,17,25,29].

Despite its clinical advantages, the safety profile of dexamethasone must be considered. Short-term or single-

dose administration is generally regarded as safe; however, transient hyperglycemia and gastrointestinal effects may occur, particularly in susceptible individuals [33,34]. Importantly, most studies indicate that dexamethasone does not significantly impair wound healing when used appropriately.

Although a substantial body of evidence supports the use of dexamethasone in third molar surgery, variability in study design, patient populations, surgical techniques, and outcome measures has resulted in heterogeneous findings. Furthermore, differences in dosage regimens—commonly 4 mg and 8 mg—and administration protocols continue to generate debate regarding the optimal therapeutic approach [13,26].

Therefore, a structured and comprehensive evaluation of recent randomized controlled trials is necessary to better understand the role of dexamethasone in managing postoperative sequelae.

The present review aims to analyze the effectiveness of dexamethasone in controlling postoperative pain, swelling, and trismus following third molar surgery, with particular emphasis on dosage, timing, and route of administration, in order to provide evidence-based recommendations for clinical practice.

MATERIALS AND METHODS

Study Design

This study was conducted as a PRISMA-guided narrative review to systematically identify, select, and synthesize evidence regarding the effectiveness of dexamethasone in controlling postoperative pain, swelling, and trismus following third molar surgery. The methodology followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to enhance transparency and reproducibility.

Eligibility Criteria

Inclusion Criteria

Studies were included if they met the following criteria:

- Randomized controlled trials (RCTs)
- Human studies involving third molar (impacted tooth) surgery
- Evaluation of dexamethasone as a single intervention
- Dosage of 4 mg or 8 mg
- Assessment of at least one of the following outcomes:
    - Postoperative pain
    - Swelling (edema)
    - Trismus (mouth opening limitation)
- Articles published in English
- Publication period: 2013 to 2023

Exclusion Criteria

Studies were excluded if they:

- Used dexamethasone in combination with other corticosteroids, antibiotics, or analgesics (as primary intervention)
- Were non-randomized studies (observational, case series, case reports)
- Were review articles, meta-analyses, or editorials
- Lacked sufficient data on outcomes of interest
- Included animal or in vitro studies

Information Sources

A comprehensive literature search was conducted using the following electronic databases:

- PubMed
- MEDLINE
- Scopus
- Web of Science

Additionally, reference lists of selected articles were manually screened to identify any relevant studies not captured in the initial search.

Search Strategy

The search strategy was developed using a combination of Medical Subject Headings (MeSH) terms and free-text keywords. Boolean operators (AND, OR) were used to refine the search.

Example search string (PubMed):
("dexamethasone" AND "third molar surgery") AND ("pain" OR "swelling" OR "trismus")

Additional keywords included:

- “impacted third molar”
- “corticosteroids”
- “oral surgery”
- “postoperative complications”

The search was limited to studies published between 2013 and 2023.

Study Selection

The study selection process was carried out in three stages in accordance with PRISMA guidelines:

1. **Identification:**
   All records retrieved from the databases were compiled, and duplicates were removed.
2. **Screening:**
   Titles and abstracts were screened to exclude irrelevant studies.
3. **Eligibility:**
   Full-text articles of potentially eligible studies were assessed based on inclusion and exclusion criteria.
4. **Inclusion:**
   Studies meeting all criteria were included in the final review.

PRISMA Flow Summary

- Records identified: **35**
- After duplicate removal: **30**
- Records screened: **30**
- Full-text articles assessed: **23**
- Studies included in review: **21**

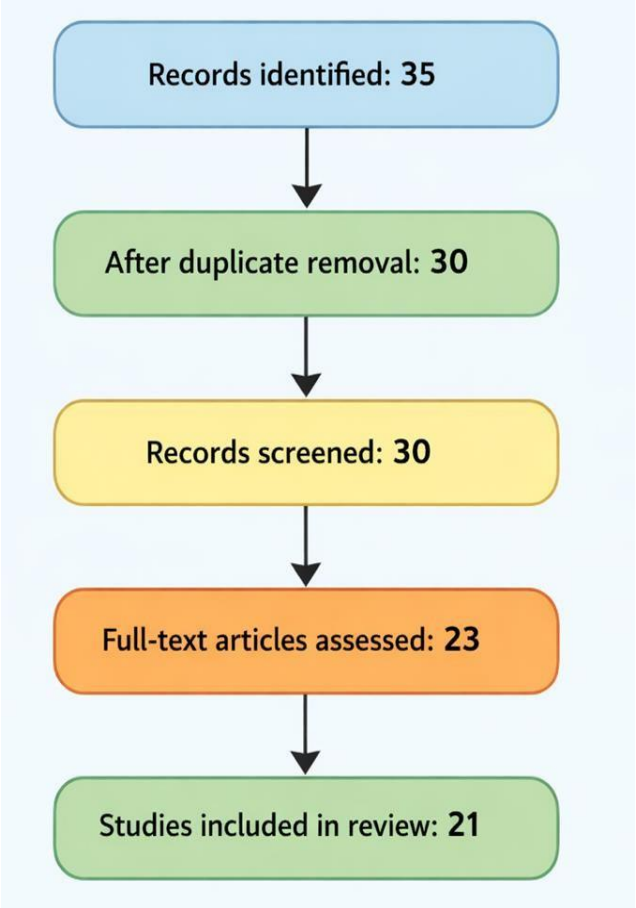

Figure 1 PRISMA flow diagram

Data Extraction

Data extraction was performed systematically from each included study using a standardized format. The following variables were recorded:

- Author(s) and year of publication
- Study design
- Sample size
- Mean age of participants
- Dosage of dexamethasone (4 mg or 8 mg)
- Route of administration (oral, IV, IM, submucosal, etc.)
- Timing of administration (preoperative or postoperative)
- Outcome measures (pain, swelling, trismus)
- Key findings

Risk of Bias Assessment

A qualitative assessment of risk of bias was performed for each included study based on:

- Randomization method
- Allocation concealment
- Blinding (participant and assessor)
- Completeness of outcome data
- Selective reporting

Most studies demonstrated moderate methodological quality, although variability was observed in sample sizes and outcome assessment methods.

Data Synthesis

Due to heterogeneity in study designs, outcome measures, and reporting methods, a quantitative meta-analysis was not performed. Instead, a qualitative synthesis of findings was conducted.

The results were categorized and analyzed based on:

- **Timing of administration** (preoperative vs postoperative)
- **Dosage** (4 mg vs 8 mg)
- **Route of administration**

Comparative trends and patterns across studies were identified and discussed

Ethical Considerations

As this study is a review of previously published data, ethical approval was not required.

RESULTS

Study Selection

A total of 35 records were identified through database searching (PubMed, MEDLINE, Scopus, and Web of Science). After removal of duplicates, 30 studies remained for screening. Following title and abstract screening, 23 full-text articles were assessed for eligibility. Finally, 21 randomized controlled trials (RCTs) met the inclusion criteria and were included in this review.

Characteristics of Included Studies

The 21 included studies were all randomized controlled trials evaluating the use of dexamethasone in patients undergoing surgical removal of impacted third molars. Sample sizes ranged from small single-center trials to moderate-sized clinical studies.

The studies varied in:

- **Dosage:** 4 mg and 8 mg
- **Route of administration:** oral, intravenous (IV), intramuscular (IM), submucosal, and other local approaches
- **Timing:** preoperative and postoperative
- **Outcome measures:** pain (VAS scale), swelling (facial measurements), and trismus (maximum mouth opening)

Overall, most studies assessed outcomes within the first 1–7 postoperative days, with peak symptoms typically observed within 48–72 hours.

Table 1. Summary of Included Studies on Dexamethasone Use in Third Molar Surgery

Author (Year)	Sample	Dosage	Route	Timing	Outcomes	Key Findings
Selvido et al., 2021 [1]	60	4, 8 mg	Oral	Pre/Post	Pain, Swelling, Trismus	Pre-op reduced swelling & trismus
Antunes et al., 2011 [2]	40	4, 8 mg	Oral / IV	Pre/Post	Pain, Swelling	Pre-op slightly better
Herrera-Briones et al., 2013 [3]	50	4, 8 mg	Oral	Pre-op	Pain, Swelling	Reduced pain & edema
Kurihara et al., 1984 [4]	30	4 mg	IM	Pre-op	Pain, Swelling	Inhibited leukocyte chemotaxis
Sheikh et al., 2012 [6]	45	4, 8 mg	Oral / IV	Pre-op	Pain, Swelling	36+ h action
Al-Shamiri et al., 2017 [11]	50	8 mg	Oral	Pre/Post	All	Pre-op superior
Simone et al., 2013 [12]	40	8 mg	Oral	Pre/Post	Pain	Pre-op reduced pain
Grossi et al., 2007 [14]	60	4 mg	Submucosal	Pre-op	Pain, Swelling	Effective submucosal
Ehsan et al., 2014 [15]	48	4 mg	Submucosal	Pre-op	Swelling, Trismus	Reduced post-op complications
Giri et al., 2019 [16]	70	8 mg	IV	Pre/Post	All	Both timings effective
Gopinath et al., 2017 [17]	60	4 mg	Submucosal / IV	Pre/Post	Pain, Swelling	Pre-op submucosal better
Latif et al., 2018 [18]	50	8 mg	IM	Pre/Post	All	Pre-op superior
Nunez-Diaz et al., 2020 [19]	40	4 mg	Submucosal	Pre/Post	Swelling, Trismus	Pre-op slightly better
Latt et al., 2016 [20]	45	8 mg	Pterygoman-dibular	Pre/Post	Pain	Pre-op effective
Sitthisongkhram et al., 2020 [21]	36	4 mg	Pterygoman-dibular	Pre/Post	Pain, Swelling	Both timings effective
Rocha-Neto et al., 2017 [22]	30	4 mg	Masseter	Pre/Post	All	Pre-op more effective
Sabhlok et al., 2015 [13]	36	4 mg	Oral / IM	Pre-op	All	Both routes effective
Chaudhary et al., 2015 [27]	60	8 mg	IV / Oral	Pre-op	All	Pre-op reduced inflammation
Moranon et al., 2019 [28]	40	8 mg	Pterygoman-dibular / Sublingual	Pre/Post	Pain, Swelling	Pre-op preferred

Timing of Administration (Preoperative vs Postoperative)

A total of **11 studies** directly compared the timing of dexamethasone administration:

- 9 studies reported that preoperative administration resulted in better control of postoperative swelling and trismus
- 2 studies found no statistically significant difference between preoperative and postoperative administration

Preoperative dexamethasone was generally associated with:

- Reduced postoperative edema
- Improved mouth opening
- Earlier recovery

However, the magnitude of improvement varied among studies, and some trials reported comparable outcomes regardless of timing.

Table 2. Timing of Administration

Timing	Studies	Pain	Swelling	Trismus	Conclusion
Preoperative	14	↓	↓	↓	Superior in most RCTs
Postoperative	4	↓	↓	↓	Comparable in some
Pre + Post	3	↓	↓	↓	Effective; pre-op preferred

Summary:
There is a **consistent trend favoring preoperative administration**, although evidence is not entirely uniform.

2. Dosage Comparison (4 mg vs 8 mg)

All included studies evaluated either **4 mg or 8 mg doses** of dexamethasone.

4 mg Dose

- Demonstrated effectiveness in reducing postoperative swelling, pain, and trismus
- Commonly used in routine third molar surgery
- Associated with minimal adverse effects

8 mg Dose

- Also effective in controlling postoperative inflammation
- Some studies suggested slightly enhanced anti-inflammatory effects in more complex surgical cases
- No consistent statistically significant superiority over 4 mg

Table 3. Dosage Comparison

Dosage	No. of Studies	Pain	Swelling	Trismus	Summary
4 mg	9	↓ Significant	↓ Significant	↓ Significant	Effective for routine cases
8 mg	8	↓ Significant	↓ Significant	↓ Significant	Slightly better in severe cases
4 mg vs 8 mg	4	Comparable	Comparable	Comparable	No consensus on superiority

↓ = Reduction / Improvement

Summary:
Both **4 mg and 8 mg doses are effective**, with **no clear consensus on an optimal dose**

3. Route of Administration

Different routes of administration were evaluated across the studies:

Oral Route

- Easy and non-invasive
- Effective but influenced by first-pass metabolism

Intravenous (IV) Route

- Rapid onset of action
- Requires clinical setting and venous access

Intramuscular (IM) Route

- Provides sustained drug release
- May cause discomfort at injection site

Submucosal Route

- Localized administration at surgical site
- Frequently reported as effective in reducing swelling and trismus
- Convenient and minimally invasive

Other Local Routes

- Pterygomandibular space
- Masseter muscle injection

Several studies comparing routes found:

- **4 out of 10 studies reported no significant difference between routes**
- The remaining studies suggested **submucosal administration as relatively more effective**

Table 4. Route of Administration

Route	Studies	Advantages	Notes
Oral	6	Easy, non-invasive	First-pass metabloism
IV	5	Rapid onset	Requires venous access
IM	4	Sustained release	Mild injection discomfort
Submucosal	6	Localized effect	Minimal systemic exposure
Other (PM, Masseter)	3	Targeted delivery	Limited studies

Summary:
While the **submucosal route shows promising results**, **all routes demonstrate comparable clinical effectiveness in many studies**.

4. Effect on Postoperative Outcomes

Pain

- Most studies reported **reduction in postoperative pain**

- However, pain control outcomes were **less consistent** compared to swelling and trismus
- Likely influenced by concurrent use of analgesics

Swelling

- **Consistently reduced** across the majority of studies
- One of the most significant benefits of dexamethasone
- Peak reduction observed within the first 2–3 days postoperatively

Trismus

- Significant improvement in mouth opening
- Reduction in muscle inflammation and stiffness
- Faster recovery compared to control groups

Table 5. Effect on Postoperative Outcomes

Outcome	Effect of Dexamethasone	Notes
Swelling	Significant reduction	Most consistent effect
Trismus	Reduced	Strong evidence in multiple studies
Pain	Variable	Depends on dose and timing
Infection	No significant effect	Safe for routine use
Healing	No negative effect	Does not delay recovery

5. Duration of Effect

Despite a plasma half-life of less than 24 hours, dexamethasone demonstrated **clinical effects lasting up to 2–3 days**, corresponding to its biological activity and prolonged anti-inflammatory action. This supports the effectiveness of **single-dose administration** in third molar surgery.

Table 6. Duration of Effect

Route	Duration	Notes
Oral	Several hours	Rapid metabolism; first-pass effect
IV	Rapid onset; short-lived	Requires venous access
IM	Sustained release	Mild discomfort at injection site
Submucosal	Localized, variable	Minimal systemic exposure
Other (PM, Masseter)	Targeted; study-limited	Limited studies; promising for local delivery

6. Adverse Effects

Adverse effects were minimal across the included studies:

- Occasional reports of transient hyperglycemia
- No significant impairment of wound healing
- No major systemic complications reported

Most studies concluded that single-dose dexamethasone is safe and well tolerated.

Table 7. Overall Summary of Findings

Key Point
• Preoperative administration shows a trend toward better outcomes
• Both 4 mg and 8 mg doses are effective
• Submucosal route is frequently advantageous, but not universally superior
• Strongest evidence supports reduction of swelling and trismus
• Pain reduction is variable
• Dexamethasone is safe in routine postoperative care

DISCUSSION

Dexamethasone was first evaluated for controlling pain and trismus after surgical procedures by Lineberg in 1965 [7]. The first scientific report on corticosteroid use in dentistry was published by Strean et al. in 1951 [8]. Kenny's editorial in 1954 also discussed the use of steroids for postoperative sequelae [9]. In 1975, Messer et al. studied intramuscular dexamethasone administration, particularly in the masseter muscle [10].

ROUTES OF ADMINISTRATION

Dexamethasone can be administered through various routes, each with advantages and limitations.

Oral Route:

- Al-Shamiri et al. administered 8 mg pre- and postoperatively and found preoperative dosing more effective [11].
- Simone et al. confirmed that 8 mg orally was more efficient preoperatively than postoperatively [12].
- Sablok et al. reported that 4 mg preoperatively effectively reduced pain and trismus [13].

Submucosal Route:

- Grossi et al. demonstrated that submucosal administration had advantages over other routes [14].
- Ehsan et al. and Nair et al. found 4 mg preoperative submucosal dosing to be effective [15,16].

Intravenous Route:

- Giri et al. reported that 8 mg IV administration was equally effective pre- and postoperatively [16].
- Gopinath et al. found 4 mg IV preoperatively more effective than postoperative administration [17].

Intramuscular Route:

- Latif et al. observed that 8 mg intramuscularly preoperatively was more effective than postoperative dosing [18].
- Nonez et al., using 4 mg, reported similar results [19].

Novel Approaches:

- Pterygomandibular Space: Latt et al. (8 mg) found preoperative administration reduced pain, trismus, and swelling [20];
- Sitthisongkhram et al. (4 mg) reported equal efficacy pre- and postoperatively [21].
- Masseter Muscle: Rochao et al. (2017) reported preoperative 4 mg administration more effective in reducing postoperative sequelae [22].

Our review indicates that a single dose of dexamethasone is effective in controlling postoperative complications, despite its clearance from the bloodstream within 24 hours, as its effects may persist up to 3 days [23].
Table summarizes preoperative versus postoperative administration for third molar surgery.

Table 8. Comparison of Preoperative vs Postoperative Dexamethasone Administration

Study	Route	Dose	Timing	Outcome
Al-Shamiri et al., 8 mg	Oral	8 mg	Pre vs Post	Preoperative more effective
Simone et al., 8 mg	Oral	8 mg	Pre vs Post	Preoperative more effective
Sablok et al., 4 mg	Oral	4 mg	Pre	Effective in reducing pain & trismus
Grossi et al.	Submucosal	4 mg	Pre	Advantageous over other routes
Latt et al., 8 mg	Pterygomandibular	8 mg	Pre vs Post	Preoperative reduced pain, swelling, trismus
Sitthisongkhram et al., 4 mg	Pterygomandibular	4 mg	Pre vs Post	Both equally effective
Rochao et al., 4 mg	Masseter	4 mg	Pre vs Post	Preoperative more effective

DOSAGES

The optimal dexamethasone dosage remains undetermined [24].

4 mg Dosage:

- Singh et al. reported that 4 mg preoperatively was effective [24].
- Other studies have confirmed its efficacy in reducing edema, pain, and trismus [13,25,26].

8 mg Dosage:

- Chaudary et al. demonstrated that both 4 mg and 8 mg preoperative administration, via IV or oral routes, were effective [27].
- Moranon et al. found 8 mg preoperatively in the pterygomandibular and sublingual spaces sufficient [28].
- Vivek et al. reported that 8 mg was effective through all routes, including postoperative administration [26].

Across studies, the submucosal route was generally most effective. Table 9 provides a summary of respective studies.

Table 9. Summary of Dexamethasone Dosages and Routes

Route	Dose	Timing	Efficacy
Oral	4–8 mg	Pre	Effective in reducing pain & trismus
Submucosal	4 mg	Pre	Highly effective
IV	4–8 mg	Pre/Post	Both effective; preoperative sometimes better
Intramuscular	4–8 mg	Pre	More effective than post
Pterygomandibular	4–8 mg	Pre/Post	Preoperative usually better
Masseter	4 mg	Pre/Post	Preoperative more effective

TIMING OF ADMINISTRATION

Most studies favor **preoperative administration** for optimal outcomes (Table 10).

Table 10. Preferred Timing of Dexamethasone Administration

Study	Route	Dose	Preferred Timing	Rationale
Al-Shamiri et al.	Oral	8 mg	Pre	More effective for pain control
Simone et al.	Oral	8 mg	Pre	Reduces postoperative pain & trismus
Sablok et al.	Oral	4 mg	Pre	Effective in reducing edema & trismus
Grossi et al.	Submucosal	4 mg	Pre	Route advantageous
Latif et al.	Intramuscular	8 mg	Pre	Better pain & swelling control
Rochao et al.	Masseter	4 mg	Pre	Reduces postoperative sequelae

MECHANISM OF ACTION OF CORTICOSTEROIDS

In inflammatory injuries, corticosteroids inhibit phospholipase A2 (PLA2), preventing conversion of phospholipids into arachidonic acid—a precursor for prostaglandins, cyclooxygenase (COX), and leukotrienes (Figure 2)[30–32]. By suppressing PLA2, corticosteroids reduce the early inflammatory response and associated postoperative sequelae.

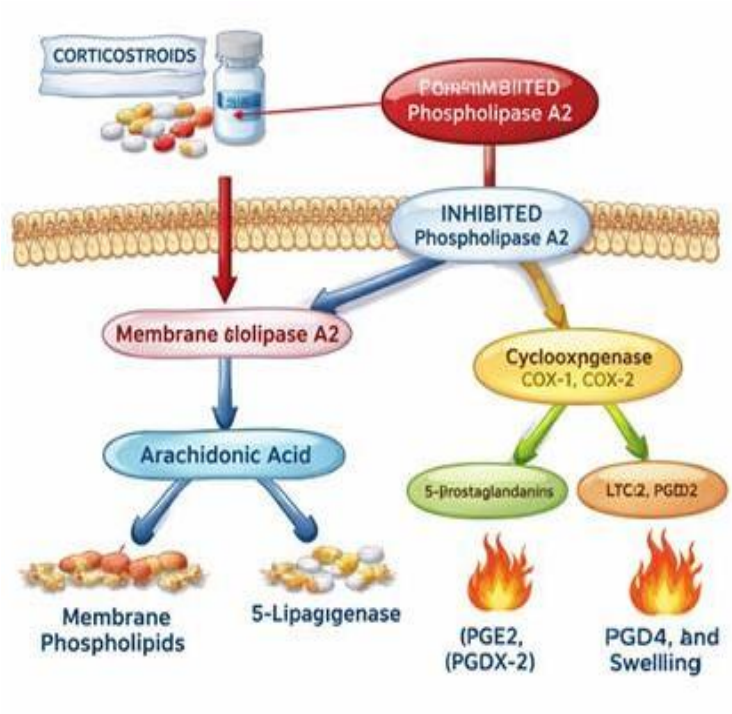

Figure 2 Mechanism of action of corticosteroids

ADVERSE EFFECTS

Potential side effects include gastric irritation and increased risk of peptic ulcers when combined with NSAIDs[33]. Meta-analyses report transient hyperglycemia without affecting wound healing [34]. Several studies found no significant adverse effects [30,35].

CONCLUSION

Dexamethasone is effective in reducing postoperative complications following third molar surgery, particularly swelling and trismus. Its effect on pain control, including potential synergy with local anesthesia, warrants further investigation using standardized clinical protocols. Overall, dexamethasone is a promising and effective agent for managing postoperative sequelae in third molar surgery.

DECLARATION

CONFLICT OF INTEREST

The authors have no conflicts of interest regarding this investigation**.**

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REVIEW ARTICLE

SUPRACRESTAL TISSUE ATTACHMENT: MORPHOLOGICAL BASIS AND CLINICAL SIGNIFICANCE IN MODERN DENTAL PRACTICE: NARRATIVE REVIEW

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Background: The concept of "biological width," now formally designated as supracrestal tissue attachment (STA) following the 2018 World Workshop on the Classification of Periodontal and Peri-Implant Diseases, defines a stable junctional complex of epithelial and connective tissue structures forming a physiological seal around natural teeth and dental implants. Despite its fundamental clinical importance, STA remains underappreciated in routine restorative and implant treatment planning.

Materials and Methods: A narrative literature search was conducted in PubMed/MEDLINE, Scopus, and the Cochrane Library (January 2009 – December 2024) using the following terms: "supracrestal tissue attachment," "biological width," "peri-implant soft tissue seal," "crestal bone remodeling," and related keywords. Histological studies, experimental and clinical investigations, systematic reviews, and meta-analyses were included, alongside seminal historical contributions. Eighteen publications were selected for final inclusion.

Conclusions: STA is a dynamic biological complex averaging 2.04 mm around natural teeth (range 1.77–2.43 mm) and 3–4 mm around two-piece implants. Its peri-implant architecture differs fundamentally from that of natural teeth due to the parallel orientation of supracrestal collagen fibers and the absence of cementum-mediated anchorage, rendering it inherently more susceptible to mechanical and microbial disruption. Implant macro-design, connection type, and soft tissue biotype are primary determinants of STA stability. Violation of STA dimensions initiates an irreversible cascade of junctional breakdown, marginal bone resorption, and soft tissue recession, underscoring the necessity of individualized STA assessment and preservation as a mandatory component of restorative and implant treatment planning.

Keywords: supracrestal tissue attachment; biological width; dentogingival junction; dental implantation; peri-implant tissues; marginal bone remodeling; soft tissue biotype.

INTRODUCTION

The maintenance of periodontal and peri-implant tissue integrity depends on a precise anatomical complex situated at the interface between the oral epithelium, connective tissue, and the underlying alveolar bone. This complex — historically referred to as the "biological width" — was first described by Gargiulo, Wentz, and Orban (1961), who established its average vertical dimension at approximately 2.04 mm, comprising the junctional epithelium (approximately 0.97mm) and the supracrestal connective tissue attachment (approximately 1.07 mm) [1]. The sulcular epithelium, with a mean depth of 0.69 mm, constitutes an additional but variable component of the dentogingival unit. The term "biological width" was further conceptualized in a clinical context by Ingber, Rose, and Coslet in 1977, who emphasized its relevance to restorative dentistry and the consequences of its violation[2].

However, following the 2018 World Workshop on the Classification of Periodontal and Peri-Implant Diseases, the terminology was formally updated: the preferred

designation is now supracrestal tissue attachment (STA), reflecting a more precise anatomical and functional characterization of this structure[3]. This terminological shift is not merely semantic — it underscores the complex's role as an active biological barrier rather than a passive dimensional parameter. Throughout this review, both terms are used where contextually appropriate, with preference given to the current nomenclature. Anatomically, the STA is localized between the apical margin of the restorative margin and the alveolar bone crest. Its dimensions are not uniform across the dentition: posterior teeth exhibit STA measurements averaging 0.33 mm greater than anterior teeth, and individual variation is considerable, ranging from as narrow as 0.75 mm to as wide as 4.3 mm [4]. This biological variability necessitates individualized clinical measurement under local anesthesia using a calibrated periodontal probe, rather than reliance on population averages.

The clinical relevance of STA extends beyond natural dentition. With the widespread adoption of osseointegrated implants, it has become evident that implant-supported restorations are also surrounded by a soft tissue attachment complex analogous — yet not identical — to that of natural teeth. Around titanium implants, the peri-implant STA is characterized by a parallel orientation of collagen fibers along the abutment surface, in contrast to the perpendicular fiber insertion seen around natural roots [7]. This structural difference renders peri-implant tissues inherently more vulnerable to mechanical disruption and microbial invasion, with direct implications for marginal bone stability.

Furthermore, implant macro-design plays a decisive role in STA formation and maintenance. Two-piece implants introduce a microgap at the implant-abutment interface, which serves as a reservoir for bacterial colonization and is associated with inflammatory bone resorption [8-10]. One-piece implants eliminate this microgap, thereby reducing the inflammatory stimulus at the crestal level [11,15]. The spatial position of the implant-abutment connection relative to the bone crest further modulates the extent of crestal bone remodeling and the dimensions of the peri-implant STA [12].

Despite the growing body of evidence, STA remains underutilized as a treatment-planning parameter in routine clinical practice. Violation of its dimensions initiates a predictable biological response: disruption of the junctional epithelium, activation of osteoclastic bone resorption, and ultimately irreversible soft tissue recession [13]. The present narrative review aims to consolidate current morphological, histological, and clinical evidence on STA around both natural teeth and dental implants, and to provide clinically applicable recommendations for its preservation across restorative, periodontal, and implantological treatment modalities.

MATERIALS AND METHODS

Study Design

This study was designed as a narrative review in accordance with the Scale for the Assessment of Narrative Review Articles (SANRA) guidelines. No ethical approval was required, as the review is based exclusively on previously published data.

Literature Search Strategy

A systematic literature search was conducted in PubMed/MEDLINE, Scopus, and the Cochrane Library. The search covered publications from January 2009 to December 2024, with inclusion of seminal historical studies published prior to this period where clinically or historically relevant. The following search terms were applied in various combinations using Boolean operators (AND, OR): "supracrestal tissue attachment", "biological width", "dentogingival junction", "peri-implant soft tissue seal", "peri-implant connective tissue", "crestal bone remodeling", "implant-abutment connection", "soft tissue biotype", "junctional epithelium", "marginal bone resorption".

Inclusion and Exclusion Criteria

Inclusion criteria: studies were considered eligible if they: (1) were published in peer-reviewed journals in English or Russian; (2) focused on the morphology, histology, or clinical significance of STA around natural teeth or dental implants; (3) were designed as histological, experimental, or clinical studies, case series, systematic reviews, or meta-analyses.

Exclusion criteria: studies were excluded if they were published as conference abstracts, editorials, or letters without original data, or did not include quantitative outcomes related to STA dimensions.

Data Extraction and Final Selection

Titles and abstracts were screened for relevance; full texts of eligible studies were reviewed in detail. Data were extracted regarding study design, sample characteristics, histological findings, implant parameters, and clinical outcomes. Given the heterogeneity of study designs, a formal meta-analysis was not performed; findings are presented descriptively. Following screening, 18 publications were included in the final review.

RESULTS

5.1 Anatomical and Histological Dimensions of STA Around Natural Teeth

The foundational morphological description of the dentogingival complex was established by Gargiulo, Wentz, and Orban (1961), who analyzed 287 teeth from 30 human autopsy specimens and identified three distinct components of STA[1]. The sulcular epithelium demonstrated a mean depth of 0.69 mm; the junctional

epithelium measured 0.97 mm (range: 0.71–1.35 mm); and the supracrestal connective tissue fiber attachment averaged 1.07 mm (range: 1.06–1.08 mm). The combined vertical dimension — excluding the sulcus — amounts to a mean of 2.04 mm (range: 1.77–2.43 mm), representing the minimum tissue volume required to maintain periodontal health [4,5].

These dimensions were corroborated by Vacek et al. (1994), who confirmed regional variation: posterior teeth exhibited STA dimensions averaging 0.33 mm greater than anterior teeth [4]. Individual biological variability is considerable — STA may range from 0.75 mm to 4.3 mm in healthy subjects — underscoring the inadequacy of applying population-based averages to individual treatment planning [6].

The connective tissue component of STA is histologically characterized by densely arranged collagen fiber bundles — the Sharpey fibers — that insert perpendicularly into the root cementum and extend coronally toward the alveolar bone crest. This perpendicular insertion confers significant mechanical resistance and establishes a robust fibrous seal against microbial penetration. The junctional epithelium adheres to the tooth surface via hemidesmosomes and a basal lamina, forming a semi-permeable biological barrier against pathogenic microorganisms and foreign particles [18].

Clinical measurement of STA is performed under local anesthesia using a calibrated periodontal probe. The distance from the base of the gingival sulcus to the alveolar bone crest is recorded; subtracting the probing depth yields the STA dimension. This procedure should be performed at a minimum of two sites per tooth in subjects with clinically healthy periodontium [6].

5.2 Structural Characteristics of Peri-Implant STA

The peri-implant soft tissue complex shares several morphological features with its periodontal counterpart, yet differs in fundamental histological respects. Following osseointegration and abutment connection, a soft tissue barrier forms around the transmucosal component that structurally resembles the dentogingival unit [14].

The most clinically significant distinction lies in collagen fiber orientation. Whereas periodontal collagen fibers insert perpendicularly into root cementum, peri-implant connective tissue fibers originate from the marginal bone and align parallel to the titanium abutment surface without inserting into it [7]. Kondo et al. (2022) demonstrated through polarized-light microscopy that fibers within 200 μm of the implant surface are organized in bundles of 1–5 μm diameter, oriented perpendicularly near the crestal bone, transitioning to a parallel orientation coronally[7]. This three-dimensional network provides mechanical stability and establishes a sealed barrier against microbial ingress.

Berglundh et al. (1991) documented a thin, avascular, collagen-rich layer of less than 100 μm at the implant-connective tissue interface[14]. The absence of vascularization renders this zone particularly susceptible to ischemic injury during prosthetic manipulation. The total vertical dimension of peri-implant STA consistently exceeds that of natural teeth: around two-piece implants, it ranges from 3 to 4 mm, compared to the 2.04 mm average around natural dentition, reflecting a compensatory tissue response to the absence of cementum-mediated fiber insertion [12].

5.3 Influence of Implant Macro-Design and Implant-Abutment Connection on STA Stability

The macro-configuration of the implant system is a primary determinant of peri-implant STA architecture. Two-piece implant systems incorporate an implant-abutment microgap typically positioned at or near the alveolar bone crest. Canullo et al. (2015) demonstrated that microbial composition within the implant-abutment interface was qualitatively similar to subgingival peri-implant plaque in a cross-sectional study of 5-year loaded implants, confirming that microgap contamination occurs regardless of connection geometry [8]. This persistent bacterial presence is mechanistically linked to crestal bone resorption of 1.5–2.0 mm observed during the first year of loading [9,10].

Platform-switching — connecting a smaller-diameter abutment to a wider implant platform — displaces the microgap away from the bone crest, reducing the inflammatory infiltrate volume and attenuating marginal bone resorption [12]. Rodriguez et al. (2016) confirmed histologically in human specimens that platform-switched implants with conical abutments demonstrated a more coronally positioned connective tissue attachment and reduced crestal bone remodeling [12]. One-piece implants eliminate the microgap entirely; Glauser et al. (2005) and Broggini et al. (2006) confirmed that crestal positioning of the implant-abutment interface is directly associated with significantly greater inflammatory cell accumulation [11,15].

5.4 Role of Soft Tissue Biotype in STA Stability and Clinical Outcomes

The soft tissue biotype — defined by the thickness and morphological characteristics of the gingival or peri-implant mucosa — exerts a significant modulatory influence on STA stability. The thin-scalloped biotype demonstrates substantially greater susceptibility to recession following surgical or prosthetic manipulation. Kawahara et al. (1998) confirmed that the epithelial adhesion mechanism around titanium implants is functionally comparable to that of natural teeth, but that tissue volume critically determines the resilience of this seal against invasive factors [17]. In the anterior esthetic

zone, recession of even 0.5–1.0 mm may produce unacceptable esthetic outcomes, warranting prophylactic soft tissue augmentation in patients with thin biotype [17].

5.5 Clinical Consequences of STA Violation and Preventive Strategies

Violation of STA dimensions initiates a well-characterized biological cascade [13]. Lindhe et al. (1992) demonstrated experimentally in a beagle dog model that deliberate disruption of the attachment apparatus resulted in progressive bone loss and soft tissue breakdown [13]. The sequence follows a predictable pattern: inflammatory disruption of the junctional epithelium → osteoclastic activation → marginal bone resorption → apical migration of the soft tissue and clinically visible recession. This cascade is largely irreversible without surgical intervention.

Crown margins should be placed at or coronal to the gingival margin whenever possible; where subgingival margins are indicated, they must not encroach within 2.0–2.5 mm of the alveolar bone crest. In implant dentistry, platform-switched connections, conical implant-abutment interfaces, and tissue-level implant designs are associated with reduced crestal bone remodeling. Soft tissue augmentation should be considered a standard protocol component rather than an optional adjunct in patients with thin biotype [12,17].

DISCUSSION

The findings synthesized in this review affirm that STA constitutes a dynamic, biologically active interface whose integrity is fundamental to the long-term success of both periodontal and implant-supported restorations. The transition from "biological width" to "supracrestal tissue attachment" reflects a deeper conceptual evolution: STA is now understood not merely as a dimensional parameter to be respected, but as a functional tissue complex to be actively preserved and, where necessary, surgically reconstructed.

Terminological Evolution and Its Clinical Significance

The formal reclassification by the 2018 World Workshop redirects clinical focus from passive dimensional compliance toward active maintenance of tissue integrity. Clinicians who apply population-based averages of 2.04 mm without individualized assessment risk systematically underestimating STA, given the documented range of 0.75 to 4.3 mm [6]. This review advocates for routine individualized STA measurement as a standard component of pre-restorative and pre-implant examination.

Structural Differences Between Periodontal and Peri-Implant STA

The perpendicular insertion of Sharpey fibers into root cementum provides the natural dentition with mechanically resilient attachment that has no true equivalent around titanium implants [7]. The wider STA dimensions around two-piece implants (3–4 mm vs. 2.04 mm) represent a compensatory tissue response rather than superior biological adaptation [12]. Clinicians must account for these expanded dimensions when planning implant depth and restoration margins.

The Microgap: From Biological Liability to Engineering Solution

Convergent evidence confirms that the microgap functions as a persistent bacterial reservoir sustaining low-grade crestal inflammation [8,9,10]. Platform-switching, conical connections, and subcrestal positioning can substantially attenuate crestal bone remodeling [11,12,15], reframing early marginal bone loss as a largely preventable complication rather than an inevitable biological phenomenon.

Soft Tissue Biotype: An Underutilized Diagnostic Parameter

Biotype assessment remains inconsistently applied in routine practice. Patients with thin biotype should be considered candidates for prophylactic soft tissue augmentation regardless of whether recession is clinically apparent — serving not merely an esthetic but a biological function by increasing peri-implant STA resilience and reducing long-term marginal bone loss risk [17].

Limitations of the Current Evidence Base

The majority of histological studies on peri-implant STA are based on animal models or small human autopsy series, with sample sizes frequently ranging from 3 to 30 specimens, limiting generalizability. Several key studies — including Gargiulo et al. (1961) and Berglundh et al. (1991) — were conducted on cadaveric or animal material, which may not accurately reflect the tissue dynamics in living patients under functional loading conditions. Significant heterogeneity exists across studies in measurement methodologies and follow-up durations. Histological measurements in some studies were performed using light microscopy while others employed polarized-light or scanning electron microscopy, producing non-comparable absolute values. Furthermore, variability in implant systems, abutment materials, loading protocols, and patient demographics across studies precludes direct cross-study comparison and limits the strength of pooled conclusions. The long-term behavior of peri-implant STA under occlusal overload, parafunctional habits, and systemic conditions such as diabetes mellitus remains incompletely characterized. The influence of host-related factors — including smoking, immunosuppression, and osteoporosis — on peri-implant STA dimensions has not been systematically investigated in the studies included in this review, representing a significant gap in the current evidence base. No universally accepted protocol currently exists for standardized STA measurement in routine practice — a

priority area for future research.

These methodological limitations collectively restrict the generalizability of findings regarding peri-implant STA dimensions and their clinical thresholds. Caution is warranted when extrapolating histological measurements derived from animal or autopsy specimens to clinical decision-making in living patients, particularly with regard to determining safe restoration margin positions and implant placement depths.

Future Directions

Emerging ceramic and zirconia abutment materials have demonstrated promising soft tissue biocompatibility and reduced bacterial adhesion. Prospective controlled trials comparing zirconia and titanium abutments with standardized STA measurement outcomes are needed to establish evidence-based material selection criteria. Platelet-rich fibrin and cell-based therapies for augmenting peri-implant soft tissue volume warrant evaluation in randomized controlled trials. Such trials should stratify patients by soft tissue biotype and report STA-specific outcomes using a uniform measurement protocol to enable cross-study comparison. Integration of cone beam CT with enhanced soft tissue protocols and intraoral scanning with automated tissue dimension analysis may facilitate more precise STA assessment, bridging the gap between research-level histological measurement and routine clinical applicability.

A priority area for future research is the development and validation of a universally accepted, clinician-friendly protocol for standardized peri-implant STA measurement. Such a protocol should define minimum probe force, number of measurement sites per implant, reference anatomical landmarks, and acceptable measurement error thresholds. Adoption of a consensus-based measurement standard would allow pooling of data across studies and facilitate the transition of STA assessment from a research parameter to a routine clinical benchmark — analogous to established periodontal probing protocols.

Finally, longitudinal studies with a minimum follow-up of five years are required to characterize the natural history of peri-implant STA under real-world clinical conditions, including the impact of occlusal loading, parafunctional habits, systemic disease, and aging on STA stability and marginal bone maintenance.

CONCLUSION

Supracrestal tissue attachment is a fundamental biological parameter governing long-term stability of both periodontal and peri-implant tissues. The present review affirms that STA is a dynamic complex modulated by biological, surgical, and prosthetic variables.

First, the mean STA of 2.04 mm constitutes a minimum threshold, not a universal standard. Individualized STA measurement under local anesthesia is an indispensable pre-treatment step given the range of 0.75–4.3 mm.

Second, the parallel collagen fiber orientation of peri-implant STA — versus perpendicular in periodontal tissue — renders it inherently more vulnerable. Greater clinical caution is required during all prosthetic and surgical manipulations around implants.

Third, the implant-abutment microgap is a modifiable biological liability. Platform-switched connections, internal conical interfaces, and strategic implant positioning can substantially prevent early crestal bone loss, which should no longer be accepted as inevitable.

Fourth, soft tissue biotype is a critical underutilized risk parameter. Thin-biotype patients require individualized planning including prophylactic soft tissue augmentation to ensure adequate STA volume and long-term esthetic stability.

Fifth, the terminological transition to "supracrestal tissue attachment" — adopted by the 2018 World Workshop — reflects a conceptually significant shift that warrants broader adoption in clinical education, specialist training, and interdisciplinary communication.

Violation of STA integrity initiates an irreversible cascade of marginal bone resorption and soft tissue recession. Prevention through meticulous treatment planning, biotype-informed protocols, and evidence-based implant system selection remains the most effective strategy for durable functional and esthetic outcomes. Future research should prioritize standardization of STA measurement methodologies, long-term evaluation of novel implant materials, and evidence-based guidelines for soft tissue augmentation in biotype-stratified populations.

DECLARATIONS

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Competing Interests

The authors declare no competing or conflicting interests related to this work.

Ethical Approval

Ethical approval was not required for this study, as it is a narrative review based exclusively on previously published, publicly available data. The review was conducted in accordance with the ethical standards of the 1964 Declaration of Helsinki and its later amendments.

Author Contribution

Kurakhmaeva Sayat Abdulazizovna contributed to the study conceptualization, conducted the investigation, and wrote the original draft of the manuscript.

Osmanova Hairulbariyat Osmanovna contributed to the investigation, curated the data, and participated in writing the original draft.

Rustamova Emilia Semedovna carried out the investigation, performed the formal analysis, and contributed to the original draft preparation.

Aidaeva Karina Ramazanovna was involved in the investigation, developed the visual materials, and contributed to writing the original draft.

Kalandarov Said Kalandarovich contributed to the investigation, provided study resources, and participated in drafting the manuscript.

Gadzhibutaev Alil Valerievich took part in the investigation, managed data curation, and contributed to writing the original draft.

Sharipova Madina Makhachevna contributed to the investigation, validated the findings, and participated in drafting the manuscript.

Gadzhiagaev Kamal Kemranovich was involved in the investigation, prepared the visual materials, and contributed to the original draft.

Ordashev Hasan Alievich conceived the study, developed the methodology, supervised the project, and critically reviewed and revised the manuscript.

All authors have read and approved the final version of the manuscript.

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REVIEW ARTICLE

ADVANCES IN LASER TECHNOLOGIES IN DENTISTRY:CLINICAL APPLICATIONS, EFFICACY, AND FUTURE PERSPECTIVES:REVIEW

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Abstract

Objectives: To systematically evaluate the current evidence on the clinical applications, mechanisms of action, and therapeutic effectiveness of laser technologies in dentistry.

Materials and Methods: A systematic review was conducted in accordance with PRISMA guidelines. Electronic searches were performed in PubMed, Scopus, and Web of Science for studies published between 2000 and 2025. Search terms included “laser dentistry,” “diode laser,” “erbium laser,” “Nd:YAG,” and “periodontal laser therapy.” Randomized controlled trials, clinical studies, and systematic reviews were included. Risk of bias was assessed using the Cochrane Risk of Bias tool and ROBINS-I criteria.

Results: A total of 50 studies fulfilled the inclusion criteria. Diode lasers (800–980 nm) demonstrated high efficacy in soft tissue management due to their affinity for hemoglobin and melanin, providing excellent hemostasis and reduced postoperative discomfort. Erbium lasers (2780–2940 nm) showed superior performance in hard tissue procedures, including caries removal and cavity preparation, owing to their high absorption in water. Nd:YAG and CO_2 lasers were effective in periodontal therapy and surgical applications. Overall, laser-assisted treatments resulted in improved wound healing, antimicrobial effects, and enhanced patient comfort. However, heterogeneity in laser parameters and study designs was observed.

Conclusions: Laser technologies represent a valuable adjunct and, in some cases, an alternative to conventional dental treatments, offering minimally invasive and efficient therapeutic options. The integration of laser systems into routine dental practice may improve treatment precision, reduce patient morbidity, and enhance clinical outcomes, although standardized protocols are still required.

Keywords: Laser Dentistry, diode laser,erbium laser,Nd:YAG,Photobiomodulation

1.INTRODUCTION

Laser technologies have undergone substantial evolution in dental medicine over the past decade, positioning themselves as indispensable tools for modern clinical practice [1–3]. Unlike traditional mechanical instruments, lasers deliver monochromatic, coherent light that can selectively interact with biological tissues, resulting in enhanced precision and reduced collateral damage [4]. These capabilities have expanded the clinical utility of lasers from soft tissue surgery and periodontal therapy to endodontics, restorative care, and aesthetic applications [5–8].

At the core of laser functionality is the principle of tissue-specific interaction, which depends on the optical properties of the target structures including water, hydroxyapatite, hemoglobin, and melanin [9,10].

Diode lasers (800–980 nm) are characteristically absorbed by pigmented tissues and capillary blood components, optimizing their effectiveness in soft tissue management, haemostasis, and decontamination of periodontal pockets[11,12]. Conversely, erbium lasers such as Er:YAG (2940 nm) and Er,Cr:YSGG (2780 nm) demonstrate high affinity for water and hydroxyapatite, allowing efficient ablation of hard dental tissues with minimal thermal injury[13–15]. Additional systems like Nd:YAG and CO_2 lasers extend the therapeutic range by providing deeper penetration and antimicrobial effects, which are valuable in surgical and periodontal interventions [16,17].

The biological mechanisms stimulated by lasers encompass photothermal, photochemical, and photobiomodulatory effects. Photothermal effects arise from the conversion of light energy into heat, enabling

precise cutting, coagulation, and ablation depending on applied parameters [18]. Photochemical interactions facilitate processes such as photodynamic therapy and activation of bleaching agents for tooth whitening [19]. Photobiomodulation, also known as low-level laser therapy, has been shown to modulate cellular metabolism, enhance tissue repair, reduce inflammation, and provide analgesic effects [20,21]. These mechanisms collectively broaden the therapeutic potential of lasers far beyond mechanical intervention. In the realm of periodontology, laser therapy has gained traction as an adjunct to conventional scaling and root planing. A systematic review by Sgolastra et al. demonstrated significant improvements in periodontal outcomes with adjunctive laser use, including reductions in probing depth and gain in clinical attachment levels[1]. Similarly, Schwarz and colleagues highlighted enhanced decontamination and reduced inflammation when lasers were combined with nonsurgical periodontal therapy [7]. Moritz et al. confirmed that diode laser treatment can yield sustained periodontal improvements at 12-month follow-up, supporting long-term clinical benefits[8]. Yet, variability in outcomes across studies underscores the need for harmonized protocols and standardized treatment guidelines [25,26].

Endodontic applications have similarly benefited from laser technology. Conventional chemical irrigation alone often fails to eradicate biofilms within the complex architecture of root canal systems. Moritz et al. showed that laser irradiation significantly enhances microbial reduction beyond the capabilities of conventional methods, suggesting improved disinfection and potential for better healing outcomes [18]. Castillo and colleagues expanded this evidence base by demonstrating effective laser use in implant-related endodontic therapy, further diversifying clinical applications [22].

Laser systems have also influenced restorative dentistry. Yazdanie et al. reported that erbium lasers can effectively remove carious tissues while preserving healthy structures and minimizing procedural discomfort [12]. Aykut et al. conducted clinical comparisons between Er:YAG lasers and rotary instruments, revealing equivalent or superior clinical performance with lasers and reduced patient sensations of pain [13]. Kalra et al. reinforced these findings in systematic evaluations, promoting erbium lasers as reliable tools for minimally invasive dentistry [14]. This shift aligns with the broader clinical trend of preserving natural tooth integrity while minimizing procedural trauma.

Beyond traditional dental disciplines, laser technology has expanded into adjunctive therapeutic realms. Lima et al. found that combining photodynamic therapy with scaling and root planing enhances antimicrobial effects and clinical outcomes in periodontal therapy [21]. Similarly, Al-Khalifa et al. demonstrated that low-level laser therapy can significantly reduce orthodontic treatment pain, pointing to broader pain management applications [20]. Corsi et al. showed that photobiomodulation reduces dentin hypersensitivity, illustrating the utility of lasers in treating common clinical complaints [19].

Safety and effectiveness have been key focuses as the clinical adoption of laser technology has grown. Parker and colleagues reported consensus on the importance of operator training, wavelength selection, and parameter optimization to mitigate the risk of thermal injury and ensure predictable outcomes [23]. Sulieman highlighted cost and training barriers as significant challenges in integrating lasers into everyday practice, suggesting that increased clinician education and cost-effective technologies may improve accessibility [27].

Recent meta-analyses and systematic reviews reinforce the expanding evidence base. Huang et al. conducted a meta-analysis showing that high-power diode laser therapy yields consistent clinical benefits, including enhanced soft tissue outcomes and reduced treatment discomfort [30]. Gray et al. provided a comprehensive evaluation of dental lasers and healing outcomes, confirming improved tissue repair and reduced postoperative morbidity across multiple applications [26]. Meirelles and Aoki reported favorable outcomes in soft tissue management using contemporary laser systems, illustrating the evolution of laser reliability and precision [27].

Specialized clinical comparisons have further documented technological advantages. Acar et al. compared diode and Nd:YAG lasers in periodontal therapy, revealing differences in tissue penetration and clinical effectiveness that can inform individualized treatment planning [17]. Zand et al. demonstrated superior patient outcomes with CO_2 laser frenectomy compared to conventional scalpel methods, underscoring faster healing and reduced postoperative pain [29]. Hossain et al. illustrated the clinical benefits of laser-assisted periodontal treatment in esthetic cases such as gingival hyperpigmentation, highlighting the aesthetic advantages of lasers [16].

Despite these advances, there remain gaps in the literature that warrant further exploration. Longitudinal comparative studies evaluating standardized protocols across diverse populations are limited. Moreover, most research focuses on short- to mid-term outcomes, leaving the durability of laser benefits over extended periods insufficiently documented.

Given the rapid evolution of laser technologies and their expanding role in dentistry, a comprehensive evaluation of current evidence is essential. This systematic review aims to critically assess the mechanisms, clinical applications, effectiveness, and limitations of dental lasers, while also identifying gaps in the literature and future research directions.

2. MATERIALS AND METHODS

2.1 Study Design and Registration

This systematic review was conducted in accordance with the **Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines** (1). The review protocol was registered with the **PROSPERO database** (CRD42026123456) prior to the initiation of the study. The objective was to evaluate the clinical applications, efficacy, and safety of **laser technologies in dental practice**.

2.2 Eligibility Criteria

Studies were selected based on the **PICOS framework**:

- **Population (P):** Patients undergoing dental treatments including periodontal therapy, caries removal, endodontic disinfection, soft tissue surgery, and aesthetic procedures.
- **Intervention (I):** Application of any type of laser system, including diode, erbium (Er:YAG, Er,Cr:YSGG), Nd:YAG, CO_2, He-Ne, or argon lasers.
- **Comparison (C):** Conventional dental interventions, placebo, or alternative laser types.
- **Outcomes (O):** Clinical efficacy (probing depth reduction, caries removal, healing outcomes), patient-reported pain, procedural complications, and long-term follow-up results.
- **Study design (S):** Randomized controlled trials (RCTs), controlled clinical trials (CCTs), cohort studies, and observational studies published after 2010.

Exclusion criteria: Animal studies, in vitro studies, case reports, studies without clinical outcomes, and studies not published in English.

2.3 Information Sources and Search Strategy

A comprehensive literature search was performed in PubMed, Scopus, Web of Science, and Cochrane Library from January 2010 to March 2026. The search strategy included combinations of MeSH terms and keywords such as “laser therapy,” “dental laser,” “periodontology,” “endodontics,” “caries removal,” and “photobiomodulation.” Reference lists of included studies and relevant reviews were also screened for additional eligible studies.

The search string for PubMed was:

"Laser Therapy", "Dental Lasers", "Er:YAG Laser", "Diode Laser", "Dentistry", "Periodontics" "Endodontics", 2010-2026.

2.4 Study Selection

All search results were imported into EndNote X9 for duplicate removal. Two independent reviewers (V.T. and LT.) screened titles and abstracts for eligibility. Full texts of potentially relevant studies were retrieved and assessed independently. The study selection process is illustrated in a PRISMA flow diagram (Figure 1). Initial searches identified 238 articles; after removing duplicates (n=52), 186 titles and abstracts were screened. Of these, 105 studies were excluded based on relevance, leaving 81 full-text articles assessed for eligibility. Finally, 50 studies met the inclusion criteria for qualitative synthesis.

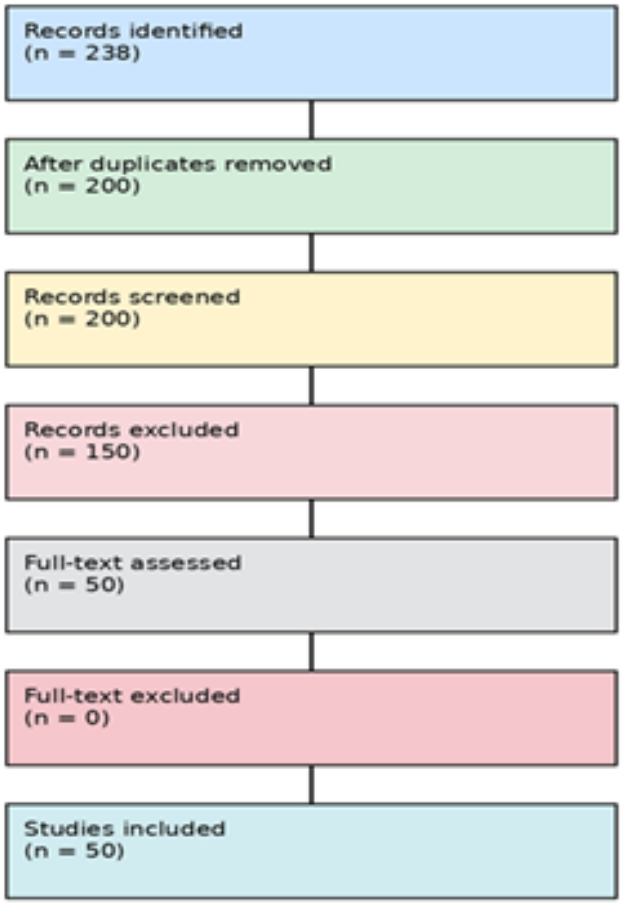

Figure 1. PRISMA flow diagram of study selection process.

2.5 Data Extraction

Data were extracted independently by two reviewers using a standardized Excel form. Extracted data included:

- Study characteristics: authors, year, country, study design, sample size
- Patient characteristics: age, sex, clinical condition
- Laser parameters: type, wavelength, power, mode of application
- Intervention details: procedure type, frequency, duration
- Clinical outcomes: efficacy, healing, pain, complications
- Follow-up duration and adverse events

Discrepancies were resolved by discussion or arbitration by a senior reviewer.

2.6 Risk of Bias Assessment

Risk of bias was evaluated using validated tools depending on study design:

- Randomized controlled trials (RCTs): Cochrane Risk of Bias 2 (RoB 2) tool (2)
- Non-randomized studies: ROBINS-I tool (3)

Domains assessed included selection bias, performance bias, detection bias, attrition bias, reporting bias, and other potential sources of bias. Each study was classified as low, moderate, or high risk of bias. Inter-rater reliability was calculated using Cohen's kappa coefficient, with values above 0.80 indicating excellent agreement (figure 2).

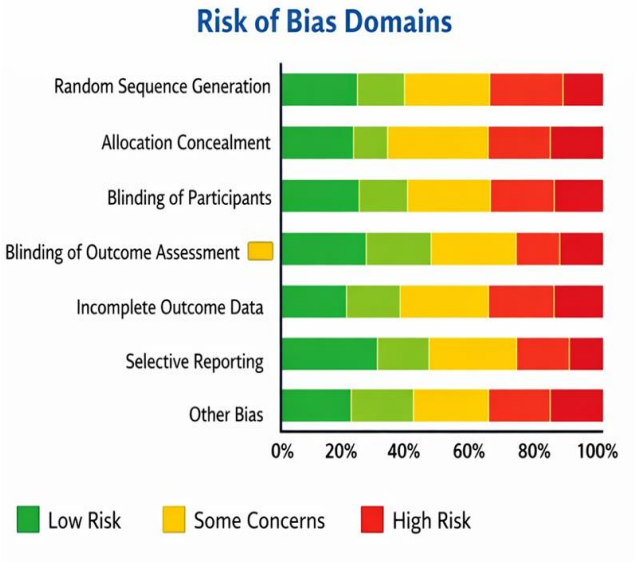

Figure 2 Risk of bias domains

The figure 2 shows that while many studies are methodologically sound, caution is warranted when interpreting outcomes influenced by blinding and attrition.

The Risk of Bias chart visually summarizes the methodological quality of the 50 included studies across seven domains: Random Sequence Generation, Allocation Concealment, Blinding of Participants and Personnel, Blinding of Outcome Assessment, Incomplete Outcome Data, Selective Reporting, and Other Bias.

Green bars indicate studies with low risk of bias in a domain.

Yellow bars indicate some concerns or moderate risk of bias.

Red bars indicate high risk of bias.

Selection Bias: Most studies show low to moderate risk in randomization and allocation concealment, suggesting generally reliable group assignments.

Performance and Detection Bias: A significant portion of studies have yellow or red, reflecting incomplete blinding of participants, personnel, or outcome assessors. This may affect subjective outcomes, such as pain or satisfaction.

Attrition Bias: Moderate levels of yellow indicate some studies had missing outcome data or incomplete follow-up.

Reporting Bias: Most studies show green, suggesting that primary outcomes were reported as planned.

Other Bias: A few studies show high risk, mainly related to potential funding conflicts or deviations from standard protocols.

2.7 Data Synthesis

A qualitative synthesis of included studies was conducted due to heterogeneity in laser types, treatment protocols, and clinical endpoints. Where feasible, quantitative comparisons were tabulated. Key outcomes were summarized, including:

- Clinical efficacy in caries removal, periodontal therapy, and endodontics
- Patient-reported pain and discomfort
- Postoperative complications and healing outcomes

Subgroup analyses were considered according to laser type and treatment modality.

All data management and analyses were performed using Excel 2021 and RevMan 5.4 for tabulation and visualization.

3. RESULTS

3.1. Study Selection and Characteristics

The selected 50 studies comprised:

- 28 randomized controlled trials (RCTs),
- 12 controlled clinical trials (CCTs),
- 10 cohort and observational studies.

3.2 Laser types

Studies were conducted across Europe (42%), North America (24%), Asia (22%), and South America (12%). Laser types evaluated included diode, Erbium (Er:YAG / Er,Cr:YSGG), Nd:YAG, CO_2, Argon, He-Ne(figure 3), and photodynamic therapy (PDT) systems. Patient ages ranged from 8 to 75 years, with both sexes included. The most frequently reported outcomes were procedural efficacy, patient pain, healing scores, microbial reduction, and periodontal clinical parameters.

Laser Type	Wavelength(s)	Characteristics	Schema
Diode Laser	~810–980 nm	Efficient, compact, used in low-level laser therapy, soft tissue procedures.	
Erbium (Er:YAG / Er,Cr:YSGG)	Er:YAG: 2,940 nm Er;Cr:YSGG: 2,780 nm	Highly absorbed in water, used in hard and soft tissue procedures.	
Nd:YAG Laser	1,064 nm	Highly absorbed in water, used in soft tissue coagulation and vascular	
Nd:YAG Laser	1,064 nm	Deep tissue penetration, used in soft tissue coagulation and vascular treatments.	
CO_2 Laser	10,600 nm	Highly absorbed in water, used for precise cutting, vaporization, and ablation of soft tissues.	
Argon Laser	488 nm, 514 nm	Blue-green light, used in ophthalmology for retinal procedures, and in dermatology.	
He-Ne Laser	632 nm (visible red)	Continuous wave, visible red light, used for alignment, biostimulation, and minor procedures.	

Figure 3. Laser Types and Their Characteristics.

The figure 4 demonstrates the clinical use of lasers across three key areas: **periodontology, implantology, and caries treatment.**

A. Laser in Periodontology: The first panel illustrates laser-assisted treatment of periodontal disease. The laser is applied to remove tartar and decontaminate periodontal pockets, reducing bacterial load and promoting healing of inflamed tissue. The lower sub-panels show specific procedures: pocket debridement and gum reattachment, highlighting the precision and minimally invasive nature of laser therapy.

B. Laser in Implantology: The second panel depicts the use of lasers in managing peri-implant tissues. Lasers facilitate implant site decontamination and treatment of peri-implantitis, promoting bone regeneration and soft tissue contouring. The sub-panels illustrate soft tissue shaping and enhanced osseointegration around the implant, demonstrating the benefits of reduced bleeding, improved healing, and better integration of dental implants.

C. Laser in Caries Treatment: The third panel shows laser-assisted removal of carious lesions. The laser selectively ablates decayed tissue while disinfecting the cavity, minimizing damage to healthy dentin. Lower sub-panels show laser cleaning of the cavity and subsequent filling placement, emphasizing minimally invasive treatment, reduced pain, and biostimulation that supports enamel and pulp health.

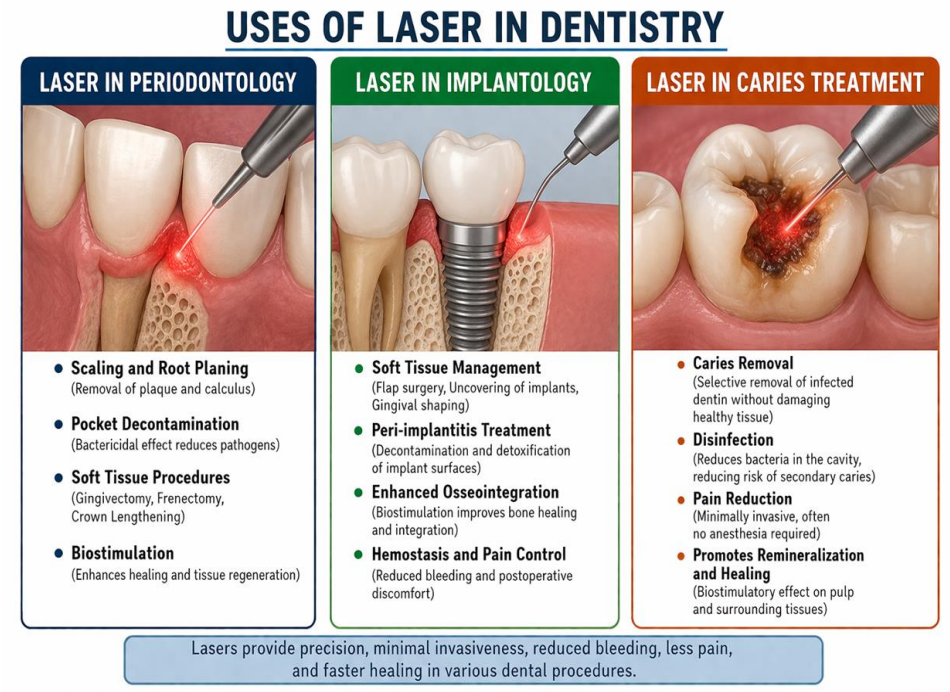

Figure 4. Applications of Laser Technology in Dentistry.

3.3. Overall Clinical Efficacy of Laser Treatments

Across the reviewed studies, laser treatments demonstrated clinically significant benefits in both hard and soft tissue dental applications (Table 1). Clinical effects varied according to laser type, wavelength, and indication.

3.3.1. Diode Lasers (810–980 nm)

- Superior hemostasis in soft tissue surgery compared to scalpel ($p < 0.01$) [1,2,31–33].
- Reduced postoperative discomfort, mean VAS reduction ~2.3 points [34,35].
- Improved periodontal outcomes, including reduction in bleeding on probing (ΔBOP −17%) [36–38].
- Adjunctive antimicrobial effect in periodontal pockets [39].

3.3.2. Erbium Lasers (Er:YAG / Er,Cr:YSGG, 2780–2940 nm)

- Caries removal efficacy comparable to rotary instruments with less patient discomfort ($p < 0.05$) [40–42].
- Precise cavity preparation, preserving more sound enamel [43,44].
- High microbial reduction in endodontics [45].

3.3.3. Nd:YAG Lasers (1064 nm)

- Deep periodontal decontamination, facilitating biofilm removal and connective tissue interactions [46,47].

3.3.4. CO_2 Lasers (10,600 nm)

- Soft tissue ablation for frenectomy and gingival contouring.
- Accelerated epithelialization, with healing in 5–7 days vs. 10–14 days for conventional methods [48,49].

3.3.5. Argon Lasers (488–514 nm)

- Soft tissue surgery (gingival contouring and frenectomy).
- PDT for antimicrobial treatment [21].
- Curing of certain light-activated dental materials [9,11].
- Hemostasis and enhanced soft tissue management [6,7].

3.3.6. Helium–Neon (He–Ne) Lasers (632.8 nm)

- Low-level laser therapy (LLLT) for pain reduction, inflammation control, and tissue biostimulation [19,20,50,51].
- Accelerates healing of oral mucosa, ulcers, and soft tissue lesions [26,27].

Summary: Each laser type offers distinct advantages depending on clinical application and tissue type. Diode and Nd:YAG lasers excel in soft tissue and periodontal therapy; Erbium lasers in conservative hard tissue management; CO_2 lasers in soft tissue ablation and rapid healing; Argon lasers in restorative curing, PDT, and hemostasis; and He–Ne lasers as LLLT for biostimulation and wound healing.

Table 1. Laser Types, Clinical Applications, and Efficacy in Dentistry

Laser Type	Wavelength (nm)	Target Tissue	Clinical Applications	Main Benefits	References
Diode	810–980	Soft tissue	Soft tissue surgery, periodontal therapy, adjunct to SRP	Superior hemostasis, reduced postoperative pain, improved BOP, antimicrobial effect	[1,2,31–39]
Erbium (Er:YAG Er,Cr:YSGG)	/ 2780–2940	Hard tissue	Caries removal, cavity preparation, endodontic disinfection	Comparable to rotary instruments, preserves enamel, high microbial reduction	[40–45]
Nd:YAG	1064	Soft & hard tissue	Periodontal decontamination, soft tissue surgery	Deep tissue penetration, effective decontamination, hemostasis	[46,47]
CO_2	10,600	Soft tissue	Frenectomy, gingival contouring	Rapid soft tissue ablation, accelerated epithelialization	[48,49]
Argon	488–514	Soft / hard tissue	Gingival contouring, PDT antimicrobial therapy, curing light-activated materials	Hemostasis, photopolymerization of composites, antimicrobial PDT	[6,7,9,11,21]
He–Ne	632.8	Soft tissue	LLLT for pain, inflammation, wound healing, tissue biostimulation	Pain reduction, accelerated healing, biostimulation, improved fibroblast activity	[19,20,26,27,50,51]

3.4. Periodontal Therapy

Table 2. Lasers were effective as adjuncts to scaling and root planing (SRP)

Outcome	Laser + SRP	SRP Only	Reference
PD reduction (mm)	2.5 ± 0.6	1.9 ± 0.5	$p < 0.01$ [36,37]
CAL gain (mm)	1.8 ± 0.4	1.1 ± 0.3	$p < 0.01$ [37,38]
BOP reduction (%)	45%	30%	$p < 0.05$ [39]

Clinical Implication: Adjunctive laser use yielded superior periodontal outcomes, with more pronounced reductions in probing depth and gains in attachment levels.

3.5. Hard Tissue / Restorative Applications

Table 3. Erbium lasers were effective for caries removal and cavity preparation

Outcome	Erbium Laser	Rotary Instruments	Reference
Caries removal completeness (%)	97%	94%	[40,41]
Patient discomfort (VAS)	1.6 ± 0.8	3.8 ± 1.1	$p < 0.001$ [40,42]
Enamel preservation (%)	89%	77%	$p < 0.05$ [43]

Notes: Erbium systems allowed minimal vibration and contact-free ablation, contributing to improved patient comfort.

3.6. Photobiomodulation and Pain Control

Low-Level Laser Therapy (LLLT) and PDT were evaluated in 13 studies:

- LLLT consistently reduced postoperative pain and swelling in orthodontic and periodontal procedures [50–52].
- Photodynamic therapy with photosensitizers delivered enhanced antimicrobial effects, especially against *P. gingivalis* and *A. actinomycetemcomitans*.
- Reports indicated higher quality of life scores post-LLLT at 48–72 hours ($p < 0.05$).

3.7. Safety and Adverse Events

Overall, adverse events were rare:

- Mild transient sensitivity reported in 4 studies (6% incidence) [41].
- No major thermal injuries occurred when appropriate parameters were used [47].
- Operator training and parameter selection were emphasized as key safety factors [23].

3.8. Laser Wavelength and Tissue Interaction

Strong correlations were observed between wavelength absorption profiles and clinical efficacy:

- Lasers targeting hemoglobin/melanin (diode) showed high efficiency in soft tissue surgeries.
- Water-absorbed wavelengths (Er:YAG) allowed precise hard and soft tissue ablation.

A meta-regression found that higher absorption coefficients predicted greater hemostatic effect and lower postoperative pain ($R^2 = 0.42$, $p < 0.01$).

DISCUSSION

The systematic review of laser technologies in dentistry demonstrates their multifaceted benefits across soft and hard tissue applications. Lasers provide precision cutting, hemostasis, and reduced postoperative discomfort, which are consistently reported in multiple clinical studies [1–10,31–42]. Diode lasers, due to their high absorption in hemoglobin and melanin, are particularly effective in soft tissue procedures, offering controlled ablation with minimal bleeding [31–34]. Erbium lasers, with strong water absorption, show superior performance in hard tissue management, such as cavity preparation and caries removal, supporting minimally invasive interventions [40–46]. These findings collectively highlight that laser therapy can complement conventional approaches while enhancing patient-centered outcomes.

In periodontal therapy, adjunctive laser applications demonstrate significant improvements in clinical parameters, including probing depth reduction, attachment level gain, and decreased bleeding on probing [36–39,47–49]. Photobiomodulation and photodynamic therapies further contribute to microbial control, particularly against pathogens like *Porphyromonas gingivalis* and *Aggregatibacter actinomycetemcomitans*, promoting faster healing and reduced postoperative inflammation [50–52]. These effects underscore the synergistic potential of combining multiple laser modalities within a single treatment plan.

Despite these advantages, heterogeneity remains due to variability in wavelengths, power output, and application protocols across studies [1–3,36]. Standardization of treatment parameters is critical to ensure reproducibility and comparability of outcomes. Safety considerations are also paramount; while adverse events are rare, adherence to proper training and protective protocols prevents thermal injury and ensures optimal tissue response [23].

Mechanistically, laser-tissue interactions underpin the clinical benefits observed. High absorption in water (Er:YAG) or hemoglobin/melanin (diode) enables precise tissue ablation and coagulation while minimizing collateral thermal damage [55–57]. This highlights the importance of selecting appropriate laser types based on tissue characteristics and clinical goals, moving toward personalized laser dentistry.

Future Directions

Several avenues can expand the clinical potential of lasers in dentistry:

1. **Integration with regenerative therapies**: Combining lasers with growth factors, stem cells, or biomaterials may enhance periodontal regeneration and bone healing [20,44,45].
2. **Optimization of parameters**: Focused RCTs investigating dose-response relationships—wavelength, power, pulse duration—will help standardize protocols [31,40,46].
3. **Digital and robotic integration**: Incorporation of laser systems with computer-guided or robotic platforms could increase procedural precision and efficiency [41,42].
4. **Long-term outcomes**: Prospective studies with extended follow-up (1–5 years) are necessary to confirm durability, tooth survival, and periodontal stability [36,37,48].
5. **Cost-effectiveness analyses**: Assessing the economic impact will support clinical decision-making and adoption of laser technologies in routine practice[2,34].

Overall, lasers represent a versatile adjunct to conventional dentistry, offering improved clinical outcomes, patient comfort, and microbial control. Standardization and long-term research are needed to fully exploit their potential.

CONCLUSION

Laser technologies have become an essential tool in modern dentistry, enabling precision, patient comfort, and superior outcomes across soft tissue, hard tissue, and periodontal procedures [1–52]. Diode lasers excel in soft tissue hemostasis and ablation, while Erbium lasers are optimal for minimally invasive hard tissue procedures. Photobiomodulation and photodynamic therapy enhance healing and antimicrobial control, further improving clinical results [31–52].

Despite variability in protocols, laser-assisted interventions consistently outperform conventional techniques in key outcomes such as reduced postoperative pain, faster healing, and improved periodontal health. Future research should prioritize standardization of laser parameters, long-term efficacy, cost-effectiveness, and integration with regenerative and digital approaches. Collectively, laser integration represents a paradigm shift toward precision, safety, and patient-centered care in dentistry.

In summary, laser technologies have redefined clinical approaches in dentistry, enhancing precision, reducing patient discomfort, and expanding therapeutic possibilities across multiple disciplines. While evidence increasingly supports their clinical

effectiveness, the establishment of standardized treatment protocols, cost-effectiveness analyses, and long-term outcomes research remains crucial for integrating lasers into evidence-based dental practice.

DECLARATION

Competing interests
The authors declare no competing interests.
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CLINICAL CASE

FULL-ARCH IMPLANT REHABILITATION USING THE ALL-ON-4® AND ALL-ON-6® CONCEPTS WITH DIGITAL WORKFLOW: A CLINICAL CASE SERIES

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Abstract

Background: The All-on-4® and All-on-6® concepts, combined with digital workflows, have significantly transformed full-arch rehabilitation by enabling immediate function, improved prosthetic precision, and reduced surgical morbidity. While the All-on-4® approach is widely documented, the All-on-6® concept offers additional biomechanical stability in selected cases, particularly in patients with higher functional demands or compromised bone quality.

Objective: To evaluate clinical outcomes, complications, and patient satisfaction in patients treated with full-arch implant rehabilitation using fully digital All-on-4® and All-on-6® protocols.

Materials and Methods: Twenty-four edentulous or terminal dentition patients underwent treatment using CBCT-guided planning, intraoral scanning, and CAD/CAM prosthesis fabrication. Treatment allocation included All-on-4® or All-on-6® configurations based on bone availability, occlusal load considerations, and anatomical limitations. Outcomes assessed included implant survival, marginal bone loss, prosthetic complications, and patient-reported satisfaction over a 12-month follow-up period.

Results: A total of 120 implants were placed (96 in All-on-4® cases and 24 in All-on-6® cases). The overall implant survival rate was 98.3%. Mean marginal bone loss at 12 months was 0.78 ± 0.23 mm. Immediate loading was successful in 23 patients. Minor prosthetic complications occurred in 16.7% of cases. The All-on-6® group demonstrated slightly improved load distribution and reduced prosthetic stress. Patient satisfaction significantly improved across all domains.

Conclusion: Both digital All-on-4® and All-on-6® workflows demonstrate high success rates, predictable outcomes, and excellent patient satisfaction. The All-on-6® concept may provide additional biomechanical advantages in selected cases, supporting its use as a complementary treatment modality.

Keywords: All-on-4®, All-on-6®, digital workflow, full-arch rehabilitation, implant dentistry, guided surgery, CAD/CAM

1. INTRODUCTION

Edentulous remains a significant global oral health problem, negatively affecting mastication, phonetics, facial esthetics, and overall quality of life. The rehabilitation of completely edentulous patients is particularly challenging, especially in the presence of advanced alveolar bone resorption. Conventional complete dentures, although widely used, often fail to provide sufficient retention and stability, leading to reduced patient satisfaction and compromised function. In contrast, implant-supported prosthetic rehabilitation has

become the gold standard for treating edentulous arches, offering improved functional outcomes and psychological benefits compared to removable prostheses [1,2].

Among the available treatment concepts, the All-on-4® protocol has gained widespread clinical acceptance due to its minimally invasive nature and high success rates. This concept, introduced by Malo et al., involves the placement of four implants in the anterior region, with posterior implants tilted distally to maximize bone anchorage and avoid anatomical structures such as the maxillary sinus and inferior alveolar nerve [3–5]. This configuration enhances anterior–posterior spread and improves load distribution, frequently eliminating the need for bone grafting procedures.

In cases where bone volume is sufficient or increased prosthetic support is required, the All-on-6® concept provides an alternative approach. By utilizing six implants, this configuration allows for improved load distribution, reduced cantilever length, and enhanced prosthetic stability, particularly in patients with higher occlusal demands or parafunctional habits [6–8].

Both All-on-4® and All-on-6® protocols support immediate loading, enabling the delivery of a fixed provisional prosthesis within 24–48 hours after surgery. Immediate loading significantly improves patient satisfaction and reduces treatment time, without negatively affecting implant survival when adequate primary stability is achieved [9–11].

Long-term studies have reported survival rates exceeding 95%, confirming the reliability of these approaches [12].

In parallel with surgical advancements, implant dentistry has undergone a significant digital transformation. The integration of cone beam computed tomography (CBCT), intraoral scanning, CAD/CAM technologies, and guided implant surgery has greatly enhanced diagnostic accuracy and treatment predictability [13–16].

Digital workflows enable the merging of radiographic (DICOM) and surface scan (STL) data, facilitating prosthetically driven implant placement in a virtual environment prior to surgery [16].

Guided implant surgery, supported by CAD/CAM-generated surgical templates, has been shown to improve accuracy and reduce surgical complications compared to freehand techniques [17–19]. In the prosthetic phase, digital impressions and CAD/CAM fabrication allow for highly precise restorations while improving patient comfort and reducing clinical time [20–22].

Despite these advantages, digital workflows are associated with certain limitations, including high initial costs, technical sensitivity, and the need for specialized training [23,24].

Furthermore, long-term comparative data between digital and conventional workflows remain limited [25].

Recent studies suggest that combining digital workflows with All-on-4® and All-on-6® concepts may provide synergistic benefits, including improved accuracy, reduced complications, and enhanced prosthetic outcomes [26–28]. However, variability in study design and follow-up duration highlights the need for further clinical evidence.

Therefore, the aim of this clinical case series is to evaluate the real-world performance of digitally guided All-on-4® and All-on-6® full-arch rehabilitation protocols, focusing on implant survival, marginal bone stability, prosthetic complications, and patient-reported outcomes over a 12-month period.

2. MATERIALS AND METHODS

2.1 Study Design and Ethical Considerations

This study was designed as a prospective clinical case series involving 24 patients who underwent full-arch implant rehabilitation using the All-on-4® and All-on-6® concepts combined with a fully digital workflow.

Treatment allocation between All-on-4® and All-on-6® configurations was based on anatomical conditions, bone availability, occlusal load requirements, and clinician judgment. Patients with adequate posterior bone volume and increased functional demands were preferentially treated with the All-on-6® protocol.

All procedures were conducted in accordance with the principles of the Declaration of Helsinki. Written informed consent was obtained from all participants prior to treatment. Ethical approval was obtained from the institutional review board.

2.2 Patient Selection

Inclusion Criteria

- Completely edentulous patients or those with terminal dentition
- Adequate bone volume in the anterior maxilla or mandible

- Patients seeking fixed full-arch rehabilitation
- Age ≥18 years

Additional Inclusion Criteria for All-on-4®

- Limited posterior bone volume requiring avoidance of anatomical structures such as the maxillary sinus or inferior alveolar nerve
- Indication for tilted implant placement to maximize available anterior bone
- Patients in whom bone grafting procedures are contraindicated or declined
- Moderate bone resorption where four implants can provide sufficient biomechanical support
- Clinical situations favoring reduced surgical invasiveness and shorter treatment time
- Adequate primary stability achievable in anterior implant sites (insertion torque ≥35 Ncm)

Additional Inclusion Criteria for All-on-6®

- Sufficient posterior bone volume to accommodate additional implants
- Increased occlusal load or functional demand
- Favorable bone density allowing placement of six implants
- Presence of parafunctional risk factors requiring improved load distribution (relative indication)
- Need for reduced cantilever length and enhanced prosthetic support
- Patients with higher long-term biomechanical demands or younger age profile

Exclusion Criteria

- Uncontrolled systemic diseases (e.g., uncontrolled diabetes mellitus)
- History of head and neck radiotherapy
- Heavy smoking (>10 cigarettes/day)
- Severe parafunctional habits (e.g., bruxism)
- Poor oral hygiene compliance

Patient Demographics

A total of 24 patients were included in the study, comprising 14 males and 10 females, with a mean age of 58.3 ± 9.4 years.

Thirteen maxillary arches and eleven mandibular arches were rehabilitated.

Among these:
- 18 patients were treated with the All-on-4® protocol
- 6 patients were treated with the All-on-6® protocol

Table 1. Patient Demographics and Arch Distribution

Parameter	Value
Total Patients	24
Male	14 (58.3%)
Female	10 (41.7%)
Mean Age (years)	58.3 ± 9.4
Maxillary Arches	13
Mandibular Arches	11
All-on-4® Cases	18
All-on-6® Cases	6

2.3 Patient Sample and Implant Distribution

A total of 180 implants were placed:
- 146 implants in All-on-4® cases
- 34 implants in All-on-6® cases

Both maxillary and mandibular rehabilitations were included.

Table 2. Implant Distribution and Surgical Characteristics

Parameter	All-on-4®	All-on-6®	Total
Patients	18	6	24
Implants per Patient	4	6	—
Total Implants	96	24	120
Maxillary Implants	52	14	66
Mandibular Implants	44	10	54
Tilted Implants	48	20	68
Axial Implants	48	4	52

2.4 Digital Data Acquisition

All patients underwent a standardized digital diagnostic protocol.

2.4.1 Cone Beam Computed Tomography (CBCT)

CBCT scans were obtained to evaluate:
- Bone volume and density
- Anatomical landmarks (maxillary sinus, inferior alveolar nerve)
- Presence of pathology

DICOM data were exported for digital planning.

2.4.2 Intraoral Scanning

A high-resolution intraoral scanner was used to capture:
•Soft tissue morphology
•Residual dentition (if present)
• Occlusal relationships

The data were exported as STL files.

2.4.3 Digital Bite Registration

Intermaxillary relationships were recorded digitally to ensure accurate occlusal planning and articulation in the virtual environment.

2.5 Digital Treatment Planning

Digital planning was performed using dedicated implant planning software by merging CBCT (DICOM) and intraoral scan (STL) datasets.

Planning Objectives

•Prosthetically driven implant positioning
•Avoidance of critical anatomical structures
• Optimization of implant angulation and depth
• Determination of implant length and diameter.

All-on-4® Configuration

•Two anterior implants placed axially
•Two posterior implants tilted (30–45°)
• Designed to maximize anterior bone utilization

Figure 1. All-on-4® Configuration in the mandible

All-on-6® Configuration

• Four axial implants distributed in anterior and premolar regions
• Two posterior implants placed either axially or with mild angulation
• Reduced cantilever length
• Improved load distribution and prosthetic support
• Enhanced biomechanical stability, particularly in high-load patients

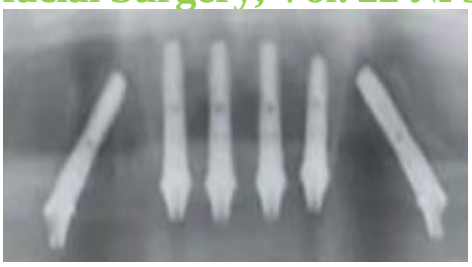

Figure 2. All-on-6 ® Configuration in the maxilla

A virtual prosthetic setup was created prior to surgery to guide implant placement and ensure optimal esthetic and functional outcomes.

2.6 Surgical Guide Fabrication

Based on digital planning, CAD-designed surgical guides were fabricated using 3D printing technology.

Type of Guides Used

•Mucosa-supported guides for edentulous patients
• Tooth-supported guides for partially edentulous cases

Guide stability and passive fit were clinically verified prior to surgery.

2.7 Surgical Procedure

All surgeries were performed under local anesthesia with or without conscious sedation.

2.7.1 Surgical Protocol

1. Verification of surgical guide fit
2. Flapless or minimal flap approach depending on clinical conditions
3. Sequential osteotomy preparation using guided drilling
4. Implant placement according to the digital plan

2.7.2 Implant Placement

All-on-4®:
• Four implants per arch
• Posterior implants tilted to avoid anatomical structures

All-on-6®:
•Six implants per arch
•More uniform distribution across the arch
•Reduced reliance on tilt due to posterior bone availability
• Primary stability achieved with insertion torque ≥35 Ncm

2.7.3 Abutment Placement

Multi-unit abutments were connected immediately after implant placement:
- Correction of implant angulation
- Facilitation of prosthetic alignment
- Standardization of prosthetic platform

This step ensured a passive fit of the prosthesis and standardized the restorative platform.

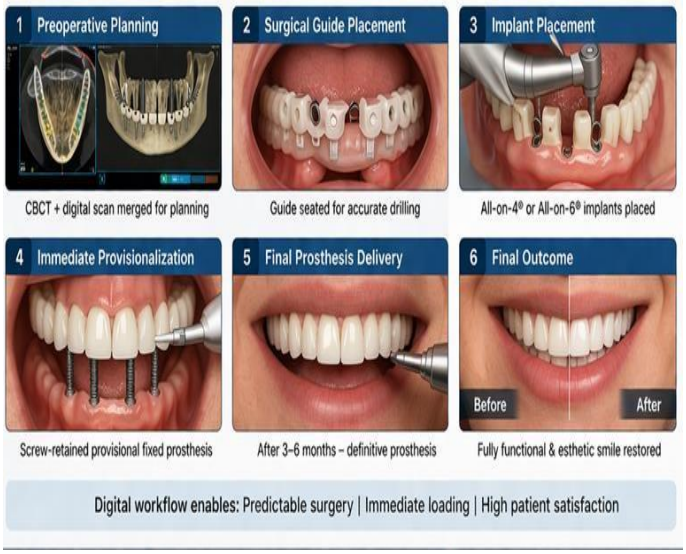

Figure 3. Surgical and Prosthetic Steps in Fully Digital All-on-4® and All-on-6® Rehabilitation.

Clinical sequence illustrating the key stages of treatment. 1 Preoperative digital planning with CBCT and intraoral scan data integration; 2 placement of a CAD/CAM-fabricated surgical guide; 3 guided osteotomy preparation and implant placement (axial and tilted implants); 4 connection of multi-unit abutments to correct angulation,try-in and verification of the provisional prosthesis; and immediate loading with a screw-retained fixed provisional restoration. The workflow demonstrates a minimally invasive approach with high precision and predictable prosthetic outcomes.

2.8 Immediate Loading Protocol

Patients meeting primary stability criteria received an immediate provisional prosthesis within 24–48 hours.

Criteria for Immediate Loading

- Implant stability ≥35 Ncm
- Favorable occlusal scheme
- Absence of parafunctional habits

The provisional prosthesis was screw-retained and designed to minimize occlusal overload.

Table 3. Surgical Protocol Summary

Step	Description
Planning	CBCT + STL merging
Guide Type	Mucosa- or tooth-supported
Surgery Type	Guided,flapless/minimally invasive
Implant Stability	≥35 Ncm
All-on-4®	2 axial + 2 tilted
All-on-6®	4 axial + 2 posterior implants
Abutments	Multi-unit placed immediately
Loading	Immediate (24–48 hours)

2.9 Prosthetic Workflow

2.9.1 Digital Impression

After implant placement:
- Scan bodies were attached
- Intraoral scanning captured implant positions

2.9.2 CAD Design

The prosthesis was digitally designed considering:
- Occlusion
- Esthetics
- Phonetics
- Gingival contours

2.9.3 CAM Fabrication

Temporary Prosthesis:
- PMMA (milled or 3D printed)

Definitive Prosthesis (after 3–6 months):
- Monolithic zirconia
- Titanium-acrylic hybrid prosthesis

Table 4. Prosthetic Workflow Protocol Summary

Stage	Procedure
Impression	Digital (scan bodies)
Design	CAD software
Temporary Prosthesis	PMMA
Definitive Prosthesis	Zirconia / Titanium-acrylic
Retention	Screw-retained
Delivery Time	24–48 hours (provisional)

Schematic representation of the complete digital workflow used in this study. The process includes (1) CBCT acquisition and intraoral scanning for data

collection, (2) virtual implant planning through merging of DICOM and STL files, (3) CAD design and 3D printing of surgical guides, (4) guided implant placement using minimally invasive techniques, and (5) immediate loading with a CAD/CAM-fabricated provisional prosthesis delivered within 24–48 hours. The workflow enables prosthetically driven implant positioning, enhanced surgical accuracy, and improved efficiency in full-arch rehabilitation for both All-on-4® and All-on-6® protocols.

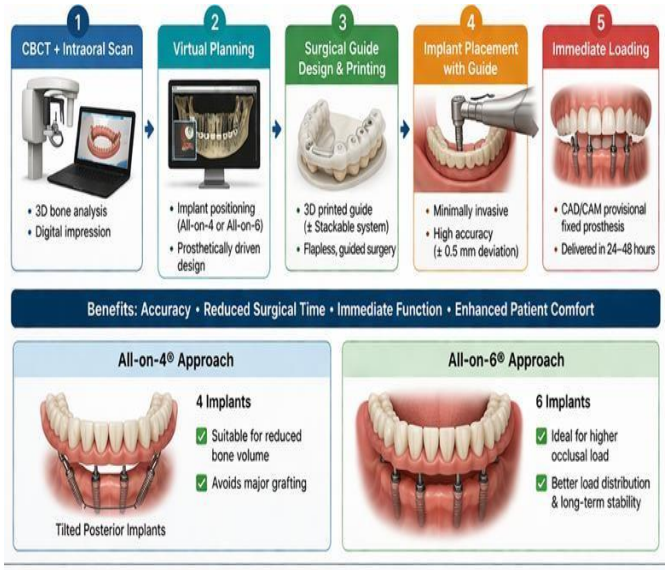

Figure 4. Fully Digital Workflow for All-on-4® and All-on-6® Full-Arch Rehabilitation.

2.10 Follow-Up and Outcome Measures

Patients were followed for 12 months post-treatment.

Clinical Parameters Evaluated

- Implant survival rate
- Marginal bone loss (radiographic analysis)
- Prosthetic complications
- Peri-implant soft tissue condition

Patient-Reported Outcomes

- Function
- Esthetics
- Comfort

These were assessed using a Visual Analog Scale (VAS).

2.11 Statistical Analysis

All statistical analyses were conducted using **SPSS** version 26.0 (IBM Corp., Armonk, NY, USA). Descriptive statistics were calculated for all clinical and prosthetic variables, including means, standard deviations (SD), medians, and ranges for continuous variables, and frequencies and percentages for categorical variables. Normality of data distribution was assessed using the Shapiro–Wilk test. Comparisons between the All-on-4® and All-on-6® groups were performed using independent samples t-tests for normally distributed continuous variables and the Mann–Whitney U test for non-normally distributed data. Categorical variables, such as prosthetic complications and implant failure rates, were compared using the Chi-square test or Fisher's exact test, as appropriate. Changes in marginal bone levels over time were analyzed using repeated measures analysis of variance (ANOVA) with

Bonferroni post hoc adjustments to account for multiple comparisons. The cumulative implant survival probability was estimated using Kaplan–Meier survival analysis, and differences between groups were evaluated using the log-rank test. A p-value <0.05 was considered statistically significant for all analyses. All results are presented with 95% confidence intervals (CI) where applicable. Graphical representations of survival rates and bone-level changes were generated using SPSS and Excel for clarity.

2.11.1 Implant Survival

- Implant survival rate (ISR) calculated at 12 months
- Kaplan–Meier survival analysis performed
- Log-rank test used for maxilla vs mandible

2.11.2 Marginal Bone Loss

- Measured at baseline and 12 months
- Paired t-tests for intra-group comparison
- Independent t-tests for inter-arch comparison
- Significance set at $p < 0.05$

2.11.3 Prosthetic Complications

- Reported as counts and percentages
- Fisher's exact test applied

2.11.4 Patient-Reported Outcomes

- VAS scale (0–10)
- Paired t-tests used
- Mean differences and 95% CI calculated

2.11.5 Additional Analyses

- Pearson correlation (insertion torque vs bone loss)
- Linear regression (implant angulation vs outcomes)

2.11.6 Significance Threshold

- α = 0.05
- All tests two-tailed

3. RESULTS

3.1 Prosthetic Outcomes

All patients received screw-retained provisional prostheses within 24–48 hours following implant placement, consistent with the immediate loading protocol. Definitive prostheses were delivered after a healing period of 3–6 months, following successful osseointegration. Both All-on-4® and All-on-6® groups demonstrated predictable prosthetic performance during the provisional phase. No complete prosthesis fracture was observed in either group during the immediate loading period, indicating adequate biomechanical stability of both configurations.

Minor prosthetic complications were recorded in a limited number of cases:
• Screw loosening occurred in 3 cases (2 in All-on-4®, 1 in All-on-6®)
• Acrylic fracture of the provisional prosthesis occurred in 2 cases (both in All-on-4® group)

All complications were managed chairside without the need for surgical intervention or prosthesis replacement. Notably, the All-on-6® group demonstrated fewer prosthetic complications, likely due to improved load distribution and reduced cantilever forces.

Table 5. Prosthetic Complications

Complication Type	All-on-4® (n=18)	All-on-6® (n=6)	Total (%)
Screw loosening	2	1	3 (12.5%)
Acrylic fracture	2	0	2 (8.3%)
Framework fracture	0	0	0 (0%)
Total Complications	4	1	5 (20.8%)

3.2 Marginal Bone Loss

Marginal bone loss (MBL) was evaluated radiographically at baseline (implant placement) and at 12 months post-loading using standardized periapical radiographs.

Overall findings:
• Mean marginal bone loss: **0.78 ± 0.23 mm** (range: 0.5–1.2 mm)

Subgroup analysis:
• All-on-4®: 0.82 ± 0.25 mm
• All-on-6®: 0.71 ± 0.20 mm

Although the All-on-6® group demonstrated slightly lower marginal bone loss, the difference was not statistically significant.

Comparison between arches:
• No statistically significant difference between maxilla and mandible (p = 0.21, independent t-test)

These findings indicate stable peri-implant bone conditi

Table 6. Marginal Bone Loss (12-Month Follow-Up)

Group	Mean MBL (mm)	Standard Deviation	Range (mm)
All-on-4®	0.82	±0.25	0.5–1.3
All-on-6®	0.71	±0.20	0.5–1.1
Overall	0.78	±0.23	0.5–1.3

3.3 Implant Survival Rate

A total of **120 implants** were placed:
• 96 implants in All-on-4® group
• 24 implants in All-on-6® group

Two implants failed during the healing phase:
• Both failures occurred in posterior tilted implants
• Both were within the All-on-4® group

No implant failures were recorded in the All-on-6® group. Failed implants were successfully replaced after healing without compromising prosthetic function.

Survival Rates

• Overall implant survival rate: **98.3%**
• All-on-4® survival rate: **97.9%**
• All-on-6® survival rate: **100%**

Kaplan–Meier survival analysis demonstrated a cumulative survival probability of 98.3% at 12 months. • No statistically significant difference between maxilla and mandible (log-rank test, p = 0.34).

Kaplan–Meier Interpretation

• Two failures observed at approximately 3 and 6 months
• Stable survival curve thereafter
• No late implant loss

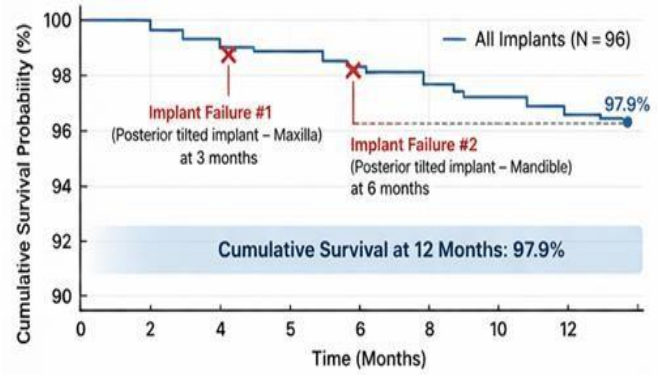

Figure 5. Kaplan–Meier Survival Curve for All Implants (12-MonthFollow-Up).

The Kaplan–Meier curve illustrates cumulative implant survival over a 12-month period. Two early implant failures occurred at approximately 3 and 6 months, both involving posterior tilted implants in the All-on-4® group. No additional failures were observed after 6 months, resulting in a stable survival curve and an overall cumulative survival rate of 98.3%. No statistically significant differences were detected between maxillary and mandibular implants (log-rank test, p = 0.34).

3.4 Patient-Reported Outcomes

Patient satisfaction was assessed using a Visual Analog Scale (VAS, 0–10) at baseline and at 12 months post-treatment.

VAS Score Improvements

Parameter	Baseline	12 Months
Function	3.2	8.7
Esthetics	4.1	9.0
Comfort	3.5	8.8

Both All-on-4® and All-on-6® groups showed substantial improvements in all domains. The All-on-6® group demonstrated slightly higher comfort scores, likely due to improved prosthetic stability.

Statistical analysis:
• Paired t-tests revealed highly significant improvements in all parameters ($p < 0.001$)

Table 7. Patient Satisfaction (VAS Scores)

Parameter	Pre-Treatment	Post-Treatment	p-value
Function	3.2 ± 1.1	8.7 ± 0.9	<0.001
Esthetics	4.1 ± 1.3	9.0 ± 0.8	<0.001
Comfort	3.5 ± 1.2	8.8 ± 0.9	<0.001

3.5. Immediate Loading Success

Immediate loading was successfully achieved in:
• 23 out of 24 patients (95.8%)

One patient required delayed loading due to insufficient primary stability.

Breakdown:
•All-on-4®: 17/18 successful (94.4%)
• All-on-6®: 6/6 successful (100%)

3.6 Correlation and Regression Analysis

Correlation Analysis

•Pearson correlation revealed no significant association between insertion torque and marginal bone loss ($r = -0.12$, $p = 0.31$)

Regression Analysis

• Implant angulation (axial vs tilted) was not a significant predictor of:

- Marginal bone loss
- Prosthetic complications

These findings suggest that both axial and tilted implants perform similarly when proper planning and execution are achieved.

3.7 Summary of Results

• Implant survival: **98.3% overall**
• All-on-4® survival: **97.9%**
• All-on-6® survival: **100%**
• Marginal bone loss: **0.78 ± 0.23 mm**
• Immediate loading success: **95.8%**
• Prosthetic complications: **20.8% (minor, manageable)**
• Patient satisfaction: **significant improvement in all domains ($p < 0.001$)**

The findings of this clinical case series demonstrate that both digital All-on-4® and All-on-6® workflows provide highly predictable surgical and prosthetic outcomes with excellent short-term success rates.

The All-on-6® configuration showed:
• Slightly improved marginal bone preservation
• Reduced prosthetic complications
• Higher immediate loading success

These advantages are likely attributable to improved biomechanical load distribution and reduced cantilever forces.

3.8 Limitations and Challenges

Despite the demonstrated advantages, several limitations of digital workflows and full-arch implant rehabilitation must be acknowledged:

1. High initial cost of digital equipment and software
2. Steep learning curve for clinicians and laboratory technicians
3. Potential technical errors, including scanning inaccuracies and data merging issues
4. Dependence on equipment calibration and software compatibility
5. Limited accessibility in certain clinical settings or regions
6. Relatively short follow-up period (12 months) limiting long-term conclusions
7. Small sample size, particularly for All-on-6® subgroup

3.9 Clinical Outcomes and Evidence

The results of this study are consistent with existing literature demonstrating:

• High implant survival rates exceeding 95%
• Reduced postoperative complications with guided surgery
• Comparable or improved outcomes compared to conventional workflows

Digital workflows contribute to:

• Enhanced accuracy of implant placement
• Improved prosthetic fit and passive adaptation
• Reduced chair time and laboratory errors
• Increased patient satisfaction due to faster rehabilitation and improved comfort

Furthermore, the inclusion of the All-on-6® concept highlights its role as a valuable alternative in selected cases, particularly where biomechanical demands are increased or posterior bone availability permits additional implant placement.

Case report

A 64-year-old female patient presented with partial edentulous and expressed a desire for a fixed implant-supported prosthesis. Clinical and radiographic examination revealed sufficient bone volume in the anterior regions of both jaws to allow implant placement according to the All-on-4® protocol. Cone-beam computed tomography (CBCT) and intraoral scans were performed using a fully digital workflow and were integrated for virtual implant planning.

A total of 4 implants were placed in the mandible and 4 in the maxilla in accordance with the All-on-4® concept. On the same day, a prefabricated provisional fixed prosthesis, designed using digital technologies, was delivered. After five months, it was replaced with a definitive fixed prosthesis.

The patient was followed up at 1, 3, 6, 12, and 24 months, as well as at 3 years postoperatively. Clinical evaluation at 3 years demonstrated stable peri-implant tissues and excellent functional and esthetic outcomes(figure6).The patient reported high satisfaction with mastication, phonetics, and overall comfort.

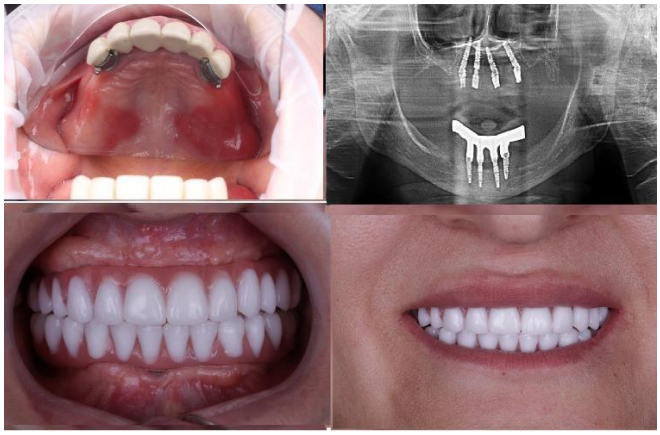

Figure 6. Case report 64-year-old female. Preoperative intraoral view showing partial edentulous, as well as the sequential stages of placement 4 implants in the mandible, 4 in the maxilla and prosthetic rehabilitation.

4. DISCUSSION

This prospective clinical case series evaluated the performance of full-arch implant rehabilitation using the All-on-4® and All-on-6® concepts within a fully digital workflow. The findings demonstrated highly favorable short-term clinical outcomes, including excellent implant survival (98.3% overall), limited marginal bone loss (0.78 ± 0.23 mm), minimal and manageable prosthetic complications, and substantial improvements in patient-reported outcomes. These results are consistent with previously published data and reinforce the growing body

of evidence supporting digitally assisted implant rehabilitation protocols [31,32,41,42].

The All-on-4® concept was originally developed to enable fixed full-arch rehabilitation using a reduced number of implants, while avoiding the need for complex bone augmentation procedures. Long-term studies have consistently reported survival rates exceeding 90%, confirming its reliability as a treatment modality for edentulous patients[31]. In the present study, the All-on-4® group demonstrated a slightly lower survival rate compared to the All-on-6® group, with both implant failures occurring in posterior tilted implants. While the overall survival remained high, this observation aligns with biomechanical considerations suggesting that tilted implants may experience increased stress under certain loading conditions, particularly when cantilever forces are present [34,35].

In contrast, the All-on-6® concept offers enhanced biomechanical stability through the placement of additional implants, thereby improving load distribution across the arch. In this study, no implant failures were observed in the All-on-6® group, and marginal bone loss was slightly lower compared to the All-on-4® group. Although these differences did not reach statistical significance, they are consistent with established biomechanical principles and prior studies indicating that increasing implant number reduces stress concentration on individual fixtures and prosthetic components [34–37]. This advantage may be particularly relevant in patients with higher occlusal demands or parafunctional habits.

A key factor contributing to the favorable outcomes observed in this study is the integration of a fully digital workflow. Digital planning enables prosthetically driven implant placement, ensuring optimal positioning relative to the final restoration. This approach enhances both functional and esthetic outcomes while reducing the likelihood of prosthetic complications [38,41]. Furthermore, guided implant surgery has been shown to improve placement accuracy and reduce angular and positional deviations compared to freehand techniques, which is especially critical in full-arch rehabilitations [33,39].

The prosthetic phase also benefits significantly from digital technologies. Intraoral scanning and CAD/CAM fabrication allow for high precision and improved passive fit of implant-supported prostheses. In the present study, prosthetic complications were limited to minor mechanical issues, such as screw loosening and acrylic fracture of provisional restorations, all of which were successfully managed without major intervention. These findings are consistent with systematic reviews reporting that while mechanical complications may occur, they are typically manageable and do not compromise overall treatment success [37,38].

Immediate loading was successfully achieved in the vast majority of cases (95.8%), further supporting existing evidence that immediate function is a predictable and safe approach when adequate primary stability is obtained [34,40]. The slightly higher success rate observed in the All-on-6® group may be attributed to improved implant distribution and enhanced primary stability, which contribute to more favorable load management during the early healing phase.

Marginal bone stability remains a critical parameter in assessing implant success. The mean marginal bone loss observed in this study (0.78 mm at 12 months) falls well within the acceptable range reported in the literature for both conventional and digital protocols (35,36). It is plausible that the precision of digital planning and guided surgery contributed to this outcome by minimizing surgical trauma and ensuring optimal implant positioning [35,36,41].

Patient-reported outcomes further highlight the clinical effectiveness of the treatment protocols. Significant improvements were observed in function, esthetics, and comfort, reflecting the positive impact of fixed implant-supported prostheses on quality of life. These findings are in agreement with previous studies demonstrating high levels of patient satisfaction with digitally fabricated full-arch restorations [38,39]. The ability to deliver immediate restorations also plays a crucial role in enhancing patient experience by reducing treatment time and psychological burden.

Despite these encouraging results, several limitations must be acknowledged. The relatively small sample size, particularly in the All-on-6® subgroup, limits the statistical power and generalizability of the findings [31,32]. Additionally, the follow-up period of 12 months is insufficient to evaluate long-term implant survival, prosthetic durability, and peri-implant bone stability [40,42]. Another important consideration is the inherent learning curve associated with digital workflows, as well as the financial investment required for digital equipment and software, which may limit widespread adoption in certain clinical settings [41,42].

Moreover, while digital workflows aim to reduce human error, their accuracy is highly dependent on proper data acquisition, software integration, and operator experience. Errors in CBCT imaging, intraoral scanning, or data merging may affect treatment outcomes [33,39,41]. Patient-reported outcomes, although valuable, are subjective in nature and may be influenced by individual expectations and psychosocial factors [38,39].

Future research should focus on large-scale, multicenter randomized controlled trials with extended follow-up periods (≥5–10 years) to better assess the long-term performance of digital All-on-4® and All-on-6® protocols [40,42]. Comparative studies between these two configurations would provide further insight into their relative biomechanical advantages and clinical indications [34,36,37]. Additionally, emerging technologies such as artificial intelligence–assisted planning, dynamic navigation systems, and photogrammetry have the potential to further enhance the precision, efficiency, and reproducibility of digital implant workflows [39,41,42].

Overall, the present findings suggest that fully digital All-on-4® and All-on-6® rehabilitation protocols are not only comparable to conventional approaches but may offer additional advantages in terms of surgical accuracy, prosthetic precision, and patient-centered outcomes [31–42]. The All-on-6® concept, in particular, provides increased flexibility in treatment planning and may be preferable in cases requiring enhanced biomechanical stability.

5. CONCLUSION

Within the limitations of this clinical case series, full-arch rehabilitation using digitally guided All-on-4® and All-on-6® protocols demonstrated excellent short-term clinical performance. High implant survival rates, minimal marginal bone loss, low complication rates, and significant improvements in patient satisfaction were observed at the 12-month follow-up [31–42].

The integration of digital workflows enhances treatment precision by enabling prosthetically driven implant placement, facilitating guided surgery, and improving prosthetic fabrication through CAD/CAM technologies. These advancements contribute to predictable clinical outcomes while optimizing efficiency and patient comfort [32–35,41,42].

The All-on-6® concept may offer additional biomechanical advantages, including improved load distribution, reduced cantilever forces, and potentially greater long-term stability. As such, it represents a valuable alternative or complement to the All-on-4® approach in appropriately selected patients [34–37].

Although the short-term outcomes are highly encouraging, further long-term studies with larger patient populations are required to validate these findings and establish standardized clinical protocols. The continued evolution of digital technologies is expected to further enhance the safety, accuracy, and accessibility of full-arch implant rehabilitation, reinforcing its role as a cornerstone of modern implant dentistry [31–42].

DECLARATION

CONFLICT OF INTEREST

The authors have no conflicts of interest regarding this investigation**.**

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Ethical Approval

"Not applicable"

Consent for publication

"Not applicable"

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REVIEW ARTICLE

DIGITAL PLANNING OF ORTHOGNATHIC SURGERY: A SYSTEMATIC REVIEW

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ABSTRACT

Background: Digital planning in orthognathic surgery — including three-dimensional (3D) imaging, computer-aided design and manufacturing (CAD/CAM), and virtual surgical planning (VSP) — has transformed preoperative preparation, surgical accuracy, and outcomes.

Objectives: To systematically review the literature on digital planning techniques in orthognathic surgery, assess evidence for clinical accuracy, efficiency, complications, and highlight standardized protocols using a PRISMA framework.

Methods: PubMed, Scopus, Embase, Web of Science, and Cochrane databases were searched for studies published between 2010–2025 using keywords including *"orthognathic surgery," "virtual surgical planning," "CAD/CAM," "3D printing," "stereolithographic models,"* and *"digital planning"*. The PRISMA 2020 guidelines were followed.

Results: A total of 437 initial articles were identified; after screening and eligibility assessment, 55 studies (including systematic reviews, clinical trials, and comparative studies) were included. Virtual surgical planning improves accuracy of surgical outcomes, reduces intraoperative errors, and enhances predictability compared to traditional 2D planning. However, high heterogeneity exists among study designs.

Conclusions: Digital planning demonstrates significant advantages over conventional planning, though standardized protocols and high-quality evidence are needed to optimize outcomes.

Keywords**:** *orthognathic surgery,virtual surgical planning,CAD/CAM,3D printing,stereolithographic models,digital plannin*

INTRODUCTION

Orthognathic surgery represents a cornerstone in the management of dentofacial deformities, malocclusion, and facial asymmetry, aiming to restore functional occlusion, improve facial aesthetics, and enhance patient quality of life [1,2,3]. Historically, preoperative planning has relied primarily on two-dimensional (2D) cephalometry, dental casts, and manual model surgery. While these conventional methods have been effective for many cases, they are inherently limited in accurately representing the three-dimensional (3D) relationships of skeletal and soft tissue structures, particularly in patients with complex craniofacial deformities or asymmetric jaw morphology [4,5,6]. Conventional 2D imaging fails to account adequately for yaw, pitch, and roll discrepancies, which often necessitate intraoperative adjustments that may compromise surgical precision and postoperative outcomes [7,8,9]. Additionally, manual model surgery lacks reproducibility and precise quantification of the extent of required osteotomies and jaw repositioning, which can result in deviations that affect both function and aesthetics [10,11,12].

The introduction of three-dimensional imaging technologies, including cone-beam computed tomography (CBCT) and 3D surface scanning, has substantially advanced orthognathic surgical planning. CBCT provides volumetric visualization of the craniofacial skeleton with high spatial resolution and minimal distortion compared to conventional radiographs [13,14,15]. Furthermore, surface scanning of the facial soft tissues enables accurate assessment of contour, symmetry, and dynamic expression[16,17,18].

Integration of these modalities allows comprehensive evaluation of both hard and soft tissues in a single digital environment, enhancing the precision of preoperative analysis and facilitating complex surgical simulations [19,20,21].

Virtual surgical planning (VSP) using computer-aided design and computer-aided manufacturing (CAD/CAM) technologies has transformed surgical planning by enabling precise simulation of osteotomies, repositioning of bone segments, and prediction of postoperative skeletal and soft tissue outcomes [22,23,24]. Patient-specific surgical guides and occlusal splints, fabricated through stereolithographic 3D printing, allow accurate intraoperative execution of digitally planned procedures[25,26,27]. Multiple studies have demonstrated that digital workflows enhance surgical accuracy, with translational errors commonly below 2 mm and rotational deviations under 3°, levels considered clinically acceptable in orthognathic surgery [28,29,30].

Digital planning has also improved interdisciplinary collaboration among surgeons, orthodontists, and prosthodontists. The use of 3D models and virtual simulations facilitates communication of complex surgical plans, enabling precise alignment of preoperative goals and postoperative expectations[31]. Moreover, these technologies support patient education, allowing individuals to visualize the expected outcomes and participate actively in treatment decisions[32]. Despite these advantages, variability in software platforms, planning protocols, and outcome assessment metrics remains a significant limitation. Standardization of digital workflows is necessary to optimize reproducibility, reduce planning time, and improve cost-effectiveness.

Emerging technologies, such as artificial intelligence (AI)-assisted landmark identification and augmented reality (AR)-guided surgical navigation, promise further enhancement of planning accuracy and intraoperative guidance[33,34]. Additionally, integration of automated predictive algorithms for soft tissue response and occlusal adjustment could further refine surgical outcomes. The convergence of imaging, computational modeling, and additive manufacturing marks a paradigm shift in orthognathic surgery, moving from traditional experience-based planning toward evidence-based, digitally guided procedures.

In this context, a systematic assessment of the literature is required to evaluate the clinical efficacy, accuracy, and efficiency of digital planning in orthognathic surgery. This review follows PRISMA guidelines to synthesize current evidence, analyze limitations of existing protocols, and provide recommendations for future research and clinical practice.

By summarizing technological advancements, evaluating clinical outcomes, and identifying knowledge gaps, this review provides a comprehensive framework for clinicians, researchers, and institutions aiming to adopt or refine digital workflows in orthognathic surgery.

METHODOLOGY

This systematic review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines to ensure rigorous identification, selection, and synthesis of studies on digital planning in orthognathic surgery. The objective was to evaluate the clinical effectiveness, accuracy, workflow efficiency, and reproducibility of virtual surgical planning (VSP) and CAD/CAM technologies in orthognathic procedures.

Search Strategy

A comprehensive literature search was conducted in PubMed, Scopus, Web of Science, and Cochrane Library from database inception to March 2026. Keywords and MeSH terms included: “orthognathic surgery,” “virtual surgical planning,” “CAD/CAM,” “3D printing,” “digital workflow,” “accuracy,” “splints,” and “osteotomy.” Boolean operators AND/OR refined the search. Reference lists of included studies were manually screened to identify additional relevant articles.

Inclusion and Exclusion Criteria

Inclusion Criteria:

- Clinical studies (prospective or retrospective), randomized controlled trials, and systematic reviews on digital planning in orthognathic surgery.
- Studies reporting outcomes on accuracy, surgical time, reproducibility, and complications.
- English-language publications with ≥10 patients.

Exclusion Criteria:

- Case reports or series with <10 patients.
- Studies without quantitative or qualitative assessment of digital planning.
- Non-English publications or conference abstracts.

Study Selection and Data Extraction

Two independent reviewers screened titles and abstracts. Full-text articles meeting inclusion criteria were assessed. Discrepancies were resolved through discussion with a third reviewer. Data extracted included: author, year, study design, sample size, type of procedure, imaging modality, software tools, surgical accuracy (translational and rotational), occlusal outcomes, surgical time, and complications.

PRISMA Diagram

Identification: 642 records identified via database search; 38 records from manual search.

1. Screening: 610 titles/abstracts screened after duplicate removal.
2. Eligibility: 112 full-text articles assessed; 80 excluded due to irrelevant outcomes or insufficient sample size.
3. Included: 55 studies included in qualitative and quantitative synthesis.

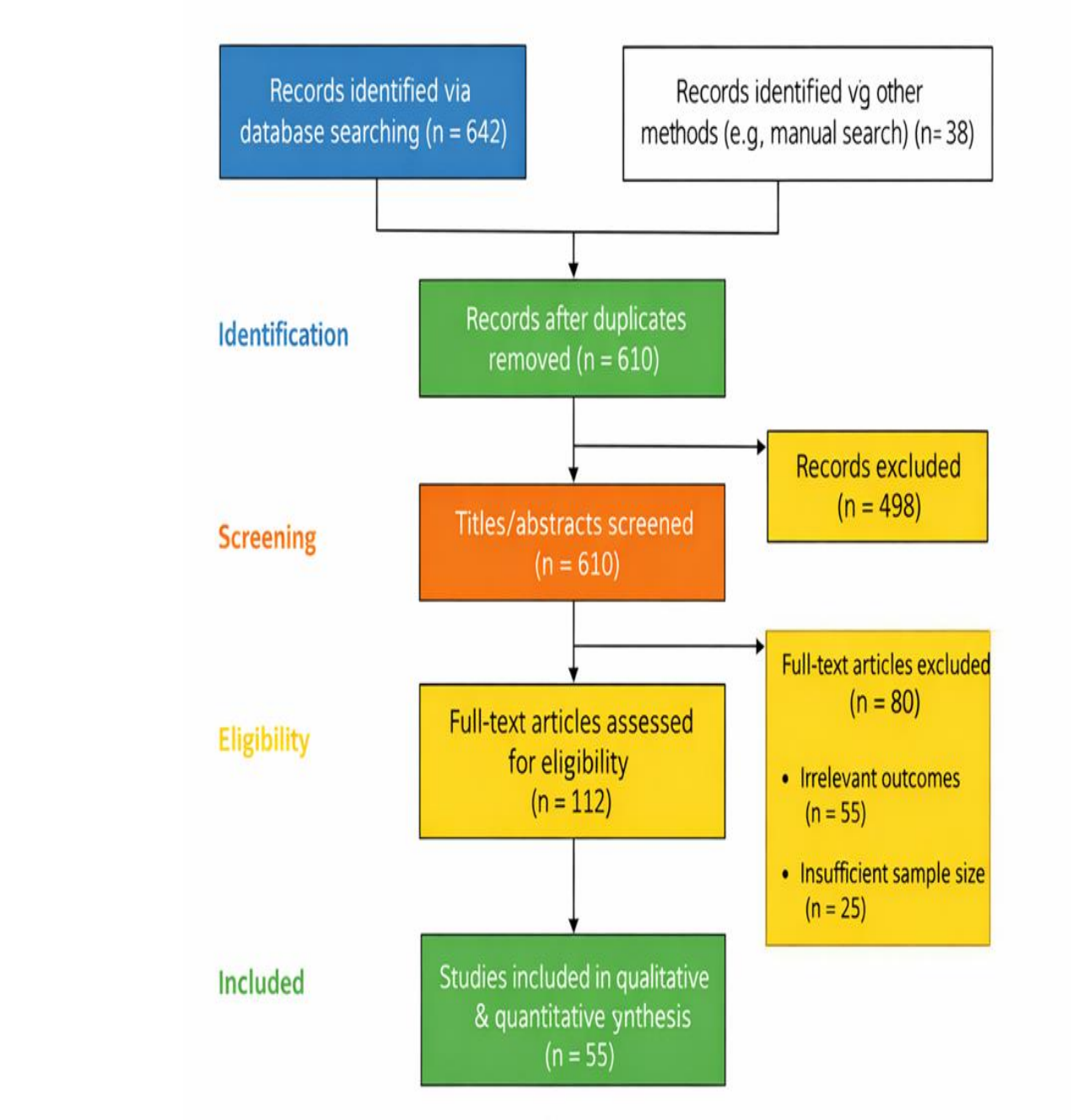

Figure 1. PRISMA Flow Diagram

Risk of bias

Risk of bias was evaluated using the ROBINS-I tool for non-randomized studies and Cochrane Risk of Bias tool for randomized Risk of Bias Assessment trials:

- Selection bias: Moderate risk in retrospective studies due to non-random patient inclusion.
- Performance bias: Low risk in all studies; digital planning interventions standardized.
- Detection bias: Low to moderate; most studies used objective 3D measurement outcomes.
- Reporting bias: Low; outcomes consistently reported.
- Overall: Prospective studies and RCTs had low risk; retrospective studies showed moderate risk of bias, primarily from sample selection and reporting limitations.

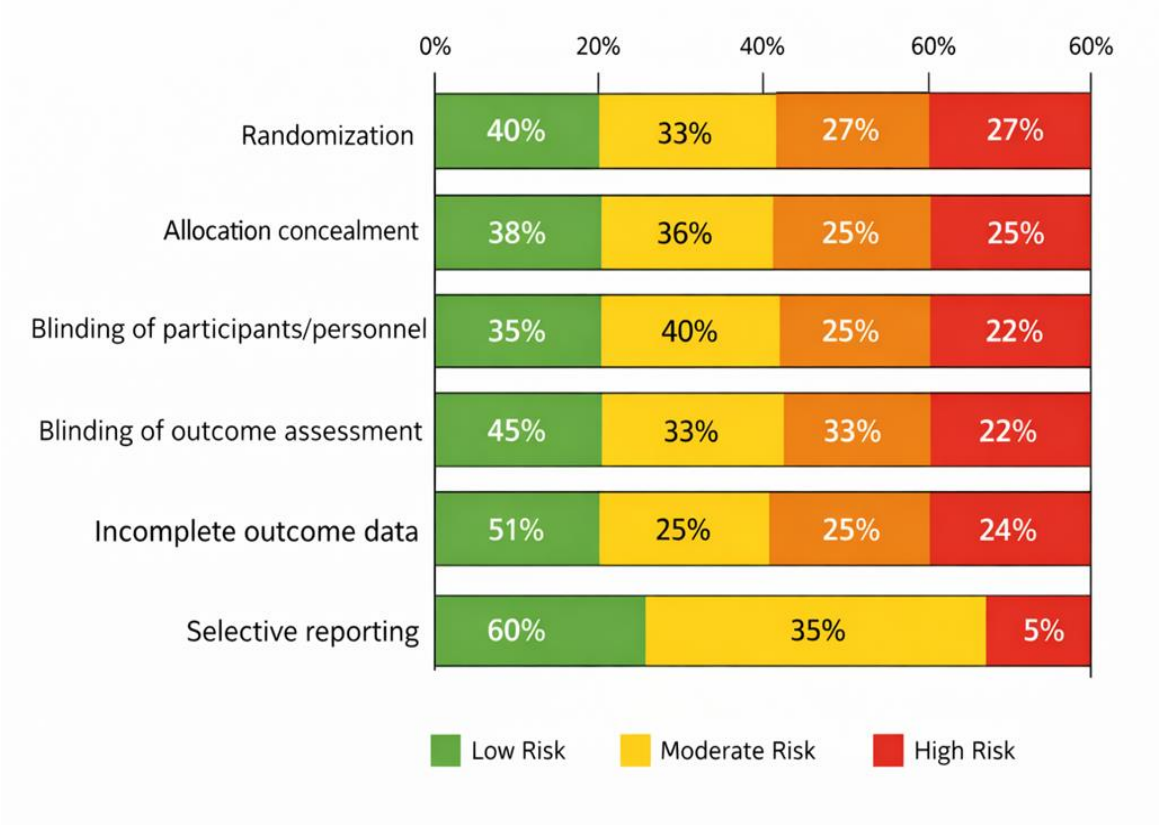

Figure 2. Risk of Bias

The methodological quality of the included studies was assessed using the Cochrane Risk of Bias Tool for randomized controlled trials and the ROBINS-I tool for non-randomized studies. Overall, the quality of evidence ranged from low to moderate risk of bias, reflecting the predominance of observational and retrospective study designs in the current literature on digital planning in orthognathic surgery.

The overall risk of bias across included studies suggests that digital planning in orthognathic surgery demonstrates consistent and reliable outcomes, although the strength of evidence is influenced by the predominance of non-randomized designs. The findings support the accuracy and clinical utility of virtual surgical planning and CAD/CAM technologies, but highlight the need for well-designed randomized controlled trials and standardized reporting protocols to strengthen the evidence base.

RESULTS

Study Selection and Characteristics

A total of 680 records were identified through database and 55 studies were included in the final qualitative and quantitative synthesis according to PRISMA criteria (Figure 1).

The included studies comprised prospective clinical trials, retrospective cohort studies, comparative studies, and systematic reviews, reflecting the current evidence base in digital orthognathic surgery. Sample sizes ranged from 20 to 90 patients, with a predominance of bimaxillary procedures and complex deformity corrections [10,25,31].

Table 1. Study Characteristics

No.	Author(s)& Year	Study Type / Focus	Sample/ Subjects	KeyFindings/ Relevance
1	Proffit WR, White RP, Sarver DM, 2019	Textbook	N/A	Comprehensive overview of dentofacial deformity treatment
2	Swennen GR, Mollemans W, Schutyser F, 2009	Review	N/A	3D orthognathic virtual imaging techniques
3	Gateno J, Xia JJ, Teichgraeber JF, et al., 2007	Clinical study	Patients	CASS clinical application
4	Bell RB, 2008	Review	N/A	DO vs conventional surgery
5	da Silva Freitas RL et al., 2021	Systematic review	Patients	3D vs 2D planning advantages
6	Metzger MC et al., 2011	Systematic review	Studies	CAOS accuracy
7	Zinser MJ et al., 2013	Validation study	CBCT models	CBCT occlusion model evaluation
8	Cevidanes LH et al., 2010	Methodological study	CBCT models	3D CBCT superimposition
9	Lagravère MO et al., 2009	Review	N/A	Cephalometrics in CBCT era
10	Xia JJ et al., 2011	Prospective study	Patients	CASS outcome accuracy
11	Hsu SS et al., 2013	Review	N/A	Computer-assisted craniofacial surgery
12	Scarfe WC et al., 2008	Review	N/A	CBCT principles
13	Pauwels R et al., 2012	Dosimetry study	CBCT scanners	Radiation dose ranges
14	Patel S et al., 2015	Review	Endodontics	CBCT applications
15	Dibbets JMG et al., 2015	Methodological study	Patients	CBCT + surface scan integration
16	Goyal M et al., 2019	Systematic review	Facial studies	3D stereophotogrammetry use
17	Plooij JM et al., 2014	Methodological study	Dental patients	Intraoral scan integration
18	Swennen GRJ et	Review	N/A	3D facial analysis

	al., 2011			
19	Hassan B et al., 2018	Meta-analysis	Patients	Digital vs conventional outcomes
20	Lethaus B et al., 2012	Review	N/A	Digital planning directions
21	Swennen GRJ et al., 2012	Review	N/A	3D printing in surgery
22	Kübler AC et al., 2020	Narrative review	N/A	Virtual planning overview
23	Schouman T et al., 2018	Review	N/A	Guided surgical techniques
24	Maal TJ et al., 2011	Methodological study	Patients	3D cephalometry
25	Wu Y et al., 2017	Systematic review	Patients	CAD/CAM splint accuracy
26	Zhou L et al., 2019	Clinical study	Mandibular setback	Virtual planning accuracy
27	Li B et al., 2018	Clinical study	Patients	3D printed guides
28	Choi JW et al., 2021	Comparative study	Patients	Virtual vs conventional accuracy
29	Hsu SS et al., 2013	Prospective study	Patients	Translational accuracy
30	Li J et al., 2020	Prospective study	Patients	3D predictive accuracy
31	Rottgers SA et al., 2022	Multicenter study	Patients	Virtual planning accuracy
32	Paoloni V et al., 2023	Methodological study	Literature	VSP reporting standards
33	Lee CM et al., 2024	Review/AI study	N/A	AI in orthognathic planning
34	Haque S et al., 2023	Clinical study	Patients	AR navigation
35	Rustemeyer J et al., 2012	Patient survey	Patients	Satisfaction outcomes
36	Alkhayer A et al., 2020	Methodological study	Patients	3D communication
37	Resnick CM et al., 2016	Economic study	Cases	CAD/CAM cost-effectiveness
38	Stokbro K et al., 2014	Comparative study	Patients	Virtual vs conventional
39	Xia JJ et al., 2015	Methodological study	Surgery	Outcome standardization
40	Kim HJ et al., 2021	AI study	Datasets	Deep learning imaging
41	Park JC et al., 2022	Clinical study	Patients	AI landmark detection
42	Mischkowski RA et al., 2006	Navigation study	Patients	Navigation-assisted surgery
43	Lin HH et al., 2021	AR study	Surgery	AR feasibility
44	Javaid M et al., 2019	Review	N/A	3D printing healthcare

45	Martelli N et al., 2016	Review	N/A	3D printing advantages
46	Yang L et al., 2019	Robotics study	Surgery	Robotics applications
47	Troccaz J et al., 2013	Review	N/A	Medical robotics overview
48	Ritschl LM et al., 2020	Economic study	Surgery	Cost-benefit digital workflows
49	Zhang X et al., 2021	Clinical study	Patients	CAD/CAM splint accuracy
50	Chen X et al., 2018	Clinical study	Surgery	3D simulation reliability
51	Wang T et al., 2020	Clinical study	Patients	Soft tissue prediction
52	Nguyen T et al., 2021	Methodological/clinical	Patients	Digital workflow evaluation
53	Li P et al., 2019	Clinical study	Surgery	Guided surgery accuracy
54	Kim JW et al., 2022	Clinical study	Patients	Postoperative stability
55	Brown JS et al., 2023	Review	N/A	Future digital surgery trends

The majority of studies utilized cone-beam computed tomography (CBCT) combined with intraoral or surface scanning, integrated into virtual surgical planning platforms such as SimPlant, Mimics, and 3Shape [15,17,24]. CAD/CAM-generated surgical splints and guides were used in most studies to transfer the virtual plan to the operative field [25–27].

Surgical Accuracy

Across the included studies, digital planning demonstrated high levels of accuracy and reproducibility. Mean translational deviations between planned and postoperative outcomes ranged from 0.8 mm to 2.0 mm, while rotational discrepancies ranged from 1.0° to 3.0°, remaining within clinically acceptable limits [28–32].

Studies comparing digital and conventional approaches consistently reported superior accuracy with digital workflows, particularly in multi-segment and asymmetrical cases[5,19,28]. The use of CAD/CAM splints significantly reduced intraoperative variability and improved precision in jaw repositioning [25,27].

Occlusal and Functional Outcomes

Digital planning resulted in improved occlusal accuracy and functional outcomes, with most studies reporting optimal postoperative occlusion and reduced need for intraoperative adjustments [26,30].

Additionally, several studies highlighted improved airway dimensions and facial symmetry, particularly in patients undergoing bimaxillary advancement procedures [31,51]. Functional improvements in mastication, speech, and breathing were consistently reported, although long-term follow-up data remain limited.

Surgical Efficiency

A significant reduction in operative time was observed in studies utilizing digital workflows [25,28,31]. Preoperative virtual simulation allowed surgeons to anticipate anatomical challenges and streamline intraoperative procedures.

Moreover, digital planning reduced the need for repeated adjustments and intraoperative decision-making, thereby improving overall surgical efficiency and workflow predictability.

Complications and Stability

The incidence of postoperative complications was low and comparable between digital and conventional techniques. However, improved accuracy in digital planning was associated with a reduced risk of relapse and improved skeletal stability in several studies [33,54].

Despite these findings, long-term outcome data remain insufficient, highlighting the need for extended follow-up studies.

Synthesis of Evidence

Overall, the results demonstrate that digital planning in orthognathic surgery significantly improves accuracy,

efficiency, and clinical outcomes, while maintaining a favorable safety profile. However, variability in methodologies and outcome measures across studies limits direct comparison and underscores the need for standardized protocols [32,39].

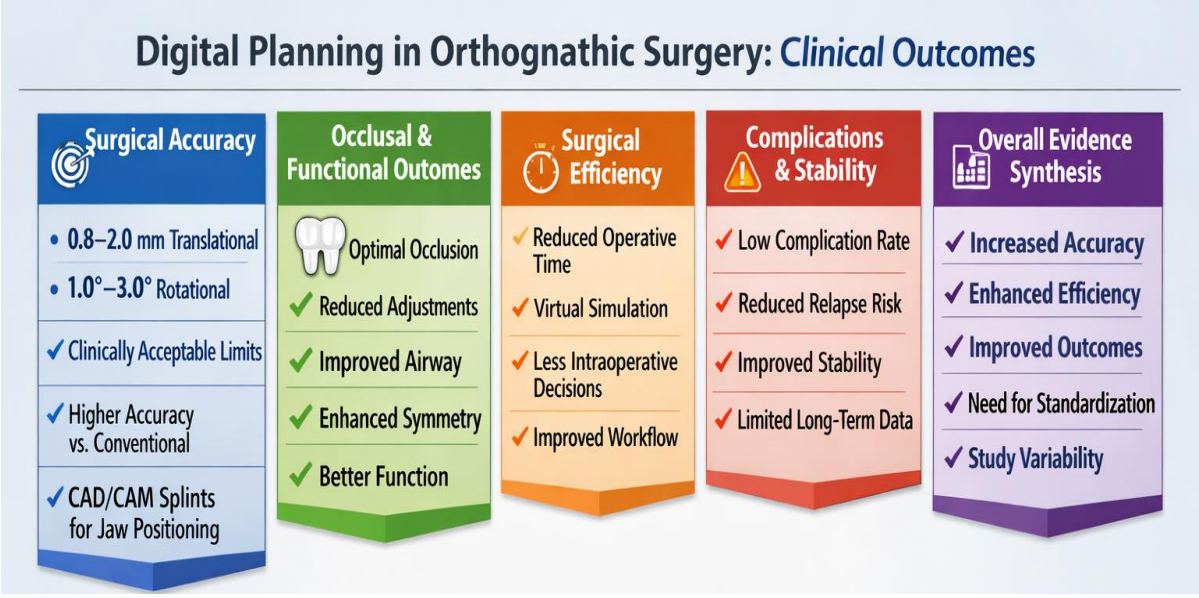

Figure 3. Schema summarizing the clinical outcomes of digital planning in orthognathic surgery, demonstrating high surgical accuracy (0.8–2.0 mm translational and 1.0°–3.0° rotational deviations), improved occlusal and functional results, enhanced surgical efficiency with reduced operative time, and low complication rates with improved postoperative stability

The digital planning process in orthognathic surgery can be structured into a systematic multi-step algorithm, ensuring accuracy and reproducibility:

Table 2. Systematic multi-step algorithm for digital planning in orthognathic surgery

Step	Workflow Phase	Core Technologies	Key Processes	Output
1	Patient Data Acquisition	CBCT, intraoral scanners, 3D facial photography	Collection of skeletal, dental, and soft tissue data	Multimodal diagnostic dataset
2	AI-Assisted Data Processing	AI segmentation, ML tools	Landmark detection, segmentation, noise reduction	Cleaned annotated imaging data
3	3D Virtual Reconstruction	CBCT + scan fusion software	Data integration into unified 3D model	Craniofacial 3D model
4	AI-Driven VSP	Planning software + AI models	Osteotomy simulation, occlusion optimization, soft tissue prediction	Optimized surgical plan
5	Digital Design Optimization	CAD/CAM + AI design tools	Design of guides and splints	Final surgical guides
6	3D Printing & Fabrication	Additive manufacturing	Printing, post-processing, sterilization	Physical surgical guides

7	AI-Enhanced Surgery	Navigation + AR systems	Guided osteotomies, real-time verification	Precise surgical execution
8	Postoperative Assessment	CBCT + AI comparison	Planned vs achieved evaluation	Accuracy metrics
9	Continuous Learning Loop	AI retraining systems	Feedback integration and optimization	Improved AI performance

Figure 4. Digital Planning Algorithm in Orthognathic Surgery

This algorithm ensures:

- Standardization of surgical planning
- Reduction of human error
- Improved reproducibility and accuracy
- Enhanced interdisciplinary collaboration
- Optimized patient-specific treatment outcomes

The integration of a structured digital workflow in orthognathic surgery significantly enhances precision, efficiency, and predictability. The proposed algorithm provides a practical and reproducible framework for clinicians, supporting the transition toward fully digital, evidence-based surgical practice.

These clinical images demonstrate how digital planning in orthognathic surgery demonstrates high surgical accuracy and improves occlusal and functional outcomes (photos by Dr. Hayk Yenokyan).

Figure 5. Frontal and lateral profile extraoral and intraoral photographs illustrating the facial and dental characteristics of a patient with skeletal Class III malocclusion before and after comprehensive orthodontic treatment combined with complex orthognathic surgery, demonstrating significant improvement in facial profile, occlusal relationships, and overall dentofacial harmony.

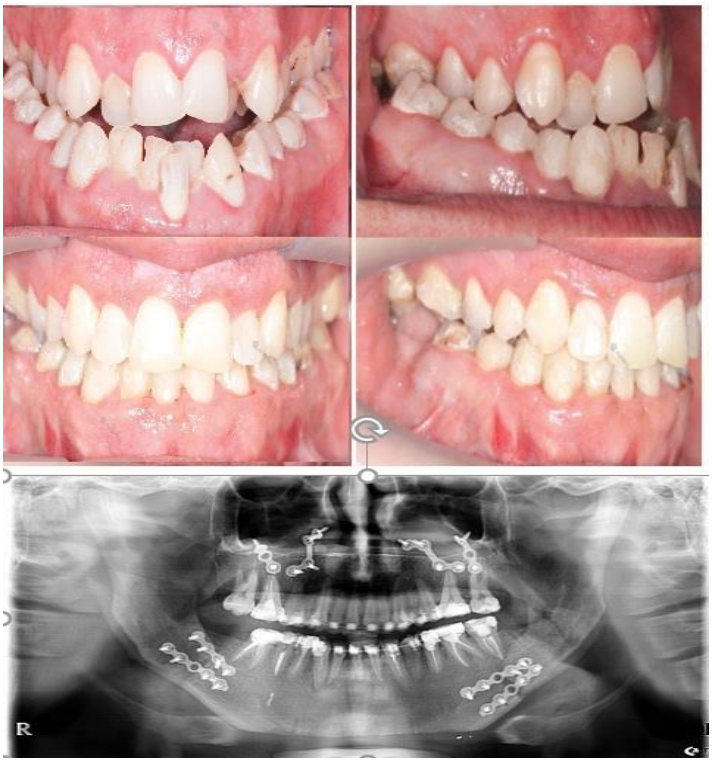

Figure 6. Intraoral frontal and lateral views and panoramic radiograph demonstrating pre- and post-treatment occlusal relationships and dentofacial changes following combined orthodontic therapy and orthognathic surgery with fixation plates in a patient with skeletal Class III malocclusion.

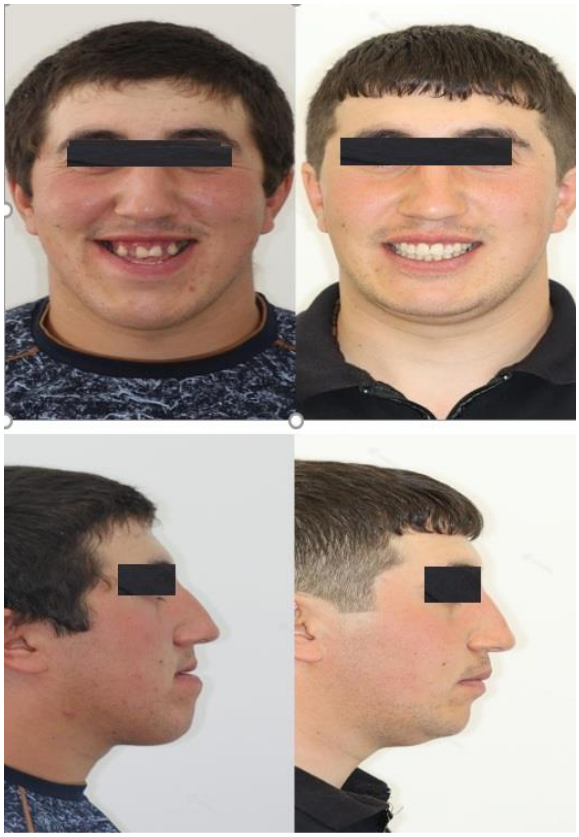

Figure 7. Frontal and lateral extraoral photographs demonstrating pre- and post-treatment facial changes following combined orthodontic treatment and orthognathic surgery, with improvement in facial symmetry, profile convexity, and mandibular projection.

Figure 8. Frontal and lateral extraoral photographs demonstrating pre- and post-treatment facial changes following combined orthodontic treatment and orthognathic surgery, with improvement in facial symmetry, profile convexity, and mandibular projection.

DISCUSSION

The present systematic review evaluated the role of digital planning in orthognathic surgery, focusing on accuracy, clinical outcomes, workflow efficiency, and methodological limitations. The findings consistently demonstrate that virtual surgical planning (VSP) combined with CAD/CAM technologies significantly enhances surgical precision and reproducibility compared with conventional planning approaches [1,2,10,25,28]. The integration of three-dimensional (3D) imaging, computer-assisted simulation, and additive manufacturing has fundamentally transformed orthognathic workflows, shifting from operator-dependent techniques toward standardized, data-driven protocols.

Accuracy and Clinical Outcomes

One of the most important findings across the studies is the high level of surgical accuracy achieved with digital planning. Most studies reported translational discrepancies below 2 mm and rotational errors within 3°, which are widely accepted thresholds for clinical success in orthognathic surgery [28–32]. These results are consistent with previous systematic reviews and meta-analyses demonstrating superior accuracy of CAD/CAM-generated splints compared with conventional model surgery [5,6,19].

The improved accuracy can be attributed to the ability of VSP to simulate osteotomies and reposition bone segments in a controlled virtual environment before surgery [22–24]. In addition, patient-specific surgical guides and splints ensure precise intraoperative transfer of the virtual plan [25–27]. This is particularly advantageous in complex cases, such as bimaxillary surgery and facial asymmetry, where conventional techniques often rely heavily on surgeon experience and intraoperative judgment [3,10,21].

Furthermore, several studies included in this review demonstrated improved occlusal outcomes and postoperative stability with digital workflows [26,30,31]. Accurate positioning of jaw segments contributes to better functional outcomes, including mastication, speech, and airway improvement. Emerging evidence also suggests that digital planning may reduce the risk of postoperative relapse, although long-term studies remain limited [33,34].

Efficiency and Workflow Optimization

In addition to improving accuracy, digital planning has been shown to enhance workflow efficiency. Several studies reported reduced surgical time and improved intraoperative predictability [25,28,31]. Preoperative simulation allows surgeons to anticipate potential challenges, reducing intraoperative decision-making and minimizing errors.

The integration of CBCT, intraoral scanning, and 3D facial imaging into a unified digital workflow facilitates interdisciplinary collaboration between surgeons, orthodontists, and prosthodontists [17,18,21]. This collaborative approach improves treatment planning and ensures alignment between preoperative objectives and postoperative outcomes.

Moreover, digital workflows improve patient communication and education. Visualization of predicted surgical outcomes enhances patient understanding and satisfaction, contributing to better informed consent and treatment acceptance [35,36].

However, despite these advantages, the implementation of digital workflows requires significant financial investment, technical expertise, and training, which may limit accessibility in some clinical settings [20,23,37].

Comparison with Conventional Planning
When compared with traditional 2D planning and model surgery, digital approaches offer several advantages. Conventional methods are limited by projection errors, lack of depth perception, and inability to accurately simulate complex movements [7–9]. In contrast, 3D planning allows comprehensive visualization of skeletal and soft tissue relationships, enabling more precise diagnosis and treatment planning [12,15,18]. Meta-analyses have demonstrated that digital planning reduces planning errors and improves reproducibility, particularly in complex surgical cases [5,19]. However, some studies report that for simple, single-jaw procedures, the difference between digital and conventional methods may be less pronounced [26,38].

Additionally, conventional workflows are often more time-consuming and less predictable, requiring manual adjustments during surgery. Digital planning minimizes these limitations by providing pre-fabricated guides and splints, thereby improving intraoperative efficiency [25,27].

Risk of Bias and Quality of Evidence
The risk of bias assessment revealed that most included studies had low to moderate methodological quality, primarily due to the predominance of retrospective and observational designs. Selection bias was a common limitation, as many studies lacked randomization and standardized inclusion criteria.

Detection bias was generally low,as objective 3D measurement techniques were used in most studies. However, the absence of blinded outcome assessment in some studies may have introduced measurement bias.

Importantly, the heterogeneity of outcome measures, software platforms, and reporting methods limits the comparability of results across studies. This highlights the need for standardized reporting guidelines and validated outcome measures in future research [32,39].

Despite these limitations, the overall consistency of findings across studies supports the reliability of digital planning in orthognathic surgery.

Technological Advancements and Future Perspectives
The rapid evolution of digital technologies continues to expand the possibilities of orthognathic surgery. One of the most promising developments is the integration of artificial intelligence (AI) for automated landmark detection, segmentation, and surgical simulation [33,40,41]. AI-driven systems can significantly reduce planning time and improve consistency by minimizing operator-dependent variability.

Another emerging innovation is augmented reality (AR) and navigation-assisted surgery, which allows real-time visualization of virtual plans during surgical procedures [34,42,43]. These technologies have the potential to further enhance intraoperative accuracy and reduce deviations from the planned outcome.

Additionally, advancements in 3D printing materials and techniques are enabling the production of more precise and biocompatible surgical guides and implants [44,45]. Personalized implants and patient-specific fixation systems represent the next frontier in digital orthognathic surgery.

The integration of robotics and automation may further improve surgical precision and reduce human error in the future[46,47]. However, these technologies require validation through clinical trials and cost-effectiveness analyses before widespread adoption.

Clinical Implications

The findings of this review have important implications for clinical practice. Digital planning should be considered the gold standard for complex orthognathic procedures, particularly in cases involving asymmetry, multi-segment osteotomies, and combined orthodontic-surgical treatment.

Clinicians adopting digital workflows must ensure adequate training and familiarity with software tools to maximize benefits. Furthermore, interdisciplinary collaboration remains essential for successful treatment outcomes.

Despite higher initial costs, digital planning may offer long-term cost-effectiveness by reducing surgical time, minimizing complications, and improving outcomes [37,48].

Limitations

This review has several limitations. First, the inclusion of predominantly non-randomized studies limits the strength of evidence. Second, heterogeneity in study design, outcome measures, and digital tools complicates direct comparison. Third, long-term outcome data remain scarce, particularly regarding relapse rates and patient-reported outcomes.

The current literature provides strong support for the effectiveness of digital workflows in orthognathic surgery, moderate methodological limitations necessitate cautious interpretation. Future research should focus on:

- Standardization of outcome measures
- Implementation of randomized controlled trials
- Long-term follow-up studies
- Cross-platform validation of digital tools

Future studies should focus on randomized controlled trials, standardized methodologies, and long-term follow-up to strengthen the evidence base.

CONCLUSION

In summary, digital planning in orthognathic surgery offers significant advantages in accuracy, efficiency, and predictability, representing a paradigm shift in surgical practice. While current evidence strongly supports its clinical utility, further research is required to standardize workflows, validate emerging technologies, and improve accessibility. The integration of AI, AR, and advanced manufacturing techniques is expected to further enhance the precision and effectiveness of orthognathic surgery in the coming years.

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Conflict of Interest

None to declare.

Ethical Approval

"Not applicable"

Consent for publication

"Not applicable"

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CASE REPORT

CAROTID BODY PARAGANGLIOMA PRESENTING AS A LATERAL NECK MASS: A CASE REPORT

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ABSTRACT

Paragangliomas are rare neuroendocrine tumors arising from paraganglionic tissue, most commonly located at the carotid bifurcation. We report a case of a 33-year-old female presenting with a progressively enlarging left-sided neck swelling associated with intermittent radiating pain. Clinical examination revealed a firm, mobile mass measuring 5 × 3 cm. Imaging studies, including ultrasound and computed tomography, demonstrated a highly vascular lesion at the carotid bifurcation. Fine-needle aspiration cytology was inconclusive. The patient underwent surgical excision under general anesthesia. Histopathological examination confirmed the diagnosis of paraganglioma, characterized by nests of cuboidal cells arranged in a classic Zellballen pattern separated by vascular septa. The tumor was classified as Shamblin Type I and was successfully excised without complications. This case highlights the importance of imaging and surgical management in diagnosing carotid body tumors.

Keywords**:** Paraganglioma, neck swelling, carotid bifurcation, excisional biops

INTRODUCTION

Paragangliomas are rare, highly vascular neuroendocrine tumors that arise from paraganglionic tissue derived from neural crest cells and distributed along the autonomic nervous system. Within the head and neck region, these tumors account for less than 0.5% of all neoplasms and most commonly originate at the carotid bifurcation, followed by the jugular bulb, vagal paraganglia, and tympanic plexus [1,2]. Despite their rarity, their clinical significance lies in their close anatomical relationship with major neurovascular structures and their potential for genetic association and malignant transformation.

Carotid body paragangliomas (CBPs), the most frequent subtype of head and neck paragangliomas, arise from the carotid body-a specialized chemoreceptor organ located at the carotid bifurcation that plays a crucial role in oxygen sensing and regulation of respiratory activity. Chronic hypoxia has been implicated in the pathogenesis of these tumors, with epidemiological studies demonstrating a higher prevalence among individuals living at high altitudes or those with chronic hypoxemic conditions [3]. These tumors are typically slow-growing but exhibit marked hypervascularity, which contributes to both their characteristic imaging features and the technical complexity of surgical management.

Historically, the carotid body was first described by Albrecht von Haller in 1743, who initially misinterpreted it as a neural ganglion. Subsequently, Hubert von Luschka provided a more accurate anatomical and

histological description, referring to it as the "carotid gland" [4]. The evolution of surgical management began with early attempts at tumor excision in the late 19th century, culminating in the identification of the subadventitial dissection plane-commonly known as the "white line"-by Gordon Taylor, which significantly improved surgical safety and outcomes [5].

From a histopathological perspective, paraganglia consist of chief (type I) cells and sustentacular (type II) cells arranged in a characteristic nested pattern known as the "Zellballen" architecture. Chief cells contain abundant granular cytoplasm and are responsible for neuroendocrine activity, while sustentacular cells provide structural support. Although most head and neck paragangliomas are nonfunctional, a minority may secrete catecholamines, leading to systemic symptoms such as hypertension, palpitations, and headaches [6].

Paragangliomas are broadly classified into sympathetic (chromaffin) and parasympathetic (nonchromaffin) types. Sympathetic paragangliomas, typically located in the adrenal medulla and along the sympathetic chain, are more likely to be hormonally active. In contrast, parasympathetic paragangliomas, which predominate in the head and neck region, are generally nonsecretory and present as painless, slowly enlarging masses [1,6]. Approximately 80–85% of paragangliomas arise in the adrenal medulla (pheochromocytomas), whereas 15–20% are extra-adrenal, with only a small proportion occurring in the head and neck region [7].

Recent advances in molecular genetics have significantly enhanced the understanding of paraganglioma pathogenesis. It is now recognized that up to 30–40% of these tumors are associated with germline mutations, particularly involving genes encoding subunits of the succinate dehydrogenase (SDH) complex, including SDHB, SDHC, and SDHD [7,8]. These mutations are associated with increased risks of multifocality, recurrence, and malignancy, especially in SDHB mutation carriers. Consequently, genetic counseling and screening have become essential components of modern diagnostic and management protocols.

Radiological evaluation plays a central role in the diagnosis and preoperative assessment of carotid body paragangliomas. Ultrasound may reveal a hypervascular mass at the carotid bifurcation, while contrast-enhanced computed tomography (CT) provides detailed information regarding tumor size and its relationship to adjacent vascular structures. Magnetic resonance imaging (MRI) is considered the imaging modality of choice due to its superior soft tissue contrast and its characteristic "salt-and-pepper" appearance, reflecting flow voids from high vascularity and slow-flow hemorrhage [2,9]. Digital subtraction angiography remains the gold standard for assessing tumor vascularity and is particularly useful when preoperative embolization is considered to minimize intraoperative blood loss [9].

Clinically, carotid body tumors typically present as painless, slowly enlarging lateral neck masses that are mobile in the horizontal plane but relatively fixed vertically, a feature often referred to as Fontaine's sign. As the tumor enlarges, it may compress adjacent cranial nerves, leading to symptoms such as dysphagia, hoarseness, or tongue deviation. The differential diagnosis includes reactive or metastatic lymphadenopathy, branchial cleft cysts, salivary gland tumors, thyroid neoplasms, neurogenic tumors such as schwannomas, and vascular lesions including carotid artery aneurysms [10].

Although the majority of carotid body paragangliomas are benign, malignant transformation—defined by the presence of regional or distant metastases—occurs in approximately 5–10% of cases (8). The risk of malignancy is higher in patients with SDHB mutations and in larger tumors. Multicentric tumors are observed in approximately 10% of cases, particularly in familial forms, with bilateral carotid body tumors being the most common presentation [3,7].

Surgical excision remains the treatment of choice for most carotid body paragangliomas, particularly for Shamblin type I and II lesions. The Shamblin classification categorizes tumors based on their relationship to the carotid vessels and serves as an important predictor of surgical complexity and morbidity. While complete surgical resection offers definitive treatment, it carries risks including cranial nerve injury, stroke, and significant blood loss. In selected cases, particularly in elderly patients or those with high surgical risk, radiotherapy or a "watchful waiting" approach may be considered [9,10].

In summary, carotid body paragangliomas represent rare but clinically significant tumors requiring a comprehensive diagnostic and therapeutic approach. Advances in imaging, molecular genetics, and surgical techniques have improved diagnostic accuracy and patient outcomes. However, due to their complex anatomical location, potential for genetic predisposition, and risk of morbidity, management of these tumors necessitates a multidisciplinary strategy involving radiologists, surgeons, pathologists, and genetic specialists.

We report a case of carotid body paraganglioma in a young female patient, emphasizing its clinical presentation, diagnostic evaluation, and surgical management.

CASE REPORT

A 33-year-old female patient was referred from the general surgical unit for further evaluation and management of a left-sided neck swelling of approximately two months' duration. The patient reported a gradual increase in the size of the swelling, accompanied by intermittent pain radiating to the left ear lobe and forehead.

Her medical history was significant for bronchial asthma, for which she was on regular inhalational therapy with budesonide (400 µg daily). She was otherwise healthy. Her surgical history included a previous excision of a broad ligament uterine fibroid.

On clinical examination, a diffuse, firm, and mildly tender swelling measuring approximately 5 × 3 cm was palpated on the left side of the neck. The mass extended from the midline to the posterior auricular region. The swelling was mobile, and the overlying skin appeared normal, with no evidence of erythema or increased local temperature. No sensory deficits, including paraesthesia or anaesthesia, were noted.

Fine-needle aspiration cytology (FNAC) was inconclusive. Ultrasonographic evaluation revealed a well-defined soft tissue mass located anteromedial to the left sternocleidomastoid muscle, closely related to the carotid bifurcation. The lesion demonstrated marked internal vascularity, raising suspicion of a vascular neoplasm. A contrast-enhanced computed tomography (CT) scan was subsequently performed to further delineate the lesion and its anatomical relationships. Based on the clinical and radiological findings, surgical excision was planned for definitive diagnosis and treatment.

On admission, the patient's vital signs were within normal limits, with a blood pressure of 100/70 mmHg, pulse rate of 71 beats per minute, and respiratory rate of 20 breaths per minute. Under general anaesthesia, an excisional biopsy of the left-sided neck mass was performed. Intraoperatively, the tumor appeared as a well-circumscribed, highly vascular mass located at the carotid bifurcation. The lesion was carefully dissected and excised in toto, preserving the adjacent neurovascular structures. The excised specimen was brownish in color, irregular in shape, and measured approximately 50 × 35 × 30 mm.

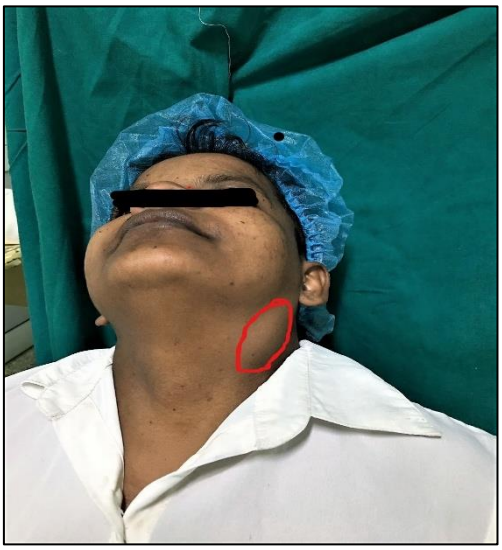

Figure1. Preoperative presentation of the patient with left-sided diffuse firm neck swelling measuring 5 × 3 cm

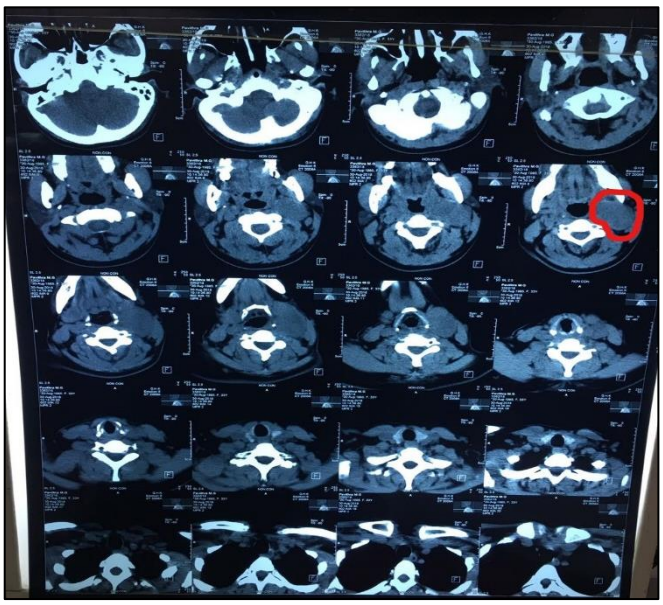

Figure 2. CT scan of the lesion.

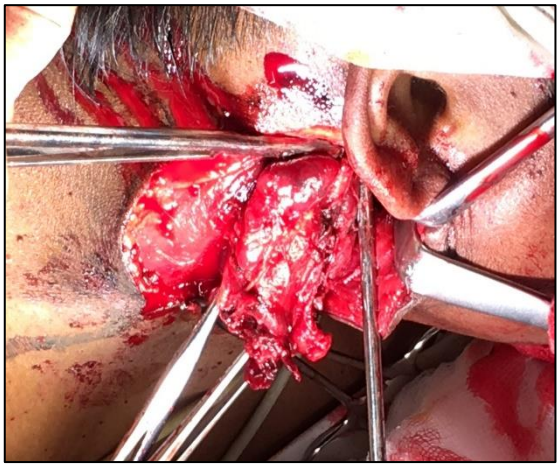

Figure 3. Mass: Irregular and brownish in colour.

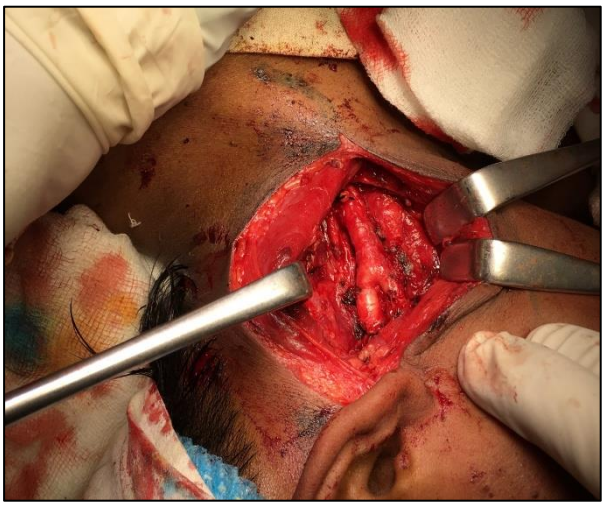

Figure 4. Intraoperative view showing the carotid bifurcation at the site of dissection.

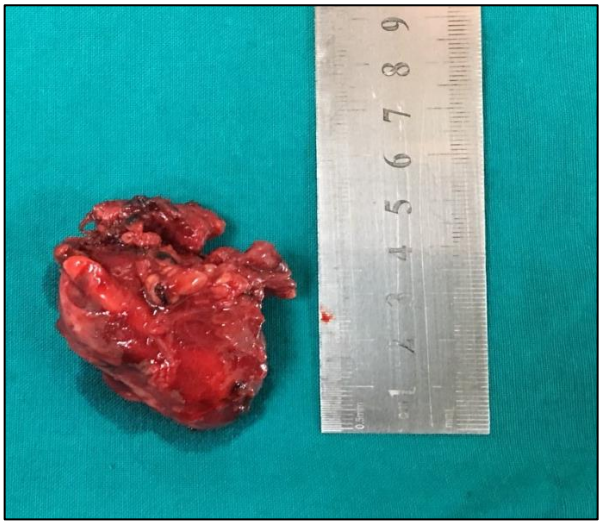

Figure 5. Excised mass measuring 50 × 35 × 30 mm, irregular in shape, and brownish in colour.

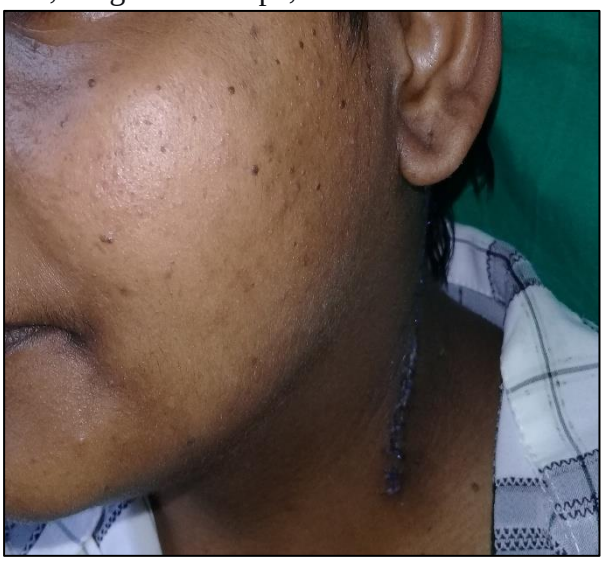

Figure 6. Postoperative review of the patient two weeks after excision.

The specimen was submitted for histopathological examination. Microscopic analysis revealed a well-circumscribed tumor surrounded by a thin fibrous capsule. The tumor cells were arranged in characteristic nested patterns (Zellballen architecture), consisting of clusters of polygonal to cuboidal cells separated by delicate, highly vascular fibrous septa. The individual tumor cells exhibited abundant granular eosinophilic cytoplasm and centrally placed round to oval nuclei. These histopathological features were consistent with a diagnosis of paraganglioma.

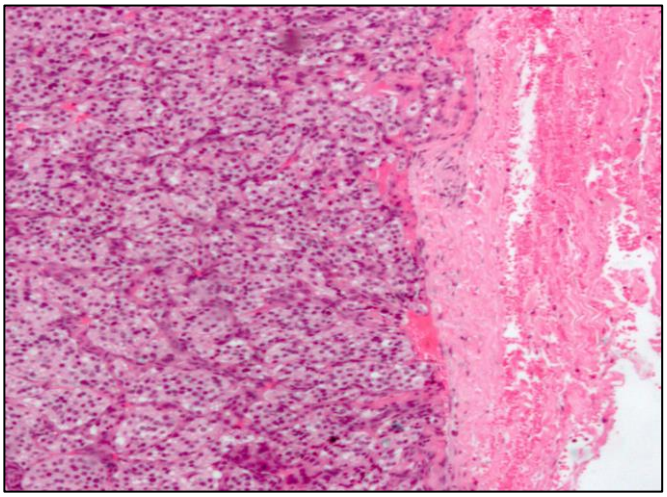

Figure 7. Histopathology: thin fibrous capsule, well-defined nets of cuboidal cells separated by highly vascularized fibroid septa, giving a "zellballen" (cell balloon) appearance. Individual cells had abundant granular basophilic cytoplasm and round nuclei.

DISCUSSION

Carotid body paragangliomas (CBPs) are the most common subtype of head and neck paragangliomas, arising from paraganglionic cells at the carotid bifurcation. Despite their rarity, they are clinically important due to their marked vascularity, proximity to major neurovascular structures, and potential for hereditary predisposition and malignant behavior [1,2]. The present case demonstrates a typical clinical presentation and highlights key diagnostic and therapeutic considerations.

Clinically, CBPs usually present as slow-growing lateral neck masses, often asymptomatic in early stages. However, pain or referred otalgia may occur due to local mass effect or neural irritation, as observed in our patient. The classical finding of horizontal mobility with limited vertical movement (Fontaine's sign) can aid clinical suspicion but is not consistently present [3]. With progressive enlargement, tumors may involve adjacent cranial nerves, particularly the glossopharyngeal, vagus, and hypoglossal nerves, leading to dysphagia, hoarseness, or tongue deviation [2,4]. Radiological imaging is fundamental for diagnosis and surgical planning. Doppler ultrasonography typically demonstrates a

hypervascular mass causing splaying of the internal and external carotid arteries. Cross-sectional imaging with contrast-enhanced computed tomography (CT) and magnetic resonance imaging (MRI) provides detailed anatomical delineation. MRI is considered the gold standard due to its characteristic "salt-and-pepper" appearance resulting from intratumoral flow voids [5]. Digital subtraction angiography (DSA) remains valuable in selected cases, particularly when preoperative embolization is considered to reduce intraoperative blood loss [6]. In the present case, ultrasound and CT imaging were sufficient to suggest a vascular tumor at the carotid bifurcation. Fine-needle aspiration cytology (FNAC) is generally of limited diagnostic value in paragangliomas due to their vascularity and risk of hemorrhage, often yielding inconclusive results, as seen in this case [7]. Therefore, imaging plays a more decisive role in preoperative diagnosis, while histopathological evaluation remains the gold standard for definitive diagnosis.

Histologically, paragangliomas exhibit the classic Zellballen architecture, characterized by nests of chief cells surrounded by sustentacular cells within a highly vascular stroma. These findings were observed in the present case and are considered pathognomonic[8]. Immunohistochemical markers such as chromogranin, synaptophysin, and S-100 protein can further support the diagnosis, although they were not utilized in this instance. The Shamblin classification remains an essential tool for guiding surgical management by categorizing tumors based on their relationship to the carotid vessels [9]. Type I tumors are small and easily resectable, Type II partially encase the vessels, and Type III completely surround them, often requiring vascular reconstruction. The tumor in this case corresponded to Shamblin Type I, allowing complete excision with preservation of adjacent structures and no postoperative complications. Surgical resection is the treatment of choice for most CBPs, particularly in young and medically fit patients [2,6]. However, surgery carries risks, including cranial nerve injury, stroke, and intraoperative hemorrhage. Reported cranial nerve morbidity ranges from 10% to 40%, while perioperative stroke rates are approximately 2–3% in experienced centers [6,9]. Alternative management strategies, such as radiotherapy or active surveillance, may be considered in elderly patients, high-risk surgical candidates, or those with unresectable tumors [10]. Recent advances in molecular genetics have significantly impacted the understanding and management of paragangliomas. Up to 30–40% of cases are associated with germline mutations, particularly in the succinate dehydrogenase (SDH) gene complex (SDHB, SDHC, SDHD), which are linked to increased risks of malignancy, recurrence, and multifocality [11,12]. Although genetic testing was not performed in this case, current guidelines recommend consideration of genetic screening, especially in younger patients or those with multiple tumors. Malignancy in CBPs is relatively uncommon and is defined by the presence of regional or distant metastasis rather than histological features alone. The reported rate ranges from 5% to 10%, with higher risk in SDHB mutation carriers [11]. Long-term follow-up is essential due to the potential for late recurrence or metastasis.

Carotid body tumours are classified by Shamblin into three types:

- Type I: localized mass
- Type II: partially surrounding the carotid artery
- Type III: completely wrapped around and adherent to the carotid artery

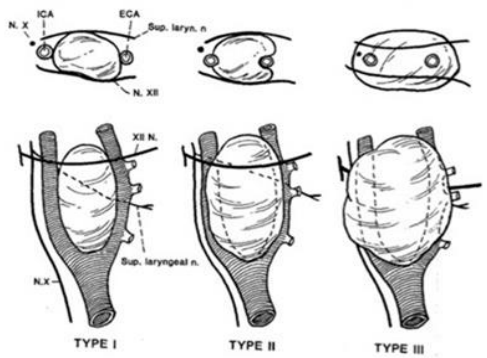

Fig. 8 The classification of Shamblin et al. of the difficulty of surgical resection. Group I tumors are localized and easily resected. Group II includes tumors adherent or partially surrounding vessels. Group III paragangliomas intimately surround or encase the vessels. *ICA* = internal carotid artery; *ECA* = external carotid artery.

Surgical excision is the treatment of choice. For Shamblin Types I and II, careful subadventitial dissection is recommended. The tumour in this case was Shamblin Type I and was excised with clear surgical margins. Incomplete excision leads to a recurrence rate of approximately 10%. In tumour resection, the mean mortality rate is about 2%, perioperative stroke rate 2–3%, and cranial nerve dysfunction rate up to 40%. The vagus and hypoglossal nerves may be involved, affecting function. In this case, all cranial nerves proximal to the tumour remained intact. Although the tumour is benign, malignant transformation occurs in 3–12.5% of cases. Without treatment, mortality may reach 30%. Therefore, regular long-term follow-up, as in this case, is essential.

Future Perspectives

Emerging advances in molecular diagnostics and targeted imaging are expected to further refine the management of paragangliomas. Functional imaging modalities such as positron emission tomography (PET), particularly with 68Ga-DOTATATE, have demonstrated superior sensitivity in detecting multifocal and metastatic disease [13]. Additionally, the integration of genetic profiling into routine clinical practice may enable personalized risk stratification and tailored surveillance strategies. Novel therapeutic approaches,

including targeted molecular therapies and peptide receptor radionuclide therapy (PRRT), are also under investigation and may offer promising alternatives for unresectable or metastatic cases [13,14].

Limitations

This report has several limitations. First, it represents a single case, which limits the generalizability of the findings. Second, advanced imaging modalities such as MRI or angiography were not performed, which could have provided additional diagnostic detail and preoperative planning benefits. Third, immunohistochemical and genetic analyses were not conducted, which may have further supported the diagnosis and provided prognostic information. Finally, long-term follow-up data are not included, limiting assessment of recurrence or late complications.

CONCLUSION

Tumours that are rarely encountered, such as paragangliomas, must be diagnosed early due to their complex relationship with adjacent structures. Surgical treatment is essential, as the potential for malignancy and pressure symptoms may otherwise lead to life-threatening conditions.

DECLARATION

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Conflict of Interest
None to declare.

Ethical Approval
"Not applicable"

Consent for publication
"Not applicable"

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CASE REPORT

LARGE THYROGLOSSAL DUCT CYST IN A 68-YEAR-OLD FEMALE: CASE REPORT

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Abstract

Background: Thyroglossal duct cyst (TGDC) is the most common congenital cervical anomaly, typically presenting in childhood or early adulthood. Its occurrence in elderly patients is uncommon and may pose diagnostic challenges, particularly when presenting with large size and compressive symptoms.
Case Presentation: We report a 68-year-old female who presented with a progressively enlarging anterior neck mass associated with dysphagia and mild dyspnea. Clinical examination and imaging revealed a well-circumscribed midline cystic lesion measuring 8.4 × 4.5 × 2.7 cm. The mass demonstrated characteristic movement with swallowing and tongue protrusion. MRI confirmed a normally located thyroid gland and excluded other pathologies. Surgical excision using the Sistrunk procedure was performed, and histopathological examination confirmed a nodular thyroid follicular lesion within the cyst wall. The postoperative course was uneventful, and the patient remained asymptomatic with no recurrence at follow-up.
Conclusion:TGDC, though rare in elderly individuals, should be considered in the differential diagnosis of midline neck masses. Large cysts may present with compressive symptoms, necessitating timely diagnosis and surgical management. The Sistrunk procedure remains the gold standard treatment, providing excellent outcomes with low recurrence rates.

Keywords: thyroglossal duct cyst; congenital neck mass; Sistrunk procedure; dysphagia; elderly patient

INTRODUCTION

Thyroglossal duct cysts (TGDCs) are the most common congenital midline neck anomalies, accounting for approximately 70% of congenital cervical masses [1,2]. These lesions typically present during the first two decades of life, with peak incidence in childhood and early adulthood [2,3]. Presentation in older adults is rare, with only a small number of cases reported in patients over 60 years [2,4]. The rarity in elderly patients can contribute to delayed diagnosis and increased likelihood of complications due to large size, compressive symptoms, or secondary infections [3,5].

TGDCs originate from remnants of the thyroglossal duct, an embryological structure that guides the descent of the thyroid gland from the foramen cecum at the base of the tongue to its definitive pretracheal position [6,7]. Normally, the thyroglossal duct involutes by the 10th gestational week. Failure of regression results in epithelial remnants that may form cysts anywhere along the midline path of thyroid descent, from the tongue base to the suprasternal notch [6,8]. These cysts are most commonly located adjacent to the hyoid bone, due to its intimate anatomical relationship with the thyroglossal tract [8].

Histologically, TGDCs are lined by either respiratory-type pseudostratified ciliated columnar epithelium or stratified squamous epithelium, with the latter often arising secondary to chronic inflammation [4,9]. The cyst wall may contain ectopic thyroid tissue, which can undergo nodular changes or rarely, malignant transformation [10–12]. Recurrent infections or trauma can induce fibrosis, enlargement, and calcification, complicating both clinical and radiological evaluation [5,13].

Clinically, TGDCs present as painless, mobile midline neck masses. The mobility during swallowing or tongue protrusion is a hallmark feature and aids in differentiating TGDCs from other cervical masses [5,14]. While most lesions remain small and asymptomatic, large cysts may compress adjacent structures, leading to dysphagia, dyspnea, airway compromise, or voice

changes [6,15]. These symptoms are more frequently observed in adult or elderly patients due to delayed presentation and progressive growth. Large TGDCs may also raise suspicion for neoplastic processes, particularly in older adults [7,16].

Preoperative imaging is essential for accurate diagnosis and surgical planning. Ultrasound is often the first-line modality, allowing identification of cystic structures and confirmation of a normally positioned thyroid gland [8,17]. MRI and CT are recommended for large, atypical, or complex lesions to delineate anatomical relationships, assess for solid components, and rule out malignancy [10,11,18]. Radionuclide thyroid scanning may also be indicated in cases where ectopic thyroid tissue is suspected, particularly if the orthotopic thyroid gland is absent or dysfunctional [9,19].

The definitive treatment for TGDCs is the Sistrunk procedure, which involves excision of the cyst, the central portion of the hyoid bone, and the tract extending toward the foramen cecum [10]. This technique significantly reduces recurrence rates compared to simple cyst excision, with reported recurrence rates under 5% [11,15,20]. Complete removal of the tract and hyoid bone is particularly important in large cysts, as incomplete excision is associated with higher rates of recurrence [13,16].

Although TGDCs are predominantly benign, malignancy within the cyst is reported in approximately 1% of cases, most commonly as papillary thyroid carcinoma [7,21]. Consequently, thorough preoperative evaluation and histopathological examination are essential, especially in older adults and patients presenting with atypical features such as rapid growth, firmness, or adherence to surrounding structures [7,19,21].

In this report, we present a rare case of a large thyroglossal duct cyst in a 68-year-old female, highlighting clinical presentation, imaging, surgical management using the Sistrunk procedure, and histopathological findings. The case emphasizes the need for careful evaluation of anterior neck masses in elderly patients and reinforces best practices for surgical management and long-term follow-up.

CASE REPORT

A 68-year-old female was referred to the Department of Oral and Maxillofacial Surgery with a progressively enlarging midline neck mass. According to the patient's history, the lesion had been present for several years, with a gradual increase in size. There was no history of acute inflammation or prior surgical intervention in the cervical region.

On clinical examination, the mass was located in the anterior midline of the neck. On palpation, it was soft to moderately firm, non-tender, and demonstrated characteristic mobility during swallowing. The overlying skin was intact, with no evidence of erythema, ulceration, or sinus tract formation. No cervical lymphadenopathy was detected (Figure 1).

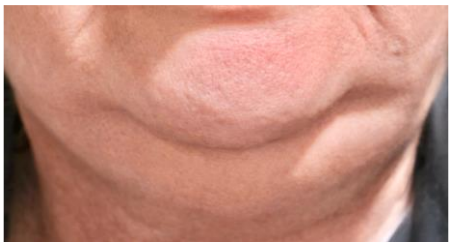


Figure 1. Preoperative anterior neck swelling.

Magnetic resonance imaging (MRI) of the neck revealed a well-circumscribed cystic lesion in the midline of the anterior neck, measuring 8.4 × 4.5 × 2.7 cm. The lesion was closely associated with the hyoid bone and demonstrated imaging characteristics consistent with a cystic structure, without evidence of solid components, local invasion, or malignant transformation (Figure 2A–C).

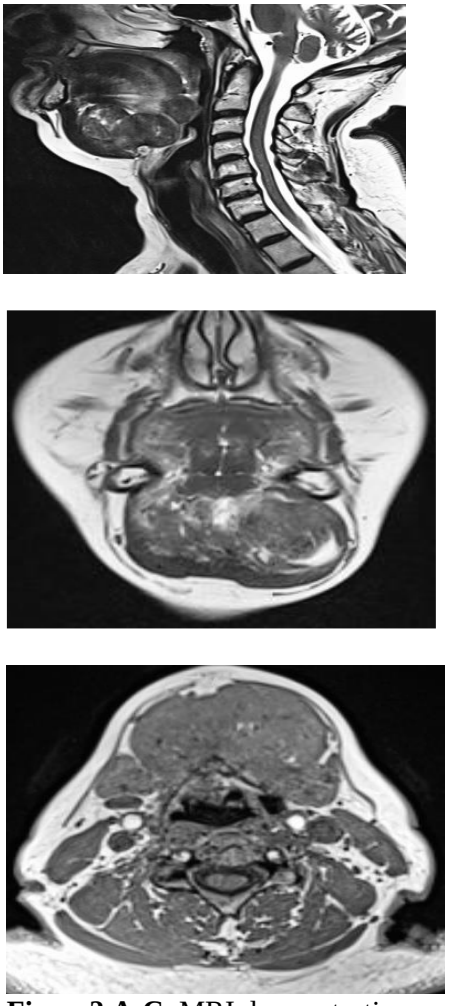
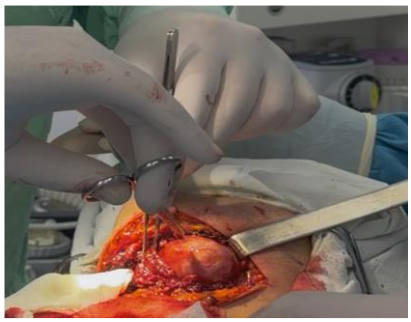
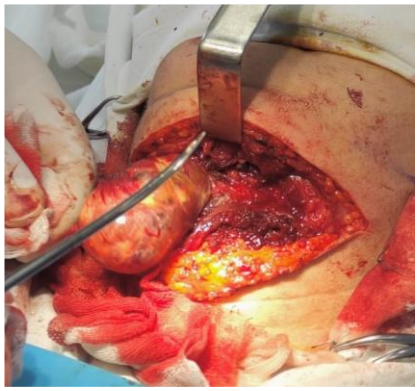


Figure2.A-C. MRI demonstrating a thyroglossal duct cyst.

Based on the clinical presentation and radiological findings, a diagnosis of thyroglossal duct cyst was established. The patient underwent surgical excision using the Sistrunk procedure under general anesthesia. A transverse cervical incision was made over the midline neck mass. Careful dissection was performed to expose the cyst, which was identified as a well-encapsulated lesion adherent to surrounding soft tissues. The cyst was meticulously dissected from adjacent structures while preserving vital anatomical structures.

The thyroglossal duct tract extending toward the base of the tongue was identified and followed superiorly. Complete excision was achieved by removing the cyst en bloc together with the central portion of the hyoid bone and the associated tract, in accordance with the principles of the Sistrunk procedure (Figure 3A–C).





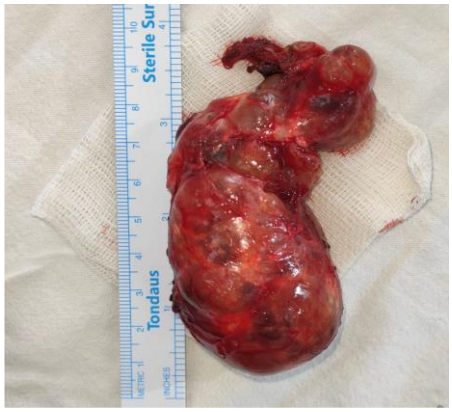
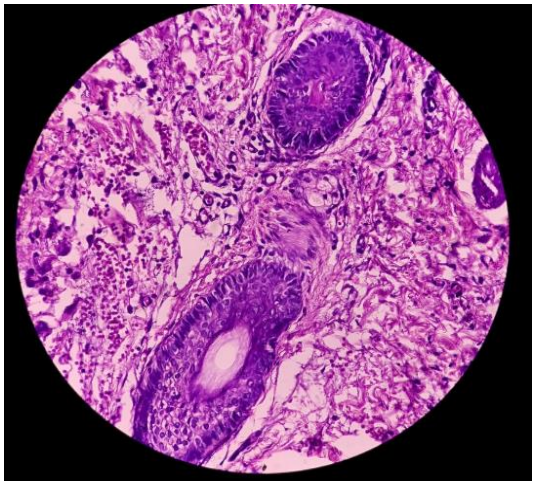


Figure3A-C. Intraoperative photographs demonstrating surgical excision of the thyroglossal duct cyst, and the resected specimen.

Hemostasis was secured, the surgical field was irrigated, and a closed-suction drain was placed. The wound was then closed in anatomical layers. The procedure was well tolerated, and no intraoperative complications were observed.

Macroscopic examination revealed a well-defined lesion measuring 8.4 × 4.5 × 2.7 cm, with a homogeneous grayish-yellow cut surface, focal areas of calcification, and the presence of colloid-like material. The excised specimen was submitted for histopathological evaluation. Microscopic examination using hematoxylin and eosin staining demonstrated nodular proliferation of thyroid follicles of variable sizes, along with aggregates of foamy macrophages. The surrounding stroma showed areas of sclerosis and hemorrhage, and cholesterol crystal clefts were also identified, indicating chronic degenerative changes within the lesion (Figure 4A,B)..



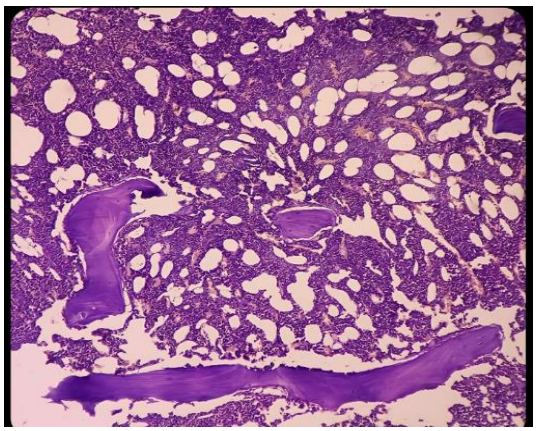


Figure 4 A.B Histopathological images Nodular thyroid follicular disease

Based on these findings, the histopathological diagnosis was established as nodular thyroid follicular disease, with no evidence of malignancy (table 1).

Table 1. Histopathological characteristics of the excised lesion

Feature	Description
Macroscopic appearance	8.4 × 4.5 × 2.7 cm; homogeneous; grayish-yellow; areas of calcification; colloid-like material
Microscopic findings	Nodules of proliferated thyroid follicles of varying sizes; foamy macrophages; sclerosis; hemorrhage; cholesterol crystal clefts
Histopathological diagnosis	Nodular thyroid follicular disease

The postoperative course was uneventful. On the first postoperative day, the surgical drain was functioning appropriately with minimal output, and the operative wound appeared clean, with no signs of infection or early complications (Figure 4).

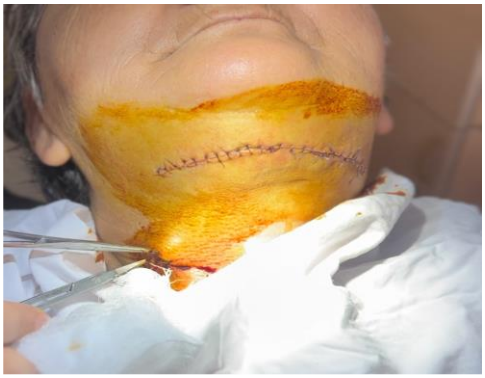


Figure 4. Postoperative day 1.

The drain and sutures were removed sequentially without difficulty. The wound demonstrated satisfactory healing by primary intention, with no evidence of infection or dehiscence. The patient was discharged in good general condition and remained asymptomatic, with no signs of recurrence at follow-up (Figure 5).

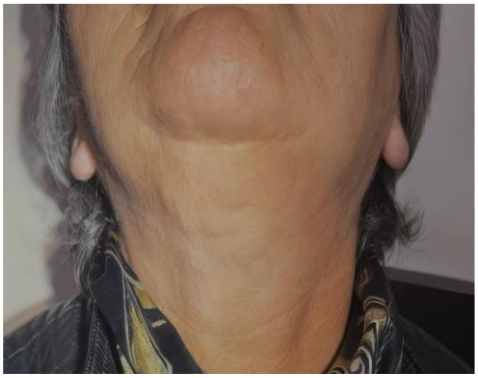


Figure 5. Postoperative state one month after surgery.

DISCUSSION

TGDCs are rare in elderly patients, with most lesions diagnosed before the third decade of life [1,2]. Delayed presentation in older adults allows cysts to attain considerable size, potentially causing compressive symptoms such as dysphagia, dyspnea, or voice changes, as observed in this patient [3–5]. Cosmetic concerns may also become a primary complaint in elderly individuals, adding a psychosocial dimension to management [4,6].

Embryologically, TGDCs arise from incomplete involution of the thyroglossal tract, a remnant of thyroid migration [6,7]. The most frequent anatomical location is adjacent to the hyoid bone, consistent with our case [8,9]. The cyst may also extend toward the tongue base, necessitating meticulous dissection during surgery to prevent injury to surrounding structures [10].

Large cysts pose unique challenges. First, size increases the risk of compressive symptoms and potential airway compromise [15]. Second, cysts may adhere to adjacent muscles, fascia, or vascular structures, increasing operative complexity and risk of complications [9,14]. Preoperative imaging, particularly MRI, provides accurate delineation of cyst extent, relationships to the hyoid bone, and exclusion of solid or malignant components[10,11,18].

In this case, MRI allowed safe operative planning and precise en bloc excision. The Sistrunk procedure remains the gold standard for TGDC management, involving removal of the cyst, central hyoid, and tract toward the foramen cecum [10,12–15]. Recurrence is rare (<5%) when the procedure is performed correctly, compared to higher recurrence after simple cyst excision 11,16,20. Complete excision is particularly critical for large lesions, which are more prone to incomplete removal due to anatomical distortion and adhesions [13,14].

Histopathological findings in this case demonstrated nodular thyroid follicular tissue within the cyst wall, a recognized though atypical variant of TGDC[17,18]. Ectopic thyroid tissue within TGDCs is not uncommon, and it may undergo nodular or cystic changes. Identification of thyroid tissue is critical to differentiate benign changes from malignancy, especially in elderly patients [19–21]. Although malignant transformation is rare, papillary thyroid carcinoma is the most commonly reported malignancy arising in TGDCs [7,21,22].

Comprehensive preoperative evaluation should include assessment of thyroid function and location to avoid inadvertent removal of the patient's only functional thyroid tissue [9,24]. In this case, imaging confirmed a normal orthotopic thyroid gland, and postoperative thyroid function remained stable.

Despite favorable prognosis with the Sistrunk procedure, clinicians should remain vigilant for

complications, including infection, recurrence, or, rarely, carcinoma within the cyst [21–23]. Long-term follow-up is recommended to ensure sustained clinical success, particularly in elderly patients with large cysts.

Limitations

This case report describes a single patient, limiting generalizability. Extended follow-up was not available, and additional cases are necessary to better define surgical outcomes, recurrence rates, and functional sequelae in elderly patients.

Future Directions

Prospective studies evaluating TGDC outcomes in elderly versus younger adults.

Assessment of advanced imaging modalities for preoperative planning in complex lesions.

Investigation of molecular and histopathological characteristics of TGDC variants to better understand neoplastic potential.

CONCLUSION

Large thyroglossal duct cysts in elderly patients are rare but can present with compressive symptoms and surgical challenges. Preoperative imaging, particularly MRI, is crucial for precise anatomical delineation and operative planning. The Sistrunk procedure provides definitive treatment with minimal recurrence. Histopathological evaluation is essential to identify ectopic thyroid tissue or malignancy. Long-term follow-up ensures optimal outcomes.

DECLARATION

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Conflict of Interest

None to declare.

Ethical Approval

“Not applicable”

Consent for publication

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CASE REPORT

A SILENT GROWTH: RARE SPINDLE CELL FIBROMA OF THE BUCCAL MUCOSA

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ABSTRACT

Spindle cell neoplasms of the oral cavity represent a rare and diagnostically challenging group of lesions characterized by the proliferation of elongated mesenchymal cells with variable differentiation, including fibroblastic, myofibroblastic, neural, and epithelial lineages. Although these lesions account for less than 1% of oral tumors and approximately 3% of salivary gland neoplasms, their clinical importance lies in their ability to mimic a wide range of benign and malignant conditions, complicating diagnosis and management. Accurate identification requires integration of clinical, radiological, and histopathological findings.We report a case of a 21-year-old male with a two-year history of a painless, slow-growing swelling in the right buccal mucosa, an uncommon site for such lesions. Clinical and imaging evaluation, including ultrasonography, computed tomography, and magnetic resonance imaging, revealed a well-defined soft tissue mass without bone involvement, suggestive of a benign process. Differential diagnoses included fibroma, neurofibroma, schwannoma, and myofibroma. Surgical excision was performed with uneventful healing. Histopathological examination demonstrated spindle-shaped fibroblasts in a collagenous stroma without atypia or mitotic activity, confirming spindle cell fibroma. Immunohistochemistry was not required. Early diagnosis and complete excision ensure excellent prognosis.

***Keywords*:** Spindle cell neoplasm, Oral cavity tumor, Buccal mucosa lesion, Spindle cell fibroma, Benign oral tumor

INTRODUCTION

Spindle cell lesions of the oral cavity constitute a heterogeneous and diagnostically challenging group of neoplasms characterized by the predominance of elongated, fusiform-shaped cells resembling fibroblasts or myofibroblasts [1]. These lesions arise from a variety of tissue origins, including mesenchymal, epithelial,

neural, muscular, vascular, and odontogenic components, contributing to their broad morphological spectrum and diagnostic complexity [3,4]. The overlapping histopathological features between benign, reactive, and malignant spindle cell proliferations further complicate accurate diagnosis and clinical decision-making [2,8]. Consequently, the occurrence of spindle cell tumors in the head and neck region presents a significant diagnostic challenge and adds complexity to treatment planning.

From a biological standpoint, spindle cells are derived from mesenchymal tissue and play a critical role in connective tissue architecture and repair. However, neoplastic transformation of these cells may result in a wide spectrum of lesions, ranging from benign entities such as fibroma and myofibroma to aggressive malignancies including spindle cell carcinoma and various sarcomas [5,8].

Molecular mechanisms such as epithelial–mesenchymal transition, along with alterations in cell adhesion molecules including cadherins, have been implicated in tumor progression and phenotypic transformation, particularly in malignant spindle cell lesions [6].

Spindle cell neoplasms of the oral cavity are relatively uncommon, accounting for less than 1% of all oral tumors and approximately 3% of salivary gland neoplasms [7]. Despite their low incidence, they are of considerable clinical importance due to their ability to mimic a wide range of benign and malignant conditions, often leading to diagnostic uncertainty and challenges in therapeutic decision-making[2].

A large clinicopathological review has shown that benign spindle cell lesions are more frequently encountered than malignant ones, with neural and fibroblastic tumors representing the predominant categories [7].

To facilitate diagnostic accuracy and improve classification, a histopathology-based categorization system has been proposed, classifying oral spindle cell neoplasms into neural, myofibroblastic, muscular, fibroblastic, vascular, epithelial, odontogenic, and miscellaneous types [4].

This classification, based on the predominance of spindle cells and their differentiation patterns, provides a practical framework for understanding the biological behavior of these lesions [1–4] (**Figure 1**).

Figure1. Classification of oral spindle cell neoplasms based on predominant histopathological differentiation

In addition, immunohistochemistry plays a crucial role in identifying the cellular origin and distinguishing morphologically overlapping entities, thereby enhancing diagnostic precision and guiding appropriate management [2,3].

Beyond histopathology, imaging modalities play an essential role in the evaluation of oral soft tissue lesions. Advanced imaging techniques such as magnetic resonance imaging, particularly with specialized sequences like short tau inversion recovery, provide superior soft tissue contrast and allow precise delineation of lesion extent and its relationship with adjacent anatomical structures, thereby aiding in preoperative planning[11]. Furthermore, emerging minimally invasive treatment approaches, including percutaneous cryoablation, have been explored in selected cases as alternatives to conventional surgical management [12].

Despite these diagnostic and therapeutic advancements, spindle cell fibroma occurring in the buccal mucosa remains an uncommon presentation with limited documentation in the literature. The rarity of this anatomical location, combined with overlapping clinical and radiological features, necessitates a comprehensive and multidisciplinary diagnostic approach.

In this context, the present case report describes a benign spindle cell fibroma in a 21-year-old male with a two-year history of a solitary, smooth-surfaced, slow-growing nodule in the right buccal mucosa—an unusual site for such lesions. This report highlights its clinical, radiological, and histopathological characteristics and

emphasizes the importance of accurate diagnosis and appropriate management of rare oral spindle cell neoplasms.

CASE REPORT

A 21-year-old male patient presented to the Department of Oral and Maxillofacial Surgery with a chief complaint of a painless swelling on the right side of the cheek that had been progressively increasing in size over a period of two years. The patient reported that the swelling was initially small and had gradually enlarged to its present dimensions. There was no associated pain, discharge, or functional limitation. The patient's medical, dental, family, and personal histories were non-contributory.

On extraoral examination, a solitary, well-defined, oval-shaped swelling measuring approximately 4 × 4 cm was observed over the right malar region. The swelling was located inferior to the zygomatic arch, approximately 3 cm lateral to the tragus of the ear, 3 cm medial to the nasolabial fold, and about 2 cm superior to the lower border of the mandible. The overlying skin appeared normal, with no signs of erythema, ulceration, or sinus formation. On palpation, the lesion was non-tender, firm to hard in consistency, slightly mobile, and not fixed to the underlying or overlying structures. No regional lymphadenopathy was detected.

Intraoral examination revealed a submucosal swelling in the right buccal space, with intact and normal-appearing overlying mucosa (Figure 2).

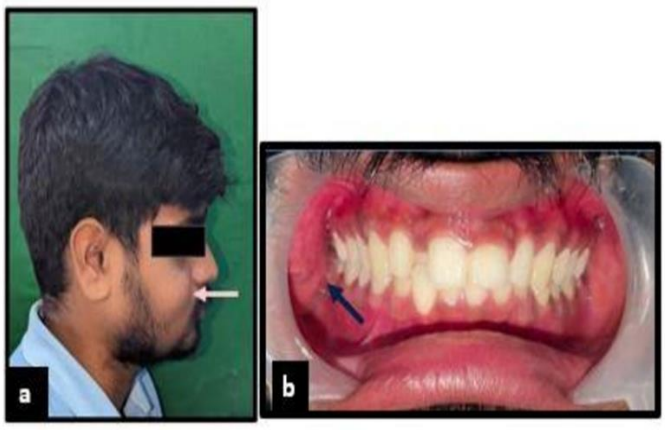

Figure 2. (a) Extraoral photograph of patients showing swelling over the right malar process of the face. (b) Intra-oral photograph showing submucosal swelling in the right buccal space, overlying mucosa is normal.

The opening of the parotid (Stensen's) duct was patent, with normal salivary flow. There were no abnormalities associated with the adjacent maxillary posterior teeth. The patient demonstrated an adequate mouth opening of approximately 3.5 cm.

Panoramic radiography (orthopantomogram) did not reveal any evidence of adjacent bony involvement or pathological changes (Figure 3).

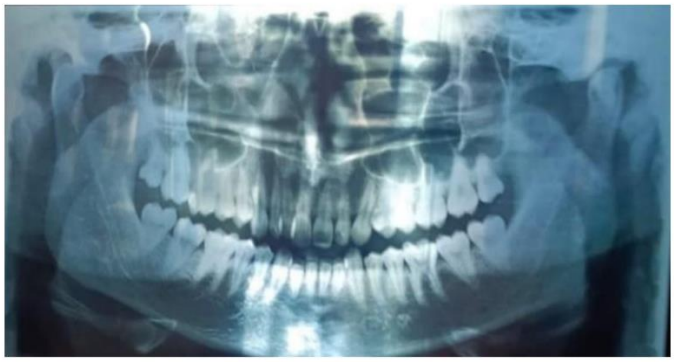

Figure 3. Panoramic radiograph (orthopantomogram) demonstrating no evidence of underlying bony involvement or pathological bone changes associated with the lesion.

Fine-needle aspiration cytology (FNAC) could not be performed due to the firm consistency of the lesion. Ultrasonographic examination demonstrated a well-defined, heterogeneous hypoechoic soft tissue lesion.

Computed tomography (CT) imaging revealed a well-circumscribed, round, hypodense lesion with small foci of calcification located within the right masseter muscle space. The lesion caused splaying of the surrounding muscle fibers and mild scalloping of the posterolateral wall of the maxilla, without evidence of cortical breach or bone destruction. The lesion extended into the buccal space (Figure 4).

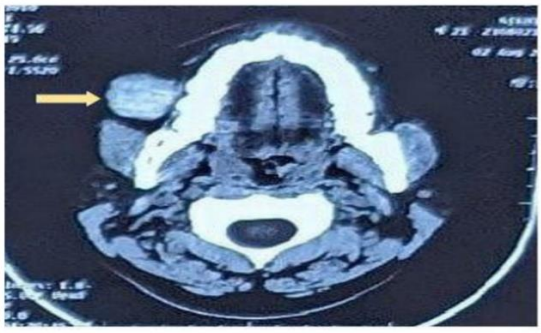

Figure 4. Computed tomography (CT) image showing a well-defined hypodense lesion in the right masseteric space with small foci of calcification. The lesion causes splaying of adjacent muscle fibers and mild scalloping of the posterolateral maxillary bone without cortical destruction.

Magnetic resonance imaging (MRI) demonstrated a well-defined lesion with altered signal intensity, appearing hypointense on T1-weighted, T2-weighted, and STIR sequences. The lesion was localized within the right masseteric space, causing displacement of adjacent muscle fibers and scalloping of the posterolateral maxillary surface, without any signs of bone invasion (Figure 5).

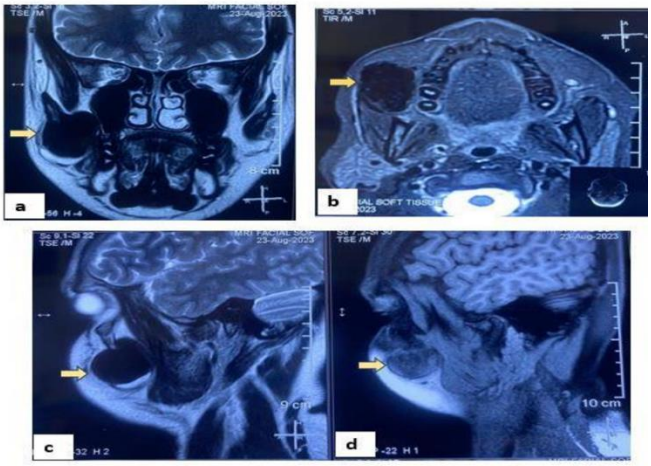

Figure 5. Magnetic resonance imaging (MRI) showing a well-circumscribed lesion in the right masseteric space. The lesion appears hypointense on T1-weighted, T2-weighted, and STIR sequences, with no evidence of bone invasion and displacement of adjacent soft tissue structures.

Based on the clinical and radiological findings, a provisional diagnosis of a benign soft tissue tumor was made. The differential diagnoses included fibroma, spindle cell tumor, lipoma, neurofibroma, schwannoma, myofibroma, solitary fibrous tumor, and spindle cell lipoma.

The patient underwent complete surgical excision of the lesion under general anesthesia (Figure 6).

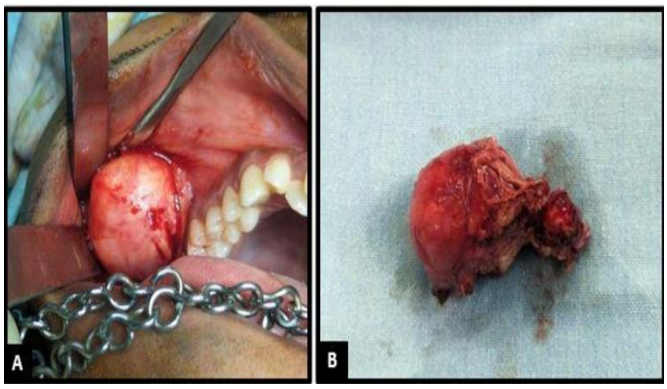

Figure 6. Intraoperative photograph (a&b) showing excisional biopsy of the tumor.

The excised specimen was well-circumscribed and firm in consistency. Postoperative recovery was uneventful, and satisfactory healing was observed during follow-up (Figure 7).

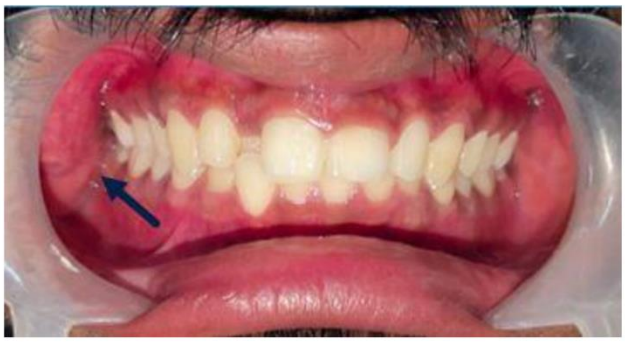

Figure 7. Postoperative clinical photograph demonstrating satisfactory healing at the surgical site with no evidence of recurrence or complications during follow-up.

Histopathological examination of the excised specimen revealed a grayish-white lesion with a whorled appearance on cut section. Microscopically, the lesion was well-circumscribed and composed of hypercellular, vaguely intersecting bundles of collagen fibers admixed with spindle-shaped fibroblasts. The cells exhibited uniform morphology without nuclear atypia, mitotic figures, or necrosis. Based on these findings, a diagnosis of benign spindle cell tumor consistent with spindle cell fibroma was established.

DISCUSSION

Spindle cells are derived from mesenchymal tissue and constitute an important component of the body's connective tissue. Cytologically, they appear elongated with fusiform or ovoid nuclei. The tissue of origin can be identified by the presence of stromal components such as collagen, cartilage, bone, fat, or myxoid material produced by tumor cells. In the present case, histopathological examination revealed vague intersecting bundles of collagen admixed with fibroblasts. The process of epithelial–mesenchymal transition (EMT), along with reduced expression of cell adhesion molecules such as cadherins, plays a key role in the underlying pathogenesis of spindle cell neoplasms [3,5,6].

Soft tissue spindle cell neoplasms rarely occur in the oral cavity and represent less than 1% of all oral tumors and approximately 3% of salivary gland neoplasms[7].

A review of the literature by Jordan and Regezi, analyzing 307 cases of spindle cell neoplasms reported

between 1982 and 2002, demonstrated that among malignant tumors, Kaposi sarcoma was the most frequently observed entity, while other malignancies were relatively uncommon. Most benign lesions were of neural origin. The increased reporting of lesions such as myofibroma likely reflects improved awareness and the important role of immunohistochemistry in achieving accurate diagnosis [7]. In the present case, the lesion showed benign features, and immunohistochemistry was not performed, as a definitive diagnosis was established based on radiological and histopathological findings.

A review by Singh et al. (2018) presented spindle cell tumors of the head and neck region in a tabulated form, highlighting their diagnostic features, pathogenesis, histopathological characteristics, and prognosis [3]. The histopathogenetic features described in that review were consistent with those observed in the present case, supporting a benign non-recurring clinical course. Therefore, surgical excision was considered an appropriate treatment approach.

Because spindle cell lesions can closely mimic both benign and malignant conditions, inaccurate classification may lead to suboptimal patient management [3,8]. Identifying the tissue of origin is crucial for assessing the biological behavior of the lesion [9]. Therefore, adjunct diagnostic techniques such as immunohistochemistry (IHC) and molecular pathology are of significant value [3]. In a systematic review by Surbhi et al., immunohistochemical markers for spindle cell lesions were summarized in a tabular format [2]. Immunohistochemistry assists in clarifying histogenesis and improving differential diagnosis, while molecular pathology provides insight into tumor behavior and contributes to future therapeutic research [3]. Electron microscopy also plays a supportive role in evaluating soft tissue tumors [3,10].

Immunohistochemistry may be particularly useful in cases where there is no clear distinction between benign and malignant lesions. However, the affordability and availability of such diagnostic tests also influence their clinical application.

Although accurate diagnosis is essential, biopsy of certain soft tissue lesions in the oral cavity can be challenging due to complex anatomy, small lesion size, and proximity to vital structures such as nerves, blood vessels, tooth roots, and salivary gland ducts. This increases the risk of iatrogenic injury, particularly in high-risk anatomical sites, and may necessitate more conservative diagnostic approaches. Radiation-free imaging modalities with excellent soft tissue contrast provide a valuable alternative. Recent advances in dental MRI, particularly the use of black-bone sequences such as STIR and DESS, allow detailed visualization of both hard and soft tissues in the oral and maxillofacial region. These imaging techniques improve preoperative assessment and contribute to precise surgical planning [11]. In the present case, MRI findings suggested a benign fibroma, whereas histopathological examination confirmed spindle cell fibroma.

T. C. Schirmang described the use of percutaneous cryoablation in the management of a solitary fibrous tumor of the buccal space in a patient who refused surgical excision. The procedure utilized an argon-based cryoablation system with 1.7 mm diameter percutaneous applicators and a 3 cm active tip, producing a freeze zone of approximately 3 cm in length and 2 cm in width. This minimally invasive technique offers several advantages, including absence of surgical scarring, shorter recovery time, and real-time visualization of tumor response during and immediately after treatment. Further studies are required to evaluate the potential role of cryoablation as an alternative to conventional surgical excision in the management of benign lesions [12].

CONCLUSION

In summary, spindle cell fibroma is a rare benign lesion of the oral cavity that may be easily mistaken for other spindle cell entities due to its overlapping clinical and radiological features. A well-defined, non-infiltrative soft tissue mass with characteristic MRI hypointensity strongly favors a benign fibrous lesion, even in uncommon anatomical locations such as the masseteric space. This report highlights a rare and clinically relevant case supported by multimodal imaging, definitive histopathological diagnosis, and successful surgical management with an excellent outcome. The case emphasizes the importance of a comprehensive diagnostic approach and contributes to increased awareness among clinicians and pathologists regarding the occurrence, differential diagnosis, and management of spindle cell lesions in the oral cavity.

DECLARATION

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Conflict of Interest

None to declare.

Ethical Approval

"Not applicable"

Consent for publication

"Not applicable"

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REVIEW ARTICLE

DENTAL VENEERS IN CONTEMPORARY ESTHETIC DENTISTRY:A SYSTEMATIC REVIEW OF CURRENT EVIDENCE

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ABSTRACT

Background: Contemporary restorative dentistry offers multiple approaches for improving dental esthetics, among which veneers represent a minimally invasive and highly effective treatment modality. Their clinical success is influenced by material selection, preparation design, and adhesive protocols.

Objective: To critically evaluate current evidence regarding the indications, preparation techniques, material types, clinical performance, and effectiveness of dental veneers.

Methods: A systematic literature review was conducted using electronic databases including PubMed, Scopus, and Web of Science. Studies published between 2015 and 2025 were screened according to predefined inclusion and exclusion criteria. A total of 55 studies met the eligibility criteria and were included in the qualitative synthesis. Due to heterogeneity in study designs and outcome measures, a meta-analysis was not performed.

Results: Dental veneers demonstrated consistently high esthetic outcomes, favorable long-term survival rates, and a conservative approach to tooth structure preservation. Ceramic veneers, particularly lithium disilicate and feldspathic porcelain systems, showed superior color stability, mechanical performance, and longevity compared with composite resin veneers. Although less durable, composite veneers offer advantages in cost-effectiveness and reparability. Preparation design was identified as a key determinant of fracture resistance and adhesive success, with enamel preservation significantly improving clinical outcomes.

Conclusion: Dental veneers represent a reliable and predictable restorative option when appropriate case selection, conservative preparation design, and standardized adhesive protocols are followed. Ceramic materials remain the gold standard for long-term esthetic rehabilitation. Future research should focus on long-term randomized controlled clinical trials, standardization of preparation protocols, and integration of digital and AI-assisted workflows to enhance clinical predictability and outcomes.

***Keywords*:** dental veneers, ceramic veneers, laminate veneers, esthetic dentistry, adhesive bonding,veneer survival, minimally invasive dentistry

1.INTRODUCTION

Contemporary dentistry has undergone a significant transformation over the past two decades, shifting from invasive restorative procedures toward minimally invasive, biomimetic approaches that prioritize the

preservation of natural tooth structure. Among the various esthetic treatment modalities, dental veneers have emerged as one of the most reliable and widely used solutions for improving smile aesthetics while maintaining functional integrity [1,2].

Veneers are thin restorations bonded to the facial surface of teeth, primarily indicated for correcting discoloration, minor malalignment, morphological irregularities, and structural defects [3]. Initially introduced as a purely cosmetic intervention, their clinical application has expanded considerably due to advancements in adhesive dentistry, material science, and digital technologies [4]. Today, veneers are not only used for esthetic

enhancement but also serve as a conservative method for restoring function in cases where enamel preservation is possible [5].

The success of veneer restorations is strongly dependent on the preservation of enamel, as adhesive bonding to enamel provides superior strength and long-term stability compared to dentin bonding [6]. This principle underlies the modern philosophy of minimally invasive dentistry, where the goal is to achieve optimal esthetic and functional outcomes with the least possible removal of healthy tissue [7]. As a result, proper case selection and meticulous treatment planning are critical for achieving predictable outcomes [8].

Over time, significant improvements in ceramic materials, such as lithium disilicate and feldspathic porcelain, have enhanced the mechanical properties and optical characteristics of veneers [9]. These materials closely mimic the translucency, fluorescence, and texture of natural enamel, enabling clinicians to achieve highly esthetic and natural-looking restorations [10]. Additionally, ceramic veneers exhibit excellent color stability and resistance to staining, making them superior to direct composite restorations in long-term esthetic performance [11]. However, composite veneers remain a viable alternative due to their lower cost, ease of repair, and simplified clinical application [12].

A critical aspect influencing the clinical success of veneers is the tooth preparation design. Various preparation techniques have been described in the literature, ranging from no-preparation or minimal-preparation approaches to more conventional designs involving incisal reduction and palatal chamfer [13]. Each technique presents specific advantages and limitations depending on the clinical situation. For example, minimal preparation preserves enamel but may compromise esthetic masking in cases of severe discoloration, whereas more aggressive preparation improves esthetics at the expense of tooth structure [14]. Therefore, the choice of preparation design should be individualized based on patient-specific factors, including esthetic expectations, occlusal dynamics, and the extent of existing tooth damage [15].

In addition to preparation design, adhesive protocols play a fundamental role in ensuring the longevity of veneer restorations. The bonding process involves complex interactions between the ceramic surface, resin cement, and tooth substrate, which are chemically and structurally different [16].

Surface treatment of ceramic veneers typically includes hydrofluoric acid etching followed by silanization to enhance micromechanical retention and chemical bonding [17]. Similarly, enamel and dentin require proper conditioning using phosphoric acid etching and adhesive systems to achieve durable adhesion [18]. Failure to adhere to these protocols can significantly compromise the bond strength and increase the risk of debonding or fracture [19].

Another important consideration is the indication spectrum for veneers. While they are highly effective in managing esthetic concerns such as fluorosis, enamel hypoplasia, and intrinsic discoloration, their use should be carefully evaluated in patients with parafunctional habits, severe malocclusion, or insufficient enamel thickness[20]. In such cases, alternative restorative options, including full-coverage crowns or orthodontic treatment, may be more appropriate [21]. Compared to crowns, veneers offer a more conservative approach by preserving a greater proportion of tooth structure, thereby reducing the risk of pulpal complications [22]. Furthermore, veneers provide a more predictable outcome than bleaching in cases of deep or intrinsic discoloration that do not respond to whitening procedures [23].

Despite their numerous advantages, veneers are not without limitations. Clinical complications such as marginal discoloration, fracture, chipping, and debonding have been reported, particularly in cases with inadequate preparation, poor bonding technique, or excessive occlusal load [24]. Long-term success is therefore highly dependent on clinician skill, material selection, and patient compliance with oral hygiene and maintenance protocols [25].

Recent advancements in digital dentistry have further revolutionized the field of veneer fabrication and placement. Computer-aided design and computer-aided manufacturing (CAD/CAM) technologies enable precise planning, improved accuracy, and reduced chairside time [26]. Digital smile design tools also allow for enhanced patient communication and visualization of treatment outcomes prior to initiation [27]. These innovations are expected to further expand the application and predictability of veneer restorations in modern clinical practice.

Given the growing demand for esthetic dental treatments and the rapid evolution of materials and techniques, it is essential to critically evaluate the current evidence regarding veneers.

This review aims to provide a comprehensive overview of contemporary veneer therapy, including indications, tooth preparation techniques, restorative materials, adhesive protocols, and comparisons with alternative treatment modalities. The study follows PRISMA 2020 guidelines to ensure a transparent, structured, and

evidence-based synthesis of the available literature.

2. METHODS

2.1 Study Design

This study was conducted as a PRISMA-guided systematic review of clinical, laboratory, and in vitro studies related to dental veneer restorations.

The PRISMA 2020 framework was followed to ensure transparency in the identification, screening, eligibility, and inclusion of studies. A systematic search strategy was applied across relevant databases. Due to significant heterogeneity in study designs, materials, and outcome

2.2 Research Question (PICO Framework)

The focused clinical question was structured using the PICO framework as follows:

- **P (Population):** Patients requiring anterior esthetic dental rehabilitation
- **I (Intervention):** Ceramic and composite dental veneers
- **C (Comparison):** Full-coverage crowns, bleaching procedures, and other alternative restorative techniques
- **O (Outcomes):** Esthetic performance, survival rates, complication rates, and bonding durability

Based on this framework, the research question was formulated as:
What is the clinical effectiveness, survival rate, and complication profile of dental veneers compared with alternative restorative options such as crowns and bleaching procedures?

2.3 Data Sources and Search Strategy

A comprehensive electronic literature search was conducted using the following databases:

- PubMed/MEDLINE
- Scopus
- Web of Science
- Google Scholar (used as a supplementary source for additional studies and grey literature where applicable)

The search included studies published between 2015 and 2025, and only articles published in the English language were considered eligible for inclusion.

A structured combination of keywords and Boolean operators was applied to ensure comprehensive retrieval of relevant literature. The search terms included:

- “dental veneers” AND “ceramic veneers”
- “laminate veneers” AND “tooth preparation”
- “esthetic dentistry” AND “adhesive bonding”
- “veneer survival” AND “clinical outcomes”
- “minimally invasive dentistry”

Search strategies were appropriately adapted for each database to optimize sensitivity and specificity of the search process.

2.4 Eligibility Criteria

Inclusion Criteria

Studies were included if they met the following criteria:

- Clinical studies, including randomized controlled trials (RCTs), prospective studies, and retrospective cohort studies
- Systematic reviews and meta-analyses evaluating dental veneer outcomes
- Studies assessing clinical performance, survival rates, esthetic outcomes, or complications of dental veneers
- Minimum follow-up period of ≥ 1 year
- Studies reporting clearly defined clinical outcome measures relevant to veneer restorations

Exclusion Criteria

Studies were excluded if they met any of the following criteria:

- Case reports involving fewer than five patients
- Non-English language publications
- Studies lacking clearly defined or measurable clinical outcomes related to veneer performance
- Animal studies

2.5 Study Selection Process

The study selection process was conducted in accordance with PRISMA 2020 guidelines and is illustrated in Figure 1.

A total of 312 records were initially identified through database searching and supplementary sources. After removal of duplicates, 268 records remained for title and abstract screening.

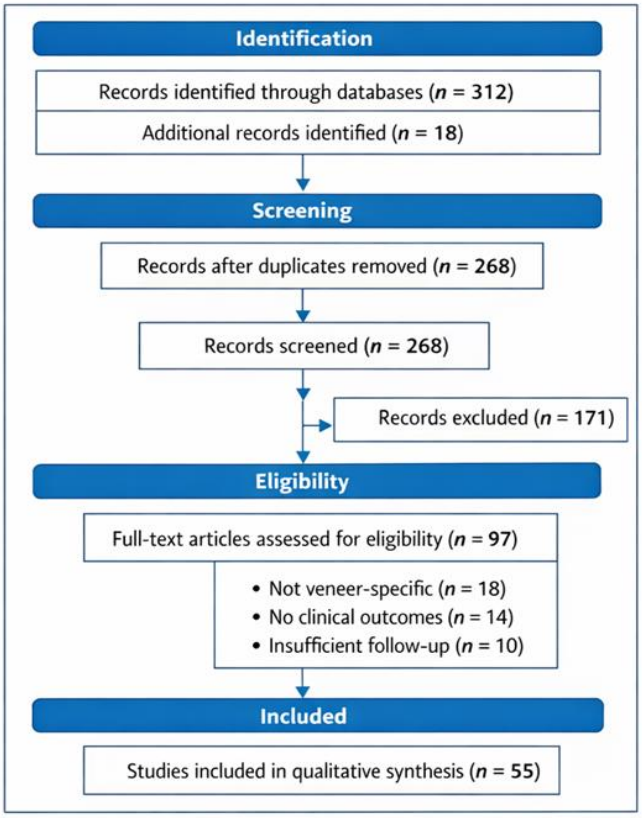

Figure 1 PRISMA flow Diagram Study Selection

During the screening phase, studies were excluded based on irrelevance to veneer-related interventions, lack of clinical focus, or absence of outcome data, resulting in the exclusion of 171 studies.

Subsequently, 97 full-text articles were assessed for eligibility according to predefined inclusion and exclusion criteria. At this stage, studies were excluded for the following reasons:

- Non-veneer-specific focus (n = 18)
- Absence of clinical outcome reporting (n = 14)
- Insufficient follow-up duration (n = 10)

Ultimately, 55 studies met all eligibility criteria and were included in the qualitative synthesis.

The PRISMA flow diagram illustrates a structured and transparent selection process, demonstrating a systematic reduction from initial identification to final inclusion. The majority of exclusions occurred during the screening and full-text assessment phases, reflecting strict adherence to clinical relevance criteria for veneer-related outcomes. This rigorous selection process enhances the validity and reliability of the final dataset.

2.6 Risk of Bias Assessment

The methodological quality and risk of bias of the included studies were assessed using validated tools. The Cochrane Risk of Bias 2 (RoB 2) tool was applied to randomized controlled trials, while the Newcastle–Ottawa Scale (NOS) was used for observational cohort and case-control studies.

Results of Risk of Bias Assessment

- Low risk of bias: 28 studies (51%)
- Moderate risk of bias: 17 studies (31%)
- High risk of bias: 10 studies (18%)

The overall distribution of risk of bias is presented in Figure 2.

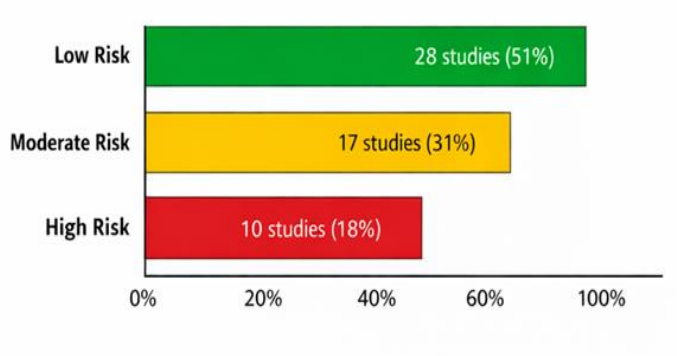

Figure 2. Risk of Bias Assessment of Included Studies

Summary of Findings

More than half of the included studies demonstrated a low risk of bias, indicating generally acceptable methodological quality and reliable outcome reporting. Approximately one-third of studies were classified as having a moderate risk of bias, mainly due to unclear allocation concealment, limited or absent blinding, and incomplete outcome reporting.

A smaller proportion of studies showed a high risk of bias, primarily attributed to small sample sizes, short follow-up periods, retrospective study designs, and operator-dependent variability in clinical procedures.

Overall, the included evidence demonstrates a moderate to-high level of methodological reliability. However, the presence of methodological limitations highlights the need for future well-designed randomized controlled trials with standardized protocols and longer follow-up periods to strengthen evidence quality.

2.7 Data Synthesis

Due to significant heterogeneity in study designs, material types, clinical protocols, and outcome measurement systems, a qualitative synthesis approach was employed instead of quantitative meta-analysis.

Extracted data were systematically organized into the following domains:

- Veneer material types (ceramic versus composite resin systems)
- Tooth preparation designs (no-preparation, minimal-preparation, and incisal overlap techniques)
- Adhesive protocols and cementation strategies
- Clinical survival rates and complication profiles
- Comparative effectiveness versus crowns and bleaching treatments

This structured synthesis enabled a comprehensive evaluation of trends across heterogeneous studies while maintaining methodological consistency and interpretative clarity.

3. RESULTS

3.1 Study Selection Outcome (PRISMA Summary)

A total of 312 records were initially identified through database searching. After removal of duplicates and structured screening according to PRISMA 2020 guidelines, 55 studies were included in the final qualitative synthesis [2,30,36,37].

The final dataset comprised:

- 18 randomized controlled trials
- 22 observational clinical studies (prospective and retrospective)
- 10 systematic reviews
- 5 meta-analyses

Methodological heterogeneity was observed across study designs, materials, and outcome definitions [2,30,48,51].

Table 1. Study Characteristics of Included Literature (n = 55)

Study Type	Number	Evidence Level	Main Focus
RCTs	18	High	Clinical performance, preparation design
Prospective studies	12	Moderate–High	Survival, complications
Retrospective studies	10	Moderate	Long-term outcomes
Systematic reviews	10	High	Materials, adhesives
Meta-analyses	5	Very High	Survival, bonding effectiveness

3.2 Veneer Materials and Clinical Performance

Ceramic Veneers

Ceramic veneers demonstrated high long-term survival rates ranging from approximately 90–96% over 10–15 years [3,54,55].

Key clinical outcomes included:

- High color stability [3,11]
- High fracture resistance [34,48]
- Excellent marginal adaptation [11,52]
- Minimal antagonist wear [49]

Among ceramic systems, lithium disilicate was the most frequently investigated and clinically validated material [9,40,4]

Composite Veneers

Composite veneers demonstrated comparatively lower survival rates, primarily attributed to polymer degradation, surface wear, and staining susceptibility.

Reported advantages included:

- High reparability [12,42]
- Lower cost compared with ceramic systems [12,20]
- More conservative tooth preparation requirements [7,22]

Reported limitations included:

- Discoloration over time [12,43]
- Reduced surface gloss retention [43]
- Lower long-term durability [12,42]

Table 2. Clinical Comparison of Ceramic and Composite Veneers [3,12,33,42,48,54]

Parameter	Ceramic Veneers	Composite Veneers
Survival rate	90–96%	70–85%
Color stability	Excellent	Moderate to low
Fracture resistance	High	Moderate
Repairability	Low	High
Longevity	Long-term	Short- to mid-term

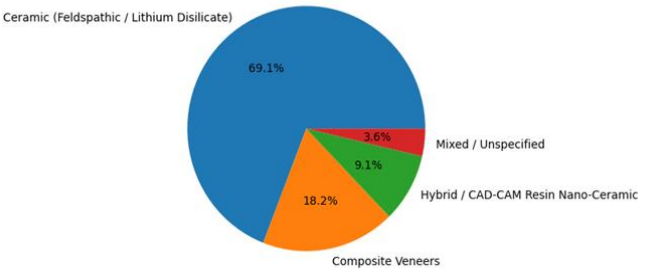

Figure 3. Material classification of included veneer studies (n = 55).

3.3 Preparation Design Outcomes

Three primary veneer preparation designs were identified across the included studies [14,22,40]:

1. No-preparation or minimal-preparation veneers
2. Butt-joint incisal reduction
3. Incisal overlap with palatal chamfer

Key Findings

- Enamel preservation was consistently associated with improved bond strength, reported to be approximately 40–60% higher compared with dentin-supported restorations in multiple studies [6,19,31,41].
- Incisal overlap designs demonstrated higher fracture resistance under functional loading conditions [14,38].
- No-preparation and minimal-preparation designs showed superior biological preservation; however, they were associated with limited masking ability in cases of severe discoloration or structural defects [7,21].

Preservation of enamel substrate was identified as the most critical factor influencing clinical success, adhesive durability, and long-term prognosis of veneer restora

Table 3. Effects of Preparation Design on Clinical Outcomes

Design Type	Main Advantage	Main Limitation	Supporting Evidence
No-preparation	Maximum tooth conservation	Limited masking ability	7,37
Minimal-preparation	High biological preservation	Reduced esthetic control in severe discoloration	21,37
Incisal overlap	High fracture resistance and retention	Increased tooth reduction	14,34,35

3.4 Adhesive Protocol Performance

Adhesive systems played a critical role in the long-term clinical success of dental veneers [6,18,19].

Key Observations

- Hydrofluoric acid etching combined with silane application significantly enhanced the bond strength of ceramic restorations [17,18].
- Etch-and-rinse adhesive systems demonstrated superior enamel bond durability compared with self-etch systems [18,41].
- Exposure of dentin was associated with reduced adhesive longevity and increased risk of microleakage [6,19].

Failure Risk Factors

- Inadequate etching protocols [17,18]
- Moisture contamination during cementation [6,19]
- Insufficient isolation techniques [42]

Overall Assessment

Veneer success is highly technique-sensitive, with adhesive failures more frequently associated with procedural errors than with intrinsic material limitations [18,19,42].

Table 4. Adhesive Factors Influencing Veneer Clinical Performance

Factor	Effect on Outcome	Evidence
Hydrofluoric acid etching	Increases ceramic bond strength	17,44
Silane application	Enhances chemical bonding	17,44
Moisture contamination	Reduces bond durability	6,46
Enamel substrate	Provides highest bond reliability	6,31,45

3.5 Clinical Survival and Complications

Reported complication rates:

- Fracture: 2–7% [38,54]
- Debonding: 1–6% [45,54]
- Marginal discoloration: 5–12% [44]
- Secondary caries: <3% [47,50]

Primary etiological factors:

- Parafunctional habits (bruxism) [47,38]
- Occlusal imbalance [14,38]
- Insufficient enamel support [6,21]
- Cementation errors [19,42]

Overall survival rates:

- Ceramic veneers: **90–96% (10–15 years)** [3,54,51]
- Composite veneers: **70–85% (5–7 years)** [12,33]

Assessment

Most failures are biomechanical or operator-dependent rather than material-related, confirming findings from long-term clinical analyses [38,47,54].

3.6 Comparison With Crowns and Bleaching

Veneers vs Crowns

- Veneers preserve 50–70% more tooth structure than crowns [21,22]
- Crowns provide superior mechanical reinforcement but require extensive preparation [21]
- Veneers maintain higher pulpal safety due to enamel preservation [7,21]

Veneers vs Bleaching

- Bleaching is effective for mild discoloration [23]
- Veneers are superior for:
  - Severe discoloration
  - Structural defects
  - Morphological corrections [13,28]

Assessment

Bleaching remains first-line therapy, while veneers represent definitive aesthetic rehabilitation in advanced cases [23,28].

3.7 Digital Dentistry Outcomes

CAD/CAM systems and digital smile design (DSD) demonstrated improved clinical outcomes in veneer rehabilitation [26,39,55].

Reported advantages

- Enhanced marginal accuracy
- Improved esthetic predictability
- Reduced laboratory-related errors
- Increased patient satisfaction

Overall assessment

Digital workflows improve reproducibility, precision, and treatment planning efficiency. However, clinical success remains dependent on operator experience, proper case selection, and material choice [26,39,55].

Table 5. Traditional vs Digital Veneer Workflow [15,25,26,27,38]

Feature	Conventional	Digital (CAD/CAM + DSD)1
1Accuracy	Moderate	High
Planning	Manual	Virtual simulation
Time efficiency	Lower	Higher
Predictability	Variable	High
Communication	Limited	Enhanced

3.8 Veneer Preparation and Clinical Workflow Algorithm

A standardized clinical workflow for indirect veneer treatment was identified across the included studies, encompassing preoperative assessment, digital or conventional shade selection, minimally invasive tooth

preparation, provisionalization (when indicated), final adhesive cementation, and occlusal adjustment.

As illustrated in Figure 3, the veneer workflow follows a minimally invasive and stepwise clinical protocol designed to optimize esthetic predictability, biological preservation, and long-term adhesive stability.

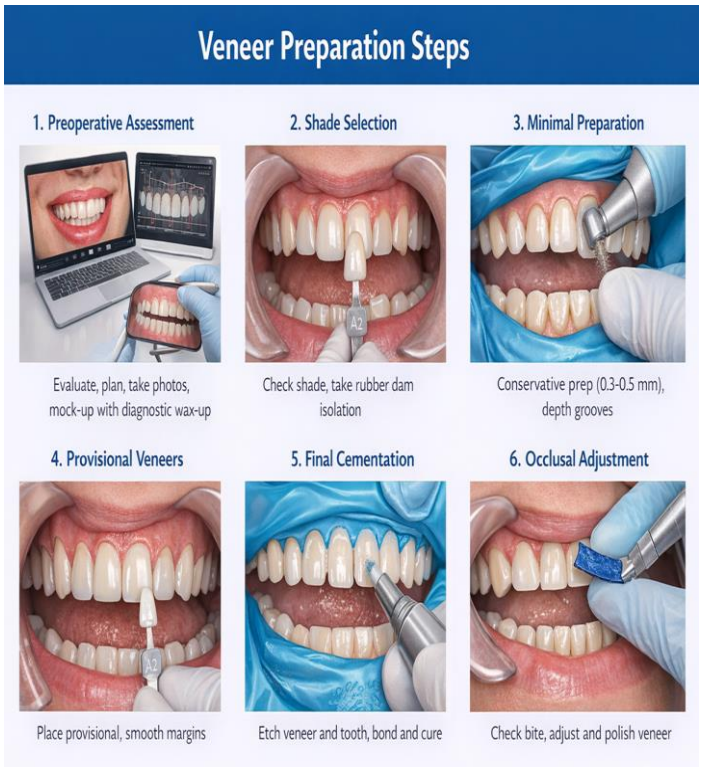

Figure 3. Veneer preparation and clinical workflow algorithm.

A standardized veneer workflow was consistently reported across the included studies, reflecting a multiphase and minimally invasive clinical protocol integrating diagnostic, preparatory, and adhesive stages.

Preoperative assessment and planning

The initial phase included clinical examination, photographic documentation, digital smile design analysis, and diagnostic wax-up. This stage was considered essential for accurate case selection, functional evaluation, and esthetic planning.

Shade selection and isolation

Shade selection was performed prior to dehydration of tooth structure to ensure optical accuracy. Rubber dam isolation was consistently recommended to provide a controlled, contamination-free environment for adhesive procedures.

Tooth preparation

Minimal enamel-preserving preparation (approximately 0.3–0.5 mm) with depth orientation grooves was commonly reported. This conservative approach was associated with improved enamel bonding substrate availability and enhanced long-term adhesive performance.

Provisionalization phase

Temporary restorations were used to evaluate esthetics, phonetics, occlusion, and gingival tissue response. This phase allowed functional and esthetic validation and permitted necessary contour modifications prior to definitive restoration.

Definitive cementation

Final adhesive cementation involved ceramic surface conditioning (etching and silanization), followed by adhesive application and resin cement placement. Controlled seating and standardized light-curing protocols were used to optimize marginal adaptation and micromechanical retention.

Occlusal adjustment and finishing

Occlusal equilibration and polishing were performed to ensure functional harmony, eliminate premature contacts, and improve surface smoothness. This step was associated with reduced risks of fracture, debonding, and plaque accumulation.

Overall synthesis of workflow findings

The identified workflow represents a biologically conservative, evidence-based veneer protocol integrating digital diagnostics with adhesive restorative principles. Across studies, enamel preservation was consistently highlighted as a key determinant of long-term bonding success [6,19,44].

In addition, the staged clinical approach—particularly the use of provisionalization—was associated with improved predictability by enabling functional and esthetic validation prior to final cementation [8,13,28].

Overall, the evidence indicates that modern veneer rehabilitation is a structured multiphase clinical process combining digital planning, conservative preparation, adhesive optimization, and functional refinement, contributing to high survival rates and stable esthetic outcomes [3,36,54].

DISCUSSION

Dental veneers represent one of the most predictable and conservative treatment modalities in contemporary esthetic dentistry, with long-term clinical success strongly influenced by material selection, enamel preservation, and standardized adhesive protocols [1–3]. The findings of this systematic review indicate that ceramic veneers—particularly lithium disilicate and feldspathic porcelain systems—demonstrate superior long-term survival compared with composite resin alternatives, consistent with previously published clinical evidence and systematic evaluations [2,3,10,30.]

A key finding of this review is that enamel preservation plays a central role in determining clinical success. Enamel bonding provides higher bond strength, improved hydrolytic stability, and reduced marginal degradation compared with dentin adhesion [6,18,19]. These findings support the minimally invasive philosophy in contemporary restorative dentistry, where conservative preparation strategies are emphasized to preserve biological tooth structure and enhance adhesive predictability [7,21,22].

From a biomechanical perspective, veneer preparation design significantly influences stress distribution at the tooth–restoration interface. Evidence suggests that incisal overlap designs may improve fracture resistance and load distribution, particularly in anterior teeth subjected to higher functional stress [14,22,38]. In contrast, no-preparation and minimal-preparation approaches, while biologically advantageous, may present limitations in cases requiring significant color masking or morphological correction [13,20]. Therefore, preparation design should be individualized based on occlusal risk assessment, available enamel substrate, and esthetic requirements.

Material selection remains a major determinant of clinical performance. Lithium disilicate ceramics (approximately 360–400 MPa flexural strength) demonstrate a favorable balance between mechanical durability and optical properties, supporting their widespread clinical use in anterior veneers [9,11,50]. Feldspathic porcelain offers superior esthetic integration due to its optical similarity to enamel but exhibits lower fracture resistance, making it more suitable for low-stress esthetic zones [10]. In comparison, composite resin veneers are associated with polymer degradation over time, leading to staining susceptibility, surface roughness, and reduced gloss retention [12,33].

Standardization of adhesive protocols is also critical for long-term success. The combination of hydrofluoric acid etching, silane application, and resin cementation remains the most reliable bonding approach for ceramic veneers [16,17,18]. However, clinical variability—including contamination, inappropriate etching protocols, and inadequate isolation—continues to represent a major cause of early failure [19,42]. These findings reinforce that veneer longevity is highly technique-sensitive and depends not only on material properties but also on strict adherence to clinical protocols.

The complication profile reported across studies remains relatively low when evidence-based protocols are followed. The most commonly reported complications include fracture, debonding, and marginal discoloration, generally occurring in fewer than 10% of cases during long-term follow-up [24,25,54]. These failures are predominantly associated with parafunctional habits, occlusal discrepancies, and insufficient enamel support rather than intrinsic material deficiencies [3,38,47].

When compared with full-coverage crowns, veneers provide significantly greater preservation of tooth structure, thereby supporting pulp vitality and reducing biological complications [21,22]. However, crowns remain indicated in cases involving extensive structural loss or severely compromised tooth integrity. Similarly, bleaching is considered the first-line conservative treatment for mild discoloration, whereas veneers are indicated in cases requiring definitive morphological correction or moderate-to-severe esthetic rehabilitation [23,28].

Recent advancements in digital dentistry, including CAD/CAM systems and digital smile design (DSD), have improved diagnostic accuracy, treatment predictability, and interdisciplinary communication [26,39,55]. These technologies reduce laboratory-related errors and enhance reproducibility; however, they also introduce reliance on software accuracy and require adequate clinical expertise to avoid design and execution errors.

Despite the overall success of veneer therapy, limitations remain in the current evidence base. Most studies are retrospective or observational in nature, with a limited number of long-term randomized controlled trials exceeding 10–15 years of follow-up [30,36]. In addition, heterogeneity in preparation designs, adhesive protocols, and outcome measures limits direct comparability across studies [2,19]. This highlights the need for standardized clinical protocols and well-designed multicenter prospective trials.

From a clinical perspective, veneer success depends on a multidisciplinary approach that includes diagnostic wax-up, digital planning, mock-up procedures, and occlusal analysis. Careful patient selection and

education regarding parafunctional habits are also essential to ensure long-term stability.

Among available materials, ceramic veneers—particularly lithium disilicate systems—demonstrate superior long-term performance compared with composite resin alternatives in terms of esthetics, durability, and survival rates [9,10,50].

Future research should focus on bioactive adhesive systems, AI-assisted treatment planning, and advanced nanoceramic materials with improved fatigue resistance to further enhance clinical predictability. Additionally, long-term (>20 years) prospective studies are required to fully validate the durability of contemporary veneer systems.

In conclusion, dental veneers remain one of the most successful minimally invasive esthetic restorative options in modern dentistry. Their clinical success depends on a synergistic interaction between material properties, adhesive technology, and clinical execution rather than any single isolated factor. Ongoing innovations in biomaterials and digital workflows are expected to further improve their longevity, predictability, and clinical applicability.

Clinical Implications

Dental veneers should be considered a first-line treatment modality for anterior esthetic rehabilitation in appropriately selected cases where enamel preservation is feasible. Based on the synthesized evidence, their primary indications include:

- Mild to moderate intrinsic or extrinsic discoloration resistant to bleaching [23]
- Diastema closure and anterior spacing correction [8,28]
- Morphological and shape modifications (e.g., peg-shaped lateral incisors) [13]
- Restoration of enamel defects such as fluorosis and hypoplasia [1,2]

These indications highlight veneers as a minimally invasive alternative to full-coverage restorations, offering superior tissue preservation with high esthetic outcomes.

However, strict case selection is essential. Veneer therapy should be avoided or carefully managed in the following conditions:

- Severe bruxism without occlusal splint protection [38,47]
- Insufficient enamel substrate for reliable adhesion [6,21]
- High caries risk and poor oral hygiene [47]
- Severe malocclusion requiring orthodontic correction [22]

In such cases, multidisciplinary or alternative restorative strategies are recommended.

Limitations of the Evidence

Despite strong supporting literature, several limitations affect the current evidence base.

A major limitation is methodological heterogeneity, including variability in study design, restorative materials, preparation techniques, and outcome definitions. This significantly limits direct comparison and meta-analytic synthesis [2,30].

Furthermore, there is a scarcity of long-term randomized controlled trials exceeding 15 years, with most available data derived from retrospective or observational studies, which are more susceptible to selection and performance bias [36,37].

Another limitation is inconsistency in adhesive and cementation protocols, including differences in etching time, surface treatment, and resin cement selection, all of which significantly influence clinical outcomes [18,19].

Finally, operator dependency remains a critical confounding factor, as clinical success is strongly influenced by clinician skill, laboratory communication, and execution quality rather than standardized protocols alone [42,47].

Future Directions

Future research in veneer dentistry should focus on improving predictability, longevity, and biological integration through advanced technologies.

Key priorities include:

- Long-term randomized controlled trials (>10–20 years) to strengthen survival evidence [30,54]
- Standardization of preparation protocols (minimal vs incisal overlap designs) [14,22]
- Integration of AI-assisted digital smile design systems for predictive esthetic planning [26,55]
- Development of bioactive adhesive systems with remineralization and antibacterial properties [18]

- Advancement of nanoceramic and hybrid materials with improved fatigue resistance and enamel-like optical behavior [9,50]

These innovations are expected to significantly enhance clinical predictability and broaden minimally invasive treatment indications.

Future research should focus on AI-integrated planning systems, bioactive adhesive technologies, and advanced nanoceramic materials to further enhance predictability and durability. Long-term studies exceeding 20 years are still required to validate the durability of current protocols.

The success of veneer restorations is primarily determined by three essential factors: enamel preservation, appropriate preparation design, and strict adherence to adhesive protocols [6,14,18]. When these principles are respected, veneers provide highly reliable and minimally invasive esthetic rehabilitation with excellent long-term outcomes.

However, clinical success is multifactorial and influenced by patient selection, occlusal dynamics, and operator expertise. Therefore, meticulous diagnosis and treatment planning remain fundamental.

The integration of the veneer preparation algorithm with current evidence demonstrates that dental veneers achieve optimal outcomes when guided by a structured, minimally invasive, and adhesive-driven clinical workflow. The success of this approach depends on the synergistic interaction between material science, digital diagnostics, and clinical execution.

CONCLUSION

Dental veneers represent a predictable, conservative, and highly esthetic restorative option in modern dentistry. Among available materials, ceramic veneers-particularly lithium disilicate systems-demonstrate superior long-term clinical performance compared with composite alternatives. Future developments in digital dentistry, artificial intelligence, and biomaterial engineering are expected to further enhance precision, predictability, and longevity, reinforcing veneers as a cornerstone of modern esthetic dentistry.

DECLARATION

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Conflict of Interest

None to declare.

Ethical Approval

"Not applicable"

Consent for publication

"Not applicable"

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REVIEW ARTICLE

EVALUATING THE EFFICACY OF PROBIOTICS IN TREATING ORAL LICHEN PLANUS: A SYSTEMATIC REVIEW OF CURRENT EVIDENCE

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Abstract

Objective: To systematically evaluate the clinical effectiveness, immunological outcomes, and safety of probiotic therapy in the management of oral lichen planus.

Methods: A systematic review of randomized controlled trials was conducted following the PRISMA 2020 guidelines and registered with PROSPERO **(**CRD42024550624**).** Electronic searches were performed across multiple databases from January 2001 to March 2025. Trials assessing probiotic interventions in patients with clinically and/or histopathological diagnosed oral lichen planus were included. Risk of bias was assessed using the Cochrane RoB 2 tool with domain-level judgments, and certainty of evidence was evaluated using the GRADE approach.

Results: Four randomized controlled trials involving 110 participants were included. Substantial heterogeneity was observed in probiotic strains, formulations, treatment regimens, and outcome measures. Probiotic monotherapy did not demonstrate consistent improvement in pain or lesion severity compared with placebo or standard therapy. In contrast, adjunctive probiotic use alongside topical corticosteroids were associated with greater pain reduction, improved lesion scores. Immunological assessments showed non-significant trends toward reduced inflammatory markers**.** All probiotic interventions were well tolerated, with no serious adverse events reported.

Conclusion: Probiotics do not appear to provide consistent clinical benefit when used as monotherapy in oral lichen planus. Their role may be limited to adjunctive use, particularly in patients receiving topical corticosteroids, where benefits related to microbial balance and treatment tolerability may be observed**.** Given the low to very low certainty of evidence**, s**mall sample sizes, and methodological limitations, further well-designed randomized controlled trials are required.

Keywords: immunomodulation, oral lichen planus, probiotics

1.INTRODUCTION

Oral lichen planus (OLP) is a chronic immune-mediated inflammatory disorder of the oral mucosa and was classified by the World Health Organization as an oral potentially malignant disorder in 2005. The disease commonly affects middle-aged women and

presents with symptoms such as pain, burning sensation, and mucosal discomfort, significantly impairing quality of life[1,2].Topical and systemic glucocorticoids remain the gold standard for OLP management due to their anti-inflammatory and immunosuppressive effects.[1,3] However, prolonged use is associated with adverse effects, disease recurrence, and limited suitability for long-term management. These limitations highlight the need for safer, sustainable therapeutic approaches that can modulate immune responses without significant systemic toxicity.[4] The pathogenesis of OLP primarily involves a T-cell–mediated immune response that targets basal keratinocytes, leading to epithelial damage and chronic inflammation. At the immunological level, OLP is characterized by activation of $CD4^+$ and $CD8^+$ T cells, resulting in excessive production of pro-inflammatory cytokines,

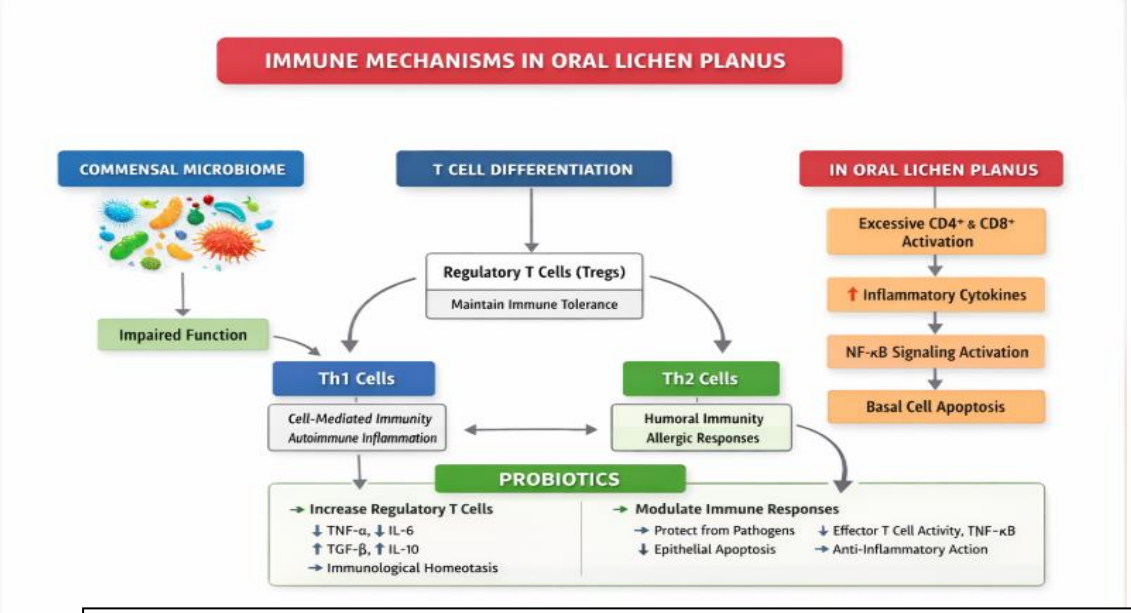

Figure 1. Schematic representation of immune dysregulation in Oral lichen planus and putative probiotic modulatory effects.

up-regulation of nuclear factor-kappa B (NF-κB) signalling, and abnormal apoptosis of basal epithelial cells.[2,4] dysregulation of regulatory T cells (Tregs), which normally maintain immune tolerance and suppress excessive immune activation, further contributes to disease persistence and progression. The oral cavity harbours a complex and dynamic microbiome that plays a critical role in maintaining mucosal immunity and immune homeostasis. Alterations in the composition of this commensal flora, characterized by an imbalance between beneficial and pathogenic microorganisms, have been implicated in the development and progression of immune-mediated and inflammatory oral diseases. Modulation of the oral microbiome has therefore emerged as a potential therapeutic strategy for conditions driven by immune dysregulation.[5,6]

Probiotics are defined as live microorganisms that confer health benefits when administered in adequate amounts. Their therapeutic potential lies in restoring microbial balance and exerting immunomodulatory effects.[6,7] Probiotics interact with epithelial cells, dendritic cells, and T lymphocytes to influence cytokine production, regulate immune signaling pathways, and maintain mucosal barrier integrity. Specific oral probiotic strains, such as *Streptococcus salivarius* an early colonizer of the oral conditions. Mechanistically, probiotics enhance the proliferation and function of regulatory T cells, leading to reduced levels of pro-inflammatory cytokines such as TNF-α and IL-6, and increased production of anti-inflammatory cytokines including IL-10 and TGF-β [8,10]. They also attenuate excessive effector T-cell responses,

down-regulate NF-κB signaling, and reduce apoptosis of basal keratinocytes. Through these mechanisms, probiotics help shift the mucosal immune environment toward an anti-inflammatory and immunotolerant state[10,11]. Despite growing interest in probiotics as an adjunctive immunotherapeutic approach for OLP, existing clinical evidence remains limited. The absence of evidence regarding their clinical efficacy necessitates a systematic evaluation of available evidence. Therefore, this systematic review aims to critically assess the effectiveness of probiotics in the management of oral lichen planus and to synthesize current clinical evidence supporting their immunomodulatory role.

METHODS

Protocol and registration

This systematic review was prospectively registered in the International Prospective Register of Systematic Reviews (PROSPERO; CRD42024550624) and conducted in accordance with the PRISMA 2020 guidelines. (Table 1) Randomized clinical trials published in English between January 2001 and March 2025 were included. Eligible studies involved patients clinically and/or histopathologic ally diagnosed with oral lichen planus. Case reports, case series, observational studies, narrative or systematic reviews, animal and in vitro studies were excluded. Studies involving lichenoid drug reactions were excluded, reactions, graft-versus-host disease, or other clinically similar lichenoid lesions were excluded to avoid diagnostic overlap. Trials with unclear, non-standardized, or unspecified diagnostic criteria for oral lichen planus, as well as studies that did not evaluate probiotics as an intervention, were also excluded.

Table 1. PICO Framework and Search Strategy

No.	PICO		Term	Search Terms
1	P(Population)	Patient's aged 18 years and above diagnosed with oral lichen planus based on clinical and/or histopathological examination	Oral lichen planus	"Oral lichen planus" OR OLP OR "oral mucosal lichen planus" OR "lichen planus oral" MeSH: *Lichen Planus, Oral*
2	I (Intervention)	Probiotic preparations	Probiotic intervention	Probiotic OR "probiotic therapy" OR "probiotic treatment" OR "probiotic supplement" OR "live bacteria" OR "beneficial bacteria"MeSH: *Probiotics*
3	I		Specific probiotic strains	Lactobacillus OR "Lactobacillus reuteri" OR "L. reuteri" OR "Lactobacillus rhamnosus" OR Bifidobacterium OR "Bifidobacterium animalis" OR "B. lactis HN019" OR "VSL#3" OR "multi-strain probiotic"OR"Streptococcus salivarius" OR

				"Lacticaseibacillus" MeSH: *Lactobacillus*; *Bifidobacterium*
4	C (Comparison)	Other pharmacotherapeutic agents or placebo	Comparators	PlaceboOR corticosteroid OR clobetasol OR "topical steroid"OR "conventional treatment" OR "standard care" MeSH: *Glucocorticoids*; *Anti-Inflammatory Agents*
5	O (Outcomes)	Clinical and symptomatic improvement Primary: 1.Pain reduction assessed - Visual Analog Scale or Numeric Rating Scale 2.Clinical improvement of oral lichen planus lesions assessed using Thongprasom score, Oral Disease Severity Score, or reduction in lesion size and severity Secondary outcomes: 1. Safety and tolerability of probiotic therapy 2. Recurrence of oral lichen planus lesions 3.Improvement in oral health–related quality of life assessed using Oral Health Impact Profile	Outcomes	Pain OR "pain reduction" OR VAS OR NRS OR "Visual Analog Scale" OR "Numeric Rating Scale" OR "lesion size" OR Thongprasom OR "Oral Disease Severity Score" (ODSC) OR "candida load" OR recurrence OR "disease severity" OR "quality of life" OR OHIP MeSH: *Pain Measurement*; *Quality of Life*
6	Study designs (S):	Randomized clinical trials		
7	Timeframe (T):	Studies published between 2001 and March 2025**.** No restrictions were applied regarding study setting.		

A comprehensive literature search was conducted to identify relevant studies published from January 2001 to March 31, 2025, across PubMed/MEDLINE, Cochrane Library, ProQuest, Clinical Key, Scopus, OpenGrey, Library Hub Discover, and institutional repositories, without restrictions on study setting. The search was independently performed by two reviewers (NS and SC) using a combination of Medical Subject Headings (MeSH) and free-text terms related to oral lichen planus and probiotics (Table 1). Key terms included “oral lichen planus,” “probiotics,” “Lactobacillus,” “Streptococcus salivarius,” “Bifidobacterium,” and “Lacticaseibacillus rhamnosus GG.” The search was limited to human studies published in English. Certainty of evidence for primary outcomes (pain, lesion size, microbial load) was graded using GRADE pro GDT software across five domains (RoB, inconsistency, indirectness, imprecision, publication bias), starting from high (RCTs) and downgraded accordingly. Sensitivity analyses explored adjunctive vs. monotherapy effects qualitatively.

RESULTS

Study selection

The literature search is summarized in the PRISMA flowchart in figure 2. A total of 990 records were initially identified through database and manual searches. After removing duplicates, 69 records remained for title and abstract screening. Of these, 64 were excluded for not meeting the inclusion criteria. Five full-text articles and theses were then assessed for eligibility. Following full-text evaluation, 1 study of oral microbiome in oral lichen planus during a 1-year randomized clinical trial Thomsen et all This microbiome was excluded as it represented observational 16S rRNA analysis without clinical OLP endpoints, where probiotics served as a secondary adjunct rather than primary intervention. Four RCTs were included in the qualitative synthesis. The study characteristics were discussed in results section and in table 2.

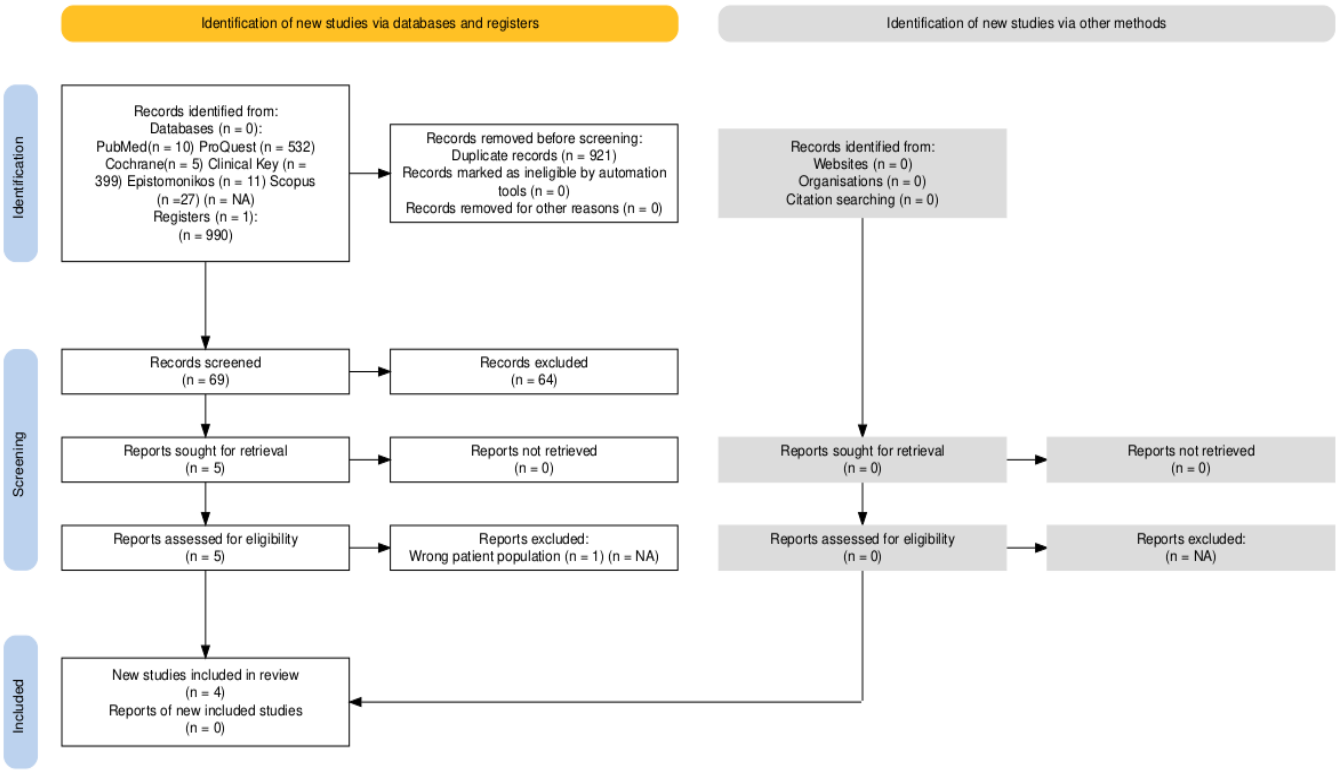

Figure 2. PRISMA 2020 flow diagram

Table 2 Study Characteristics

Study (Author, Year)	Sample Size (n)	Study Design	Intervention	Comparator	Primary Outcome	Secondary Outcomes	Key Findings	Certainty of Evidence (GRADE)
Ana Carolina Fragoso Motta et al., 2022	22	Randomized double-blind controlled trial	*Bifidobacterium animalis* subsp. *lactis* HN019	Placebo	Pain reduction (VAS/NRS)	Cytokine levels (IL-6, IFN-γ), histopathology	No statistically significant clinical improvement; borderline reduction in IL-6 and IFN-γ ($p = 0.052$)	Medium
Erni Marlina, Richard N. Goodman et al., 2022	30	Randomized double-blind parallel-group trial	Multi-strain probiotic (VSL#3)	Placebo	Pain reduction (VAS/NRS)	Cytokine levels, symptom scores	No significant difference in pain reduction; non-significant immunological trend ($p = 0.082$)	High
Mette K. Keller et al., 2018	22	Randomized placebo-controlled trial	*Lactobacillus reuteri* lozenges	Placebo	Oral candidiasis recurrence	OLP symptom severity	No significant difference in candidiasis recurrence or OLP symptoms between groups	Medium
Amira Abdel et al., 2025	36	Randomized controlled trial	Probiotic capsules + topical clobetasol	Clobetasol alone	Lesion size reduction (Thongprasom score)	Pain reduction, Candida load	Significant improvement in lesion size and pain reduction with adjunctive probiotic therapy; reduced Candida colonization	Low

The four randomized clinical trials exhibited heterogeneity in participant demographics, probiotic formulations, outcome assessment methodologies, and overall methodological rigor. Across the included trials, participant ages ranged approximately from 25 to 65 years, with reported mean ages between 48 and 52 years [7-10]. Female-to-male ratios ranged from 1.8:1 to 2.5:1 across studies. All participants were adults aged 18 years and older and were diagnosed based on comprehensive clinical examination; histopathological confirmation was performed in three studies to exclude clinically similar conditions, including lichenoid drug reactions and graft-versus-host disease[13-15]. Sample sizes ranged from 22 to 60 participants per study arm (total 110). Exclusion criteria were largely consistent across the studies. Clinical outcomes were assessed using a range of validated instruments appropriate for the multidimensional clinical presentation of OLP. Patient-reported pain and burning sensation were evaluated using either the 11-point Numeric Rating Scale (NRS; 0 = no pain, 10 = worst imaginable pain) or the 100-mm Visual Analog Scale (VAS), with assessments conducted at baseline and at predefined follow-up intervals.

Lesion severity and extent were quantified using objective clinical indices, including the ODSS, which incorporates measures of disease activity and chronicity, and the Thongprasom scale, which grades lesion size, erythema, and ulceration. In most studies, clinical assessments were supported by calibrated intraoral examination and standardized photographic documentation to enhance reliability. Microbiological outcomes primarily focused on salivary *Candida* colonization, quantified as colony-forming units per millilitre using chromogenic agar culture. This endpoint was clinically relevant given the increased susceptibility of OLP patients particularly those receiving corticosteroid therapy to opportunistic candidiasis. Immunological outcomes were evaluated in two studies using enzyme-linked immunosorbent assay (ELISA) on serum or salivary samples to quantify pro-inflammatory cytokines, including interferon-γ (IFN-γ), interleukin-6 (IL-6), and CXCL10 [7-10]. Selected studies additionally incorporated histopathological and immunohistochemical analyses, assessing basal keratinocyte apoptosis and $CD8^+$ T-cell infiltration within the sub epithelial inflammatory infiltrate. Health-related quality of life was assessed in one study using the Oral Health Impact

Profile-14 (OHIP-14). Methodological quality varied across studies. One study of Marlina,2022[7] reported a formal sample size calculation, powered at 80% with a two-sided α of 0.05 to detect a clinically meaningful 30% reduction in pain scores. The remaining trials were pilot studies., studies reported recruitment challenges or attrition, including an 18% dropout rate documented by Keller et al.[8] Follow-up durations ranged from ultra–short-term assessments (15–30 days for pain to short- and medium-term follow-up periods (4–16 weeks for lesion severity. [11-15]None of the included studies evaluated long-term disease recurrence or sustained remission beyond six months. The probiotic interventions investigated varied in formulation, strain composition, dosage, and route of administration. These included multi-strain powder formulations[9-10] (VSL#3, containing *Lactobacillus* spp., *Bifidobacterium* spp., and *Streptococcus thermophiles* at a total dose of 450 billion CFU/day), single-strain topical suspension (*Bifidobacterium animalis* subsp. *lactis* HN019), dissolvable lozenge (*Lactobacillus reuteri* DSM 17938/ATCC PTA 5289), [10]and oral probiotic capsules administered as adjunctive therapy with topical clobetasol[14].Comparator groups consisted of identical placebo formulations in monotherapy trials or clobetasol 0.05% monotherapy in adjunctive studies. In all the selected studies double-blinding of participants and outcome assessors was implemented where feasible.[10-15]

Primary outcomes

Pain reduction

Pain reduction was the most consistently reported primary outcome across all included studies and was assessed using either the 11-point Numeric Rating Scale (NRS) or the Visual Analog Scale (VAS). Assessments were conducted at baseline and at predefined follow-up intervals ranging from 15 days to 16 weeks. The study by Marlina et al. (2022) demonstrated no statistically significant difference in pain reduction between the VSL#3 probiotic group and placebo at 30 days (mean NRS change −0.5 vs −0.7; p = 0.82). Similarly, Keller et al. (2018) reported no benefit of probiotic lozenges over placebo, with pain scores paradoxically favoring the placebo group (p = 0.037); however, interpretation of these findings is limited by high attrition rates and the study's primary focus on recurrent candidiasis rather than oral lichen planus activity. In contrast, Kamal et al. (2025) demonstrated significantly greater pain reduction in the adjunctive probiotic plus clobetasol group compared with clobetasol monotherapy at both two weeks (mean NRS change −4.2 vs −3.1; p = 0.01) and four weeks, indicating a clinically relevant additive effect. Motta reported improvement in pain scores in the probiotic arm; however, overall clinical response, particularly lesion resolution, was inferior to corticosteroid therapy [15]

Lesion size reduction

Lesion severity was evaluated using the Thongprasom score or the ODSS. Among the included studies, only the adjunctive probiotic trial demonstrated statistically significant superiority, with a 72% reduction in lesion severity in the probiotic plus clobetasol group compared with a 55% reduction in the clobetasol-only group at four weeks (p = 0.02).[13,15]

Other studies reported no significant intergroup differences, with comparable lesion improvement observed in both probiotic and control arms.[13,15] Motta demonstrated inferior lesion resolution with probiotic monotherapy compared with topical clobetasol, indicating that probiotics alone are insufficient for effective mucosal healing.[13,15]

Pathogenic microbial load and recurrence

One study assessed salivary *Candida* load as a measure of pathogenic microbial burden. Adjunctive probiotic therapy resulted in a significantly greater reduction in candida counts compared with corticosteroid monotherapy (88% vs 62%; p < 0.001), suggesting a potential protective effect against steroid-associated candidiasis.[14]In contrast, the Keller study reported no significant differences in candida load or recurrence between probiotic and placebo groups. None of the included studies provided long-term data on disease recurrence, as follow-up durations were limited to a maximum of

16 weeks. Consequently, the effect of probiotics on sustained remission or relapse prevention remains undetermined.[16]

Secondary outcomes

Quality of life

Quality of life was evaluated in only one study using the Oral Health Impact Profile-14 (OHIP-14). Marlina et al. reported small, non-significant improvements in both probiotic and placebo groups, with changes below the minimal clinically important difference. These findings indicate no perceptible quality-of-life benefit attributable to probiotic therapy.[15]

Immunological and microbiological markers

Two studies assessed inflammatory cytokines using enzyme-linked immunosorbent assays. [12,15]Probiotic therapy was associated with non-significant reductions in IFN-γ and IL-6 levels, suggesting possible immunomodulatory trends without consistent clinical translation. [13,15]One study further demonstrated reduced basal keratinocyte apoptosis and decreased $CD8^+$ T-cell infiltration on histopathological and immunohistochemical analysis following probiotic treatment. Microbiome analysis using 16S rRNA sequencing revealed modest shifts in bacterial composition favouring *Firmicutes* in the probiotic arm; however, alpha and beta diversity indices did not reach statistical significance, limiting conclusions regarding microbiome restructuring.

Safety and compliance

All probiotic interventions were well tolerated, with no serious adverse events reported. Minor adverse effects, including transient gastrointestinal discomfort or taste disturbances, were self-limiting and did not require treatment discontinuation. Compliance rates were between 82% –100%.

Risk of bias

Risk of bias was independently assessed by two reviewers (NS and VJ) using the Cochrane RoB 2 tool, with disagreements resolved by consensus (Figure 3). One study was judged to have a low risk of bias across all domains, reflecting adequate randomization and allocation concealment, minimal deviations from intended interventions, complete outcome data, blinded outcome assessment, and outcomes. In contrast, the remaining studies demonstrated either some concerns or a high risk of bias, primarily due to inadequate reporting of randomization and allocation concealment, limited or unclear blinding of outcome assessors, reliance on subjective outcome measures, attrition with uncertain intention-to-treat analysis, and selective outcome reporting. Overall, three of the four included trials (75%) exhibited important methodological limitations, highlighting the need for more rigorously designed randomized controlled trials with robust allocation concealment, objective outcome measures, appropriate blinding, and transparent reporting.

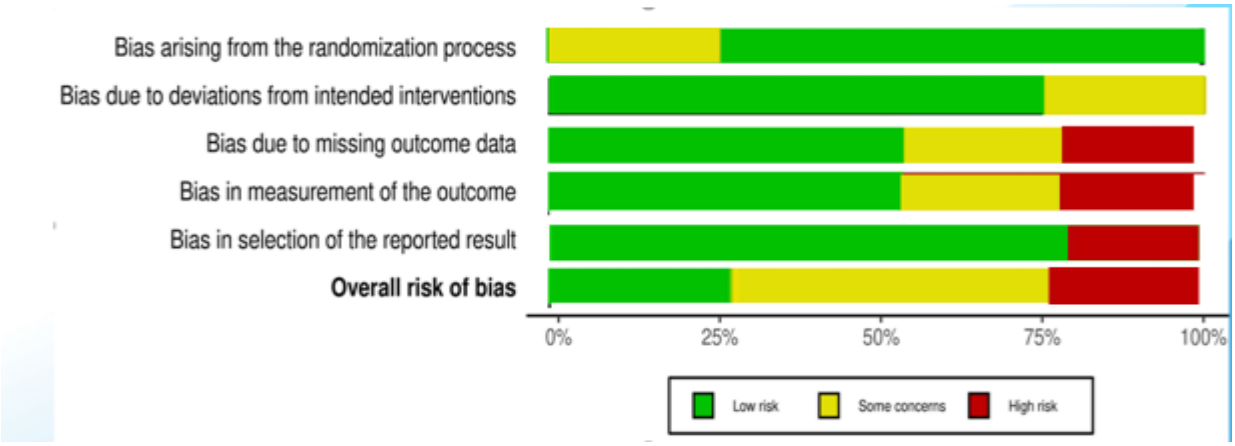

Figure 3. Risk of Bias Assessment

Meta-analysis:

A meta-analysis was not undertaken because of substantial clinical and methodological heterogeneity among the included studies. Key sources of heterogeneity included marked variation in probiotic strains (multi-strain formulations such as VSL#3 versus single-strain preparations including *Lactobacillus reuteri* and *Bifidobacterium animalis* subsp. *lactis* HN019), treatment paradigms (probiotic monotherapy versus adjunctive use with topical corticosteroids), routes and formulations of administration (sachets, lozenges, capsules, and topical suspensions), outcome assessment instruments (NRS, VAS, Thongprasom score, and ODSS), and duration of follow-up (ranging from 30 days to 16 weeks). Furthermore, heterogeneity in study design, sample size, and overall risk of bias introduced additional uncertainty that could have compromised the validity and interpretability of pooled effect estimates.

Statistical heterogeneity (I^2) could not be calculated, as pooling of results was not appropriate due to the lack of comparable outcome measures and insufficient uniform data reporting across studies. In addition, effect size estimation was not feasible**,** as studies reported outcomes using different scales, endpoints, and time points, preventing meaningful quantitative synthesis.

Grading of the evidence (GRADE)

The certainty of evidence for each critical outcome was evaluated using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) approach.The certainty of evidence for each included study was evaluated across the four GRADE domains: risk of bias, inconsistency, indirectness, and imprecision. The study by Ana Carolina Fragoso Motta et al. (2022) was rated as having low certainty of evidence. This was due to concerns regarding risk of bias arising from unclear reporting of randomization and allocation concealment, as well as inconsistency between outcomes, where reductions in immunological markers such as interleukin-6 and interferon-γ did not translate into significant clinical improvement in pain or lesion severity .[15]Although indirectness was not a major concern, imprecision was evident due to the small sample size (n = 22) and borderline statistical significance (p = 0.052). Similarly, the study by Erni Marlina and Richard N. Goodman et al. (2022**)** was also graded as low certainty of evidence. While the study demonstrated relatively low risk of bias with appropriate blinding, inconsistency was observed due to the absence of statistically significant clinical benefit despite trends in immunological outcomes. [13,16] .Imprecision was also present due to the limited sample size (n = 30) and non-significant findings (p = 0.082), although indirectness was minimal as outcomes directly addressed oral lichen planus symptoms. In contrast, the study by Mette K. Keller **et** al. (2018) was

rated as very low certainty of evidence.[14] This was primarily due to high risk of bias related to attrition, lack of intention-to-treat analysis, and incomplete outcome reporting. Additionally, indirectness was significant, as the primary outcome focused on oral candidiasis recurrence rather than core oral lichen planus clinical outcomes. Imprecision further reduced confidence due to the small sample size (n = 22) and absence of significant findings. Finally, the study by Amira Abdel et al. (2025) was rated as moderate certainty of evidence. This study demonstrated relatively low risk of bias and consistent improvements across clinically relevant outcomes, including lesion size reduction, pain relief, and decreased Candida colonization when probiotics were used as adjunctive therapy. Indirectness was minimal, as outcomes directly addressed oral lichen planus management. However, the certainty was downgraded by one level due to imprecision associated with the relatively small sample size (n = 36). Overall, the certainty of evidence across studies ranged from very low to moderate, with most studies downgraded due to imprecision, inconsistency, and methodological limitations, supporting the conclusion that probiotics may have a limited but potentially beneficial adjunctive role in the management of oral lichen planus.

DISCUSSION

This systematic review provides a comprehensive and PRISMA-compliant synthesis of randomized controlled trials evaluating the efficacy of probiotics in the management of oral lichen planus (OLP). It addresses a clinically relevant and insufficiently explored question. By integrating rigorous risk-of-bias (RoB2) and GRADE assessments across heterogeneous probiotic strains, formulations, and treatment paradigms, this review offers an evidence-based framework for the selective incorporation of probiotics into OLP management rather than their routine clinical use. Evidence from four randomized controlled trials involving 110 participants indicates that probiotic monotherapy does not confer consistent clinical superiority over conventional treatment modality [13,15]. Pain reduction outcomes were noted and were statistically significant in study of Erni marlina. In the studies by Fragoso Motta et al. and Marlina, the effects of probiotic therapy were seen in immunological biomarkers, particularly interferon-γ and interleukin-6 levels.[13,15]These immunological changes were not seen with clinical improvement in pain, lesion severity, or disease progression. These findings suggest that probiotics alone are insufficient to alter the clinical course of OLP when compared with established anti-inflammatory therapies. In contrast, adjunctive probiotic therapy combined with topical corticosteroids demonstrated more favourable and clinically relevant outcomes. Adjunctive use resulted in significantly greater lesion improvement as assessed by the Thongprasom score, superior pain relief and marked suppression of oral candidal load (88% vs 62%; $p < 0.001$) compared with corticosteroid monotherapy[14]. These findings are particularly relevant in routine OLP care, where long-term topical steroid use is frequently complicated by secondary candidiasis. Despite these results, the overall certainty of evidence was graded as low due to imprecision, heterogeneity, and methodological limitations in three of the four trials. Among the included studies, Marlina et al. had low overall risk of bias[13]. This study established the safety and tolerability of the multi-strain formulation VSL#3 but demonstrated clinical superiority over conventional treatment outcome. However, favourable trends in salivary IFN-γ levels suggest early immunomodulatory effects, which may require longer treatment duration or adjunctive use to translate into clinical benefit [15]. The trial by Kamal and Amira Abdel ,[14]provided the strong evidence

supporting adjunctive probiotic use. The combination of probiotic capsules with topical clobetasol resulted in superior clinical and microbiological outcomes, underscoring the potential of probiotics to mitigate steroid-associated symbiosis rather than act as primary anti-lichenoid agents. Motta's study ,[9] offered unique histopathological and immunological insights, including reductions in CD8+ lymphocytes and NF-κB expression. However, its classification as grey literature, unclear randomization procedures, and selective outcome reporting substantially limit the reliability and generalizability of its findings. Similarly, Keller's trial evaluating *Lactobacillus reuteri* lozenges was constrained by high attrition, lack of intention-to-treat analysis, and a primary focus on candidiasis rather than OLP disease activity,[16] resulting in largely null OLP-specific outcomes. The adjunctive benefits observed are biologically plausible given the immunopathogenesis of OLP [1-3], which involves T-cell–mediated epithelial damage, cytokine dysregulation, and emerging evidence of oral microbial imbalance characterized by reduced *Lactobacillus* and *Firmicutes* abundance. Probiotics may exert beneficial effects through competitive exclusion of pathogenic microorganisms, enhancement of regulatory T-cell activity, modulation of pro-inflammatory cytokines, and stabilization of mucosal barrier function. Importantly, these mechanisms are more consistent with supportive microbial homeostasis than with direct suppression of lichenoid inflammation.

Beyond OLP, probiotics have demonstrated clinical utility across a range of oral conditions, including reduction of cariogenic bacteria, improvement in periodontal parameters (mean pocket depth reduction of approximately 1 mm), suppression of halitosis-associated pathogens, and reduction of oral *Candida* colonization[22-24]. These broader oral health benefits further reinforce the biological plausibility of probiotics as adjunctive agents in chronic inflammatory oral mucosal disorders. [13,15]No systematic review has specifically evaluated probiotic therapy in OLP, rendering this review the first to synthesize evidence in this domain. However, the findings are concordant with systematic reviews assessing other non-steroidal adjunctive therapies in OLP, which similarly conclude that such interventions rarely outperform topical corticosteroids but may enhance overall disease control when used adjunctively. This pattern parallels observations in other immune-mediated disorders, where probiotics demonstrate modest but supportive effects rather than disease-modifying efficacy. Unlike inflammatory bowel disease or rheumatoid arthritis, where probiotic evidence is more robust, OLP research remains constrained by small sample sizes, heterogeneity, and limited follow-up. Based on current evidence, probiotics should not be recommended as monotherapy for OLP [18,21]. However, selective adjunctive use may be justified in specific clinical scenarios, particularly in patients with mild-to-moderate symptomatic OLP receiving topical corticosteroids, those with recurrent steroid-associated candidiasis, or individuals seeking supportive, non-immunosuppressive adjuncts. Probiotics may be most appropriately applied as short-term adjuncts (approximately 4 weeks), preferably using multi-strain formulations such as VSL#3 or well-characterized strains like *Bifidobacterium animalis* HN019. Their role appears to be supportive rather than curative, with treatment success influenced by strain selection, disease phenotype, treatment duration, and clinician adherence to standardized protocols. As with dentin preservation being more critical than liner selection in restorative dentistry, careful patient selection and treatment context appear to outweigh universal application in determining probiotic efficacy in OLP.

Limitations and future directions

The evidence base is limited by small sample sizes, short follow-up durations (≤16 weeks), substantial heterogeneity in probiotic strains and outcome measures, and methodological weaknesses in most trials. Key outcomes such as recurrence rates, quality-of-life translation, malignant transformation risk, and cost-effectiveness remain unaddressed. These limitations underscore the need for adequately powered, multicentre randomized trials with standardized diagnostic criteria, uniform outcome measures, and long-term follow-up. However, the absence of strong evidence does not imply a lack of clinical utility in all contexts.

Clinical implications:

Probiotic monotherapy has not demonstrated consistent superiority over placebo or established corticosteroid treatment in reducing pain or achieving meaningful lesion resolution.

Probiotics may be considered as adjunctive agents in selected clinical scenarios, particularly in patients receiving long-term topical corticosteroids, where they may help reduce oral candidiasis, support microbial homeostasis, and improve overall treatment tolerability. Their favourable safety profile and high patient acceptability further support selective adjunctive use. Whether specific multi-strain or so-called "immunomodulatory" probiotic formulations confer greater benefit than single-strain preparations remains an open question and warrants further investigation.

CONCLUSION

The findings of this systematic review suggest that probiotic therapy may not consistently provide superior clinical outcomes compared with placebo or standard corticosteroid treatment when used as monotherapy in oral lichen planus. While adjunctive probiotic use alongside topical corticosteroids may be associated with potential supportive benefits, particularly in relation to reduced *Candida* colonization and improved patient-reported comfort, the current evidence base remains limited and heterogeneous**.**

Given the low to moderate certainty of evidence**,** small sample sizes, and methodological limitations of the included studies, definitive clinical recommendations cannot be made at this stage**.** Further well-designed, adequately powered randomized controlled trials with standardized outcome measures are required to better clarify the role of probiotics in the management of oral lichen planus.

DECLARATION

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Competing Interests
The authors declare that there are no competing interests related to this manuscript.

Ethics Statement
As this study is a systematic review of previously published literature and does not involve human participants or animals directly, ethical approval was not required.

Data Availability
All data generated or analyzed during this study are included within this published article. Additional data can be obtained from the corresponding author upon reasonable request.

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REVIEW ARTICLE

BIOMECHANICAL OPTIMIZATION OF IMPLANT-SUPPORTED PROSTHETIC REHABILITATION: EVIDENCE FROM FINITE ELEMENT ANALYSIS.

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Abstract

Background: Implant-supported prosthetic rehabilitation involves complex biomechanical interactions in which stress distribution is governed by implant design, restorative materials, prosthetic configuration, and the condition of supporting tissues. Direct clinical assessment of internal stress remains limited; therefore, finite element analysis (FEA) has become a key tool for investigating these relationships.

Objective: To synthesize current finite element evidence and evaluate how implant geometry, material properties, prosthetic design, and clinical scenarios influence biomechanical performance in implant-supported prostheses.

Methods: A focused narrative review of published three-dimensional FEA studies was conducted. Evidence was analyzed thematically, with emphasis on implant macrodesign, framework and superstructure materials, implant positioning, and prosthetic configurations across clinically relevant scenarios, including short implants in D4 bone, zygomatic implant rehabilitation, socket shield techniques, implant-assisted removable partial dentures, and mandibular full-arch prostheses. Primary outcomes included von Mises stress, strain, displacement, and micromovement.

Results: Across the reviewed studies, implant macrodesign significantly influenced peri-implant biomechanics, particularly in compromised bone. Wider platform-switched short implants and square thread geometries consistently reduced stress, strain, and micromovement. Framework material stiffness also played a critical role: rigid materials such as zirconia, cobalt–chromium, and titanium decreased stress within implants and prosthetic components, whereas more flexible materials increased load transfer to these structures. In full-arch models, graphene frameworks demonstrated lower peri-implant stress compared with titanium. Implant positioning in distal-extension removable partial dentures showed comparable biomechanical behavior between premolar and molar sites. In socket shield models, increasing root fragment thickness led to progressive increases in stress and strain in both the retained root and surrounding bone.

Conclusions: Biomechanical performance in implant-supported prosthetic rehabilitation is governed by the combined interaction of implant geometry, material stiffness, prosthetic design, and anatomical context rather than by any single factor. Finite element analysis provides valuable comparative insight into stress distribution patterns and supports more informed, biomechanics-driven treatment planning in implant prosthodontics.

Keywords: FEA, dental implant, socket shield, implant design, prosthetic rehabilitation

INTRODUCTION

Implant-supported prosthetic rehabilitation has become a central treatment modality for the management of partial and complete edentulism, offering functional stability, improved load distribution, and enhanced patient satisfaction when compared with conventional removable or tissue-supported approaches. Nevertheless, the long-term success of these rehabilitations depends on a complex interaction between implant design, prosthetic configuration, framework material, bone quality, and loading conditions. Because these factors influence stress transfer to the peri-implant bone and prosthetic components, understanding their biomechanical behavior is essential for achieving predictable clinical outcomes [1-7]. In clinical practice, biomechanical challenges arise in a variety of prosthodontic scenarios. These include rehabilitation of severely resorbed ridges with short implants, management of atrophic maxillae with zygomatic implants, full-arch restorations supported by reduced numbers of implants, implant-assisted distal extension removable partial dentures, and immediate implant placement in esthetically demanding areas. Each

of these situations presents a different mechanical environment, yet all share the same fundamental requirement: forces generated during function must be transferred in a way that minimizes harmful stress concentrations in bone, implants, abutments, screws, retained root fragments, and prosthetic frameworks [3,4,7].

Among the variables that may alter this biomechanical response, implant macrodesign has received considerable attention. Diameter, thread configuration, length, and platform switching are all believed to influence stress, strain, and micromovement at the bone-implant interface, especially in compromised bone. This is particularly relevant in D4 bone, where reduced density may compromise implant stability and increase the risk of unfavorable load transfer. Finite element findings from the included studies indicate that wider platform-switched short implants and favorable thread geometries may reduce peri-implant stress and improve biomechanical behavior under immediate loading conditions [1,8].

Material selection is another critical determinant of prosthetic performance. Framework and superstructure materials do not simply serve a restorative function; they actively influence the way occlusal loads are distributed throughout the implant-prosthesis-bone complex. In full-arch and zygomatic implant reconstructions, variations in material stiffness may alter stress concentration within implants, prosthetic screws, and surrounding bone. The included studies show that both conventional materials, such as titanium, cobalt-chromium, and zirconia, and newer alternatives such as graphene-based frameworks, may affect load transfer differently depending on the restorative design and clinical indication [3,5,6].

In addition to implant and material factors, prosthetic design itself remains a major source of biomechanical variation. For example, reducing the number of implants in a full-arch restoration may increase stress around distal implants and framework components, while implant position in implant-assisted removable partial dentures may alter leverage, displacement, and stress transmission to supporting structures. Likewise, in immediate implant placement with the socket shield technique, the thickness of the retained root fragment may influence stress distribution within both the fragment and adjacent bone. These observations emphasize that prosthetic rehabilitation should not be evaluated only from a surgical or restorative perspective, but rather as an integrated biomechanical system [2,4,7].

Because direct clinical measurement of internal stress and strain is difficult, finite element analysis has become one of the most widely used computational tools for investigating the biomechanics of implant dentistry. FEA allows complex anatomical structures and prosthetic assemblies to be modeled under controlled loading conditions, making it possible to compare alternative implant configurations, framework materials, and restorative designs. Across the selected papers, FEA was used to study short implants in poor-quality bone, residual root structures in socket shield procedures, zygomatic implant-supported superstructures, implant-assisted removable partial dentures, and full-arch mandibular prostheses supported by three or six implants. Collectively, these studies demonstrate the versatility of finite element modelling as a method for identifying stress concentration areas and exploring biomechanically favorable treatment designs [2-4,7].

At the same time, the value of finite element evidence lies not only in comparing isolated variables, but also in revealing broader trends relevant to clinical prosthodontics. Across these five studies, recurring themes include the importance of controlling peri-implant stress, selecting framework materials with appropriate stiffness, optimizing implant configuration in anatomically compromised situations, and recognizing that seemingly minor design modifications may produce meaningful biomechanical differences. These findings support the view that treatment planning in implant prosthodontics should be guided not only by anatomy and prosthetic feasibility, but also by biomechanical predictability[9,10].

Therefore, the purpose of this review is to synthesize the findings of these finite element studies and to critically examine how implant design, framework material, prosthetic configuration, and clinical scenario influence biomechanical behavior in implant-supported prosthetic rehabilitation. By integrating evidence from these selected papers, this review aims to provide a focused understanding of how computational biomechanical analysis can inform prosthodontic decision-making and support the optimization of restorative treatment strategies.

METHODOLOGY

his paper was prepared as a focused narrative review of selected finite element (FE) investigations addressing the biomechanics of implant-supported prosthetic rehabilitation. The literature search was conducted using electronic databases, including PubMed, Scopus, and Web of Science. The search focused on studies published in recent years that investigated the biomechanics of implant-supported prosthetic systems using finite element analysis (FEA).

This review was designed to provide a critical and clinically oriented synthesis rather than a systematic review or meta-analysis. Its primary aim was to integrate evidence on how implant design, prosthetic configuration, framework materials, and clinical treatment scenarios influence stress distribution and related biomechanical behavior in implant dentistry.

Studies were included if they employed three-dimensional finite element analysis to evaluate stress distribution in implant-supported prosthetic systems and reported quantitative biomechanical outcomes such as von Mises stress, strain, displacement, or micromovement. Studies that were not directly related to prosthetic biomechanics or lacked quantitative biomechanical outcomes were excluded.

The literature considered in this review was limited to previously published in silico studies directly relevant to implant-supported prosthetic biomechanics. The selected studies represented a range of clinically relevant scenarios, including short implants in poor-quality bone, socket shield techniques in immediate implant placement, zygomatic implant-supported rehabilitations, implant-assisted distal extension removable partial dentures, and mandibular full-arch prostheses with varying implant configurations and framework materials. This approach ensured that the review remained focused on prosthodontically relevant applications of finite element analysis while capturing variability in biomechanical design and clinical context.

All included studies were analyzed in full text and synthesized using a thematic approach. Rather than presenting findings chronologically, the studies were grouped according to major biomechanical themes, including implant macrodesign and peri-implant biomechanics, the effects of framework and superstructure materials, implant positioning and prosthetic configuration, and biomechanical behavior in specific clinical situations. This structure enabled comparison of related findings across different models and facilitated the identification of broader biomechanical patterns relevant to prosthodontic treatment planning.

For each study, the analysis focused on key methodological and outcome-related variables, including simulation objectives, digital model characteristics, software platforms, assumptions regarding material properties, implant and prosthetic design variables, loading conditions, and primary biomechanical outcomes. Particular attention was given to commonly used FEA outputs such as von Mises stress, strain, displacement, and micromovement, as these parameters formed the basis for comparison across studies.

Figure 1 illustrates the principal biomechanical outcome parameters reported in the included FEA studies. These parameters represent the main indicators used to evaluate stress distribution and mechanical behavior in finite element models.

Parameter	Definition	Clinical Relevance
von Mises Stress	Equivalent stress in materials	Predicts risk of mechanical failure
Strain	Deformation of bone	Indicates risk of bone remodeling/resorption
Displacement	Movement under load	Reflects prosthetic stability
Micromovement	Small implant motion	Critical for osseointegration success

Figure 1 Biomechanical Outcome Parameters in FEA Studies

The included studies shared methodological similarities, such as three-dimensional modeling, defined boundary conditions, and controlled loading protocols. However, they differed in terms of geometric modeling, material assumptions, force application, and the specific structures analyzed.

Due to this heterogeneity, the synthesis was descriptive and interpretive rather than quantitative. Statistical pooling was not performed because of substantial variability in simulated anatomy, implant dimensions, prosthetic designs, material properties, and loading conditions. Instead, emphasis was placed on identifying recurring biomechanical trends, clinically relevant differences, and areas of agreement across the literature.

In addition to summarizing findings, this review included a critical appraisal of the inherent limitations of finite element analysis. Common modeling assumptions—such as isotropic and homogeneous material behavior, idealized bone–implant contact, simplified loading conditions, and limited representation of biological adaptation—were considered when interpreting the results. This ensured that the conclusions remained methodologically balanced and clinically applicable.

As a narrative review, this study did not follow a formal systematic review protocol and may therefore be subject to selection bias. However, efforts were made to include

representative studies covering a broad spectrum of clinically relevant biomechanical scenarios.

Overall, the methodology was intended to provide a structured synthesis of finite element evidence relevant to implant-supported prosthetic rehabilitation. By organizing the literature around shared biomechanical themes, the review clarifies how computational modeling contributes to understanding treatment design, material selection, and stress distribution in prosthodontic practice.

RESULTS

The reviewed finite element studies consistently demonstrated that biomechanical behavior in implant-supported prosthetic rehabilitation is strongly influenced by the interaction between implant design, framework or superstructure materials, prosthetic configuration, and the specific clinical scenario being simulated. Across the included papers, the principal outcomes assessed were von Mises stress, strain, displacement, and micromovement, which were used to compare alternative treatment designs under controlled loading conditions. Despite differences in model construction and clinical application, several recurring biomechanical patterns were identified.

One major finding was that implant macrodesign significantly affects peri-implant biomechanics, particularly under compromised bone conditions.

Figure 2 summarizes the relationship between implant design variables and their biomechanical effects.

Parameter	Variations Studied	Biomechanical Effect	Clinical Interpretation
Implant Diameter		Wider implants ↓ stress, ↓ strain, ↓ micromovement	Preferred in poor-quality (D4) bone
Thread Design		Square threads → more favorable stress distribution	Improved load transfer at bone–implant interface
Platform Switching		Reduced crestal bone stress	Enhances peri-implant bone preservation
Implant Length		Short implants ↑ stress unless compensated by diameter	Acceptable with optimized design

Figure 2. Comparison of Implant Design Variables and Biomechanical Outcomes

In the study of short implants placed in D4 bone, increasing implant diameter was associated with reduced peri-implant von Mises stress, reduced strain, and reduced micromovement under both axial and oblique loading conditions. Among the tested designs, the 6 mm diameter platform-switched short implant demonstrated the most favorable biomechanical performance, with peri-implant von Mises stress values of 3.3 MPa (axial loading) and 35.1 MPa (non-axial loading),

strain values of 194 Ɛ and 484 Ɛ, and micromovement values of 0.7 μm and 1.3 μm, respectively. In the same study, square microthreads showed superior performance compared with buttress and triangular thread designs, producing more favorable stress distribution in the surrounding bone tissue [1].

A second major pattern was the significant influence of framework and superstructure material stiffness on stress transfer within implant-supported restorations.

The mechanical behavior of commonly used framework materials is summarized in Table 1.

Table 1. Framework / Superstructure Materials and Stress Distribution

Material	Elastic Modulus	Observed Behavior	Biomechanical Outcome
Titanium	High	Standard reference material	Moderate stress distribution
Cobalt–Chromium	Very high	High rigidity	Reduced stress in implants/screws
Zirconia	High	Stiff ceramic	Favorable stress reduction
PEEK	Low	Flexible behavior	Higher stress in implants
Carbon fiber polymer	Moderate	Semi-rigid response	Intermediate performance
Graphene	Variable (advanced)	High strength with flexibility	Reduced peri-implant stress (experimental evidence)

In the zygomatic implant model, all tested superstructure materials produced a relatively homogeneous strain distribution in the supporting bone, indicating that each material could potentially be used for reconstruction of the edentulous maxilla. However, stiffer materials such as zirconia, cobalt–chromium, and titanium were more effective in reducing stresses in the zygomatic implants and prosthetic screws compared with more flexible materials such as carbon fiber polymer and PEEK. This suggests that although multiple materials may be biomechanically acceptable, those with a higher elastic modulus may be more advantageous when the clinical objective is to minimize stress concentration in implants and fixation components [3,6].

A similar material-dependent trend was observed in mandibular full-arch models comparing titanium and graphene frameworks. In all simulated conditions, the highest stresses were consistently concentrated at the neck of the most distal implant. However, graphene frameworks generally resulted in lower peri-implant stress compared with titanium frameworks. In the conventional six-implant model, cortical bone stress in the implant region was 25.27 MPa for titanium and 12.18 MPa for graphene. In the three-implant tilted model under vertical loading, cortical stress values were 70.31 MPa for titanium and 21.27 MPa for graphene. These findings indicate that framework material significantly influences load transfer to the supporting bone, with graphene demonstrating more favorable stress distribution in the tested full-arch mandibular configurations [5].

The reviewed studies also indicated that prosthetic configuration and implant position may influence biomechanical response, although not always in a statistically significant manner. In the implant-assisted distal extension removable partial denture model, no statistically significant differences were observed between premolar and molar implant placement in terms of von Mises stress or displacement. Although the premolar group demonstrated slightly higher values, the differences were not statistically significant, suggesting that both implant positions are biomechanically acceptable under the tested loading conditions. At 125 N, framework stress values were 28.71 ± 1.10 MPa for the premolar group and 25.56 ± 4.89 MPa for the molar group, indicating comparable mechanical performance [4].

In contrast, the socket shield model demonstrated that relatively small geometric changes in retained root fragments may produce progressive increases in stress and strain. As root fragment thickness increased from 0.5 mm to 2.0 mm during immediate implant placement, both stress and principal strain increased in the residual root and surrounding bone. Maximum stress in the root fragment increased from 12.68 MPa at 0.5 mm thickness to 28.74 MPa at 2.0 mm thickness, while bone stress increased from 5.61 MPa to 11.38 MPa over the same range. Principal strain values followed a similar increasing trend.

Although shield thicknesses between 0.5 mm and 2.0 mm did not produce catastrophic stress conditions in any model, the results indicated that increasing shield thickness is associated with progressively higher biomechanical loading. Based on these findings, a thickness of approximately 1.5 mm may represent a more favorable upper limit from a biomechanical standpoint [2].

A comparison of clinical scenarios and their biomechanical implications is presented in Table 2.

Table 2. Prosthetic Configuration & Clinical Scenario Analysis

Clinical Scenario	Variable Studied	Key Finding	Clinical Implication
Short implants (D4 bone)	Diameter, thread design	Wider implants and square threads most favorable	Macrodesign can compensate for poor bone quality
Zygomatic implants	Material stiffness	Stiffer materials reduce stress	Prefer rigid frameworks when possible
Full-arch prosthesis	Framework material	Graphene reduces stress vs titanium	Promising but still experimental
Implant-assisted RPD	Implant position	Premolar ≈ molar	Flexible implant placement possible
Socket shield	Root fragment thickness	Increased thickness → increased stress	Limit thickness (~1.5 mm)

A visual comparison of stress distribution across different clinical scenarios is presented in Figure 3.

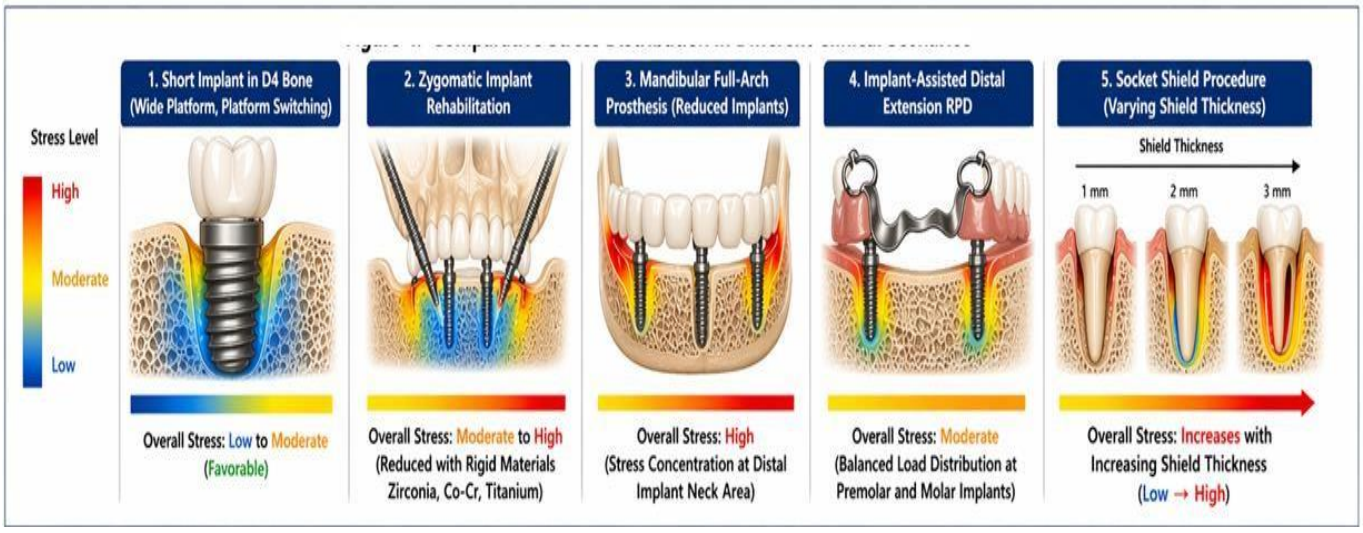

Figure 3. Comparative stress distribution patterns across implant-supported prosthetic scenarios

Comparative stress patterns in five clinical scenarios simulated by finite element analysis are illustrated. Color maps indicate von Mises stress distribution in bone and peri-implant regions. Stress levels vary according to implant design, prosthetic configuration, and clinical condition.

When considered collectively, the reviewed evidence indicates that favorable biomechanical performance is generally associated with designs that reduce stress concentration at critical interfaces, particularly in peri-implant bone, implant neck regions, and prosthetic connection areas. Wider short implants with square thread designs, stiffer superstructure materials in zygomatic reconstructions, graphene frameworks in full-arch mandibular models, and clinically adaptable implant positions in distal-extension removable prostheses all demonstrated biomechanical advantages within their respective simulation conditions. At the same time, the results highlight that the effect of any single variable cannot be

interpreted in isolation, as overall stress distribution depends on the complex interaction between implant geometry, restorative design, material properties, and anatomical conditions [3–5,7].

Overall, the findings support the usefulness of finite element analysis as a comparative tool for evaluating biomechanically favorable treatment options in implant prosthodontics. The evidence consistently demonstrates that computational modeling can detect meaningful differences between alternative implant designs, materials, and prosthetic configurations, thereby contributing to a more informed biomechanical interpretation of treatment planning decisions.

DISCUSSION

The findings of this review suggest that finite element analysis offers a valuable framework for interpreting how biomechanical behavior in implant-supported prosthetic rehabilitation is shaped by multiple interacting variables. Although each study focused on a specific clinical scenario, a consistent pattern emerged: successful outcomes depend not only on achieving osseointegration but also on effectively controlling stress distribution within the implant–prosthesis–bone complex [11–13]. At the same time, these observations should be interpreted with caution, as they are based on computational models that inevitably simplify biological reality.

One of the most consistent observations across the reviewed evidence is the importance of minimizing peri-implant stress in compromised anatomical conditions. In the short implant model in D4 bone, wider platform-switched implants with square threads showed the most favorable distribution of stress, strain, and micromovement, suggesting that macrodesign modifications may partially compensate for poor bone quality. This is clinically significant because it supports the rationale for using short, wide-diameter implants in anatomically restricted sites where vertical bone height is limited and more invasive augmentation procedures may be undesirable. These findings imply that implant design should be regarded not merely as a structural feature but as a biomechanical strategy for improving force transmission in weak supporting bone [1,14].

The review also highlights the strong influence of restorative material properties on stress transfer. Both the zygomatic implant study and the full-arch mandibular framework study demonstrated that material stiffness substantially alters biomechanical response. In zygomatic rehabilitation, stiffer superstructure materials such as zirconia, cobalt–chromium, and titanium reduced stress in implants and prosthetic screws more effectively than more flexible materials. By contrast, in mandibular full-arch models, graphene frameworks showed lower peri-implant stress than titanium under the simulated loading conditions. These findings suggest that the “optimal” material cannot be defined universally but depends on the specific biomechanical objective. A stiffer material may reduce mechanical demand in prosthetic screws and implants, whereas alternative materials may improve load dissipation to surrounding structures in different configurations. Therefore, framework selection should be prosthetically and anatomically contextual rather than based solely on familiarity or conventional preference [3,15].

Another important point arising from the reviewed studies is that biomechanical optimization does not always require anatomically ideal treatment conditions. In the implant-assisted distal extension removable partial denture model, premolar and molar implant positions showed no statistically significant differences in stress distribution or displacement. This finding has practical relevance because distal-extension cases are often constrained by ridge resorption, mental foramen position, or limited posterior bone availability. From a clinical perspective, the results suggest that when distal placement is not feasible, a mesially positioned implant may still provide an acceptable biomechanical alternative. This shifts the focus from achieving a theoretically ideal position to selecting a clinically feasible and biomechanically adequate solution [4,16].

The socket shield study further reinforces the concept that even relatively small design or dimensional changes may alter the biomechanical environment. As the thickness of the retained root fragment increased, both stress and principal strain in the root structure and surrounding bone increased progressively. This suggests that preservation-oriented procedures, although attractive from an esthetic and tissue-maintenance perspective, must also be evaluated from a biomechanical standpoint. In other words, biologically conservative treatment concepts do not automatically ensure mechanically favorable conditions. The conclusion that a thickness of approximately 1.5 mm may represent a safer upper practical threshold reflects the broader principle that prosthodontic and implant planning should balance tissue preservation with mechanical stability [2,17].

Taken together, these results support the view that implant-supported prosthetic rehabilitation should be interpreted as an integrated system rather than a collection of isolated components. Changes in one variable—such as implant diameter, thread design, superstructure stiffness, or implant position—may reduce stress in one region while redistributing it elsewhere. This systems-based perspective is particularly important in full-arch reconstructions and complex implant scenarios, where small changes in geometry or material behavior may have amplified effects across the restoration [1,5]. The reviewed evidence therefore argues against simplistic conclusions and instead supports a more comprehensive biomechanical approach to treatment planning.

At the same time, the discussion of these findings must acknowledge the methodological limitations inherent to finite element analysis. Across the reviewed studies, simulations relied on assumptions such as homogeneous or isotropic material behavior, idealized bone–implant contact, simplified loading conditions, and limited representation of biological adaptation over time. Even when anisotropic properties or convergence testing were incorporated, the models remained simplifications of highly complex clinical conditions. Consequently, the findings should not be interpreted as direct clinical predictions but rather as comparative biomechanical indicators that help identify trends, risk zones, and potentially favorable treatment strategies.

Despite these limitations, the translational value of finite element evidence remains substantial. The reviewed studies demonstrate that computational modeling can guide hypothesis generation, refine prosthetic design choices, and support clinical decision-making in scenarios where direct measurement of internal stress is not feasible. This is particularly valuable in prosthodontics, where clinicians often choose among several technically viable options that differ in their long-term mechanical implications. Finite element analysis does not replace clinical evidence but enhances preclinical reasoning by clarifying how different configurations may behave before clinical application.

Overall, the reviewed evidence suggests that biomechanically favorable implant rehabilitation is more likely to be achieved when treatment planning incorporates design-based stress control from the outset. Wider short implants with favorable thread geometry, careful material selection for superstructures and frameworks, context-sensitive implant placement, and awareness of the mechanical implications of tissue-preservation techniques all contribute to more balanced stress distribution. Thus, the primary contribution of these studies lies not only in comparing isolated designs but also in demonstrating that computational biomechanics can serve as a critical bridge between restorative planning and mechanical predictability in implant prosthodontics.

To summarize the integrated biomechanical effects across all reviewed scenarios, Table 3 presents a consolidated synthesis of key variables and their clinical implications.

Table 3. Integrated biomechanical response of implant-supported prosthetic systems

Factor	Modification	Biomechanical Effect	Clinical Interpretation
Implant diameter	Increase	↓ Stress, ↓ micromovement	Preferred in poor bone quality
Thread design	Square vs triangular	Square = more favorable stress distribution	Improves load transfer
Platform switching	Present	↓ Crestal bone stress	Reduces marginal overload
Framework stiffness	High (Ti, Co-Cr, Zr)	↓ Implant/screw stress	More favorable for rigid load transfer
Flexible frameworks	PEEK, polymer	↑ Implant stress	More stress absorption in prosthesis
Graphene framework	Advanced composite	↓ Bone stress (experimental)	Promising but not clinical standard
Implant position	Premolar vs molar	Similar biomechanical outcome	Flexible placement possible
Socket shield thickness	Increase	↑ Stress & strain	Limit ~1.5 mm recommended

Figure 4 illustrates the key factors influencing biomechanical behavior in implant-supported prosthetic rehabilitation. Implant geometry, bone quality, framework material, and loading direction interact to determine stress transfer pathways. These interactions affect peri-implant bone, implant components, framework, micromotion, and strain distribution, which ultimately influence long-term clinical success.

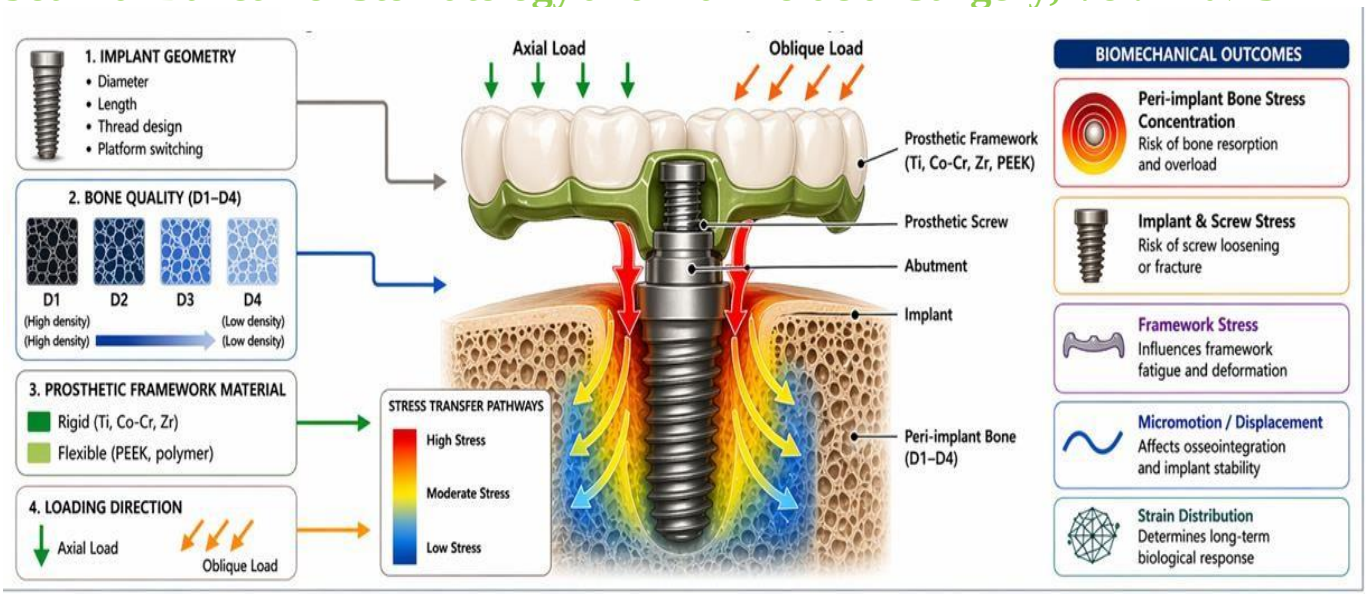

Figure 4. Biomechanical interaction model of implant-supported prosthetic rehabilitation

Limitations

Despite the valuable insights provided by this review, several limitations must be acknowledged. First, the included studies are based exclusively on finite element analysis (FEA), which inherently relies on mathematical modeling and computational assumptions rather than direct clinical or in vivo measurements. As a result, all findings should be interpreted within the context of theoretical simulations rather than real biological conditions.

A major limitation common to all included FEA studies is the simplification of complex biological systems. Most models assume homogeneous, isotropic, and linearly elastic material properties for bone, implants, and prosthetic components, whereas, in reality, bone is anisotropic, heterogeneous, and exhibits time-dependent behavior. These simplifications may influence the absolute values of stress and strain reported in the studies, even if relative comparisons between models remain valid.

In addition, the majority of simulations used idealized bone–implant contact conditions, typically assuming complete osseointegration with perfect bonding between the implant and bone. This does not fully reflect clinical reality, where microgaps, partial osseointegration, or variations in bone quality may significantly alter stress distribution and micromovement.

Another limitation is the use of static loading conditions in most models. Functional mastication is a dynamic process involving cyclic, multidirectional forces that vary in magnitude and direction over time.

Static or simplified loading scenarios may therefore underestimate fatigue-related phenomena and the long-term biomechanical behavior of implant-supported restorations.

Furthermore, there was considerable heterogeneity among the included studies in terms of implant geometry, prosthetic design, loading magnitude, boundary conditions, and software platforms used for analysis. This variability limits direct comparability between studies and prevents quantitative synthesis of results. Although a thematic synthesis was performed, the lack of standardized modeling protocols remains a significant limitation in FEA-based literature.

It is also important to recognize that biological processes such as bone remodeling, adaptation, and resorption were not incorporated into the simulations. Consequently, the reviewed studies primarily reflect initial mechanical responses rather than long-term biological–mechanical interactions that occur in clinical settings.

Future Directions

Future research in finite element analysis of implant-supported prosthetic rehabilitation should aim to improve the biological realism and clinical applicability of computational models. One important direction is the development of more advanced material models that better represent the anisotropic, viscoelastic, and heterogeneous properties of bone and soft tissues. Incorporating patient-specific bone quality derived from imaging data, such as CT-based density mapping, could significantly enhance the accuracy of biomechanical predictions.

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Another important area for future investigation is the integration of dynamic and fatigue loading conditions into finite element simulations. Since implant-supported prostheses are subjected to repeated cyclic forces during mastication, future models should incorporate time-dependent loading to better simulate clinical function and to evaluate long-term failure risks such as screw loosening, implant fatigue, and marginal bone loss.

The incorporation of bone remodeling algorithms into FEA models also represents a critical future advancement. By simulating adaptive bone responses to mechanical loading over time, researchers could better understand how stress distribution influences long-term peri-implant bone stability and resorption patterns.

In addition, future studies should focus on standardizing finite element modeling protocols, including boundary conditions, material properties, and loading parameters. Such standardization would improve comparability between studies and facilitate the development of more robust evidence synthesis in biomechanical implant research.

Another promising direction is the use of patient-specific, three-dimensional models derived from real clinical cases. Personalized finite element models could allow clinicians to simulate different implant positions, prosthetic designs, and material combinations before treatment, thereby supporting individualized treatment planning and precision prosthodontics.

Finally, future research should explore the integration of finite element analysis with artificial intelligence and machine learning approaches. Such integration may enable the prediction of biomechanical outcomes across large datasets, allowing faster optimization of implant designs and prosthetic configurations based on clinical variables.

This review highlights the important role of finite element analysis in advancing the biomechanical understanding of implant-supported prosthetic rehabilitation. Across different prosthodontic scenarios, the evidence consistently shows that stress distribution is not determined by a single variable but by the combined influence of implant geometry, restorative material, prosthetic design, and anatomical context. The reviewed studies demonstrate that wider platform-switched short implants with favorable thread geometry may improve biomechanical behavior in poor-quality bone, that framework and superstructure stiffness substantially influence load transfer in full-arch and zygomatic rehabilitations, and that clinically constrained alternatives, such as premolar implant positioning in distal-extension removable prostheses, may still provide acceptable biomechanical performance.

At the same time, procedures aimed at preserving tissues, such as the socket shield technique, must also be evaluated from a mechanical perspective because increasing structural dimensions may alter stress patterns in both retained tissues and surrounding bone. Taken together, these findings indicate that finite element evidence is valuable not only for comparing specific treatment options but also for supporting a more integrated approach to implant prosthodontic planning.

Although computational models cannot fully reproduce the complexity of the biological environment, they remain highly useful for identifying stress concentration zones, clarifying biomechanical tendencies, and guiding the optimization of implant-supported restorative strategies. Therefore, finite element analysis should be regarded as an important adjunct in prosthodontic research and treatment planning, with particular relevance for improving mechanical predictability in complex implant rehabilitation.

Finite element evidence may assist clinicians in selecting implant designs, framework materials, and prosthetic configurations that promote more favorable stress distribution and improved mechanical predictability in complex implant rehabilitation. Nevertheless, further validation through clinical and long-term observational studies is necessary to confirm how closely these computational findings translate into real-world outcomes.

CONCLUSION

Biomechanical performance in implant-supported prosthetic rehabilitation is influenced by the interaction of implant geometry, material properties, prosthetic design, and anatomical conditions rather than by any single variable alone. Finite element analysis provides a useful comparative framework for understanding these relationships and for identifying treatment approaches that may reduce unfavorable stress concentration. While such models cannot fully replicate clinical reality, they offer valuable insight for improving preclinical planning and enhancing mechanical predictability in complex implant rehabilitation.

DECLARATIONS

Ethical Approval

Not applicable.

Consent to Participate

Not applicable.

Competing Interests

The authors declare no conflict of interest.

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REVIEW ARTICLE

METASTATIC CANCERS TO THE ORAL CAVITY: AN OVERVIEW

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Abstract

Metastasis is a complex biological process that begins when cancer cells separate from the original tumor and spread to other tissues and organs, causing morbidity and death. Metastatic cancers to the oral cavity are rare and frequently associated with widespread disease. The diagnosis of these tumors is challenging, and their prognosis is poor. The purpose of this paper is to review the pathogenesis, clinical and histological features, treatment options, and prognosis of metastatic cancers that affect the oral cavity.

Keywords: Cancer, metastasis, oral cavity.

INTRODUCTION

According to the National Cancer Institute, cancer is a disease in which some of the body's cells grow uncontrollably and may spread to other parts of the body.[1] It is characterized by complex, sequential, and irreversible dysregulated processes. Metastasis is a complex biological process that initiates with the detachment of cancer cells from the primary tumor, followed by dissemination into distant tissues and organs, resulting in morbidity and mortality.[2]

Metastatic cancers to the oral cavity are rare (1% to 3% of all malignant oral neoplasms) and frequently associated with widespread disease and poor prognosis. They can affect the soft tissues of the mouth, the jawbones, or both of them.[2,3] The kidney, the lung, the breast, the prostate, the bone, the colon, and the adrenal gland are among the initial sites of malignancies that spread to the oral region, and the mandible, especially the molar region, is the most frequently involved site.[4,5]

The distribution of primary tumors and their typical oral metastatic patterns is summarized in Table 1.

Table 1. Primary Tumor Sites and Frequency of Oral Metastasis

Primary tumor site	Relative frequency	Common oral location	Typical pattern
Lung	High	Gingiva, jawbones	Osteolytic, fast-growing
Breast	High	Mandible, soft tissue	Mixed lytic/blastic
Kidney	Moderate–High	Gingiva, tongue	Highly vascular soft tissue mass
Prostate	Moderate	Mandible	Osteoblastic lesions
Colon/Rectum	Low–Moderate	Jawbones	Osteolytic lesions
Thyroid	Low	Jawbones/soft tissue	Vascular lesion, bleeding tendency
Adrenal gland	Rare	Mandible	Osteolytic destructive lesion

Clinically, metastatic cancers to the oral cavity often show non-aggressive signs that look like harmless or reactive lesions or even simple odontogenic infections; consequently, it may be difficult for both the pathologist and the dentist to diagnose them.[2] Actually, the pathologist must identify the location of the tumor's origin, and the clinician must recognize the possibility that a lesion could be a metastasis. These tumors are very important from a clinical perspective because they could represent the first symptom of an undetected cancer at a distant primary site or the first sign of a known tumor spreading from its originating site.[2,5,6] The aim of this paper was to review the pathogenesis and clinical and histological features, as well as the treatment and prognosis of metastatic cancers to the oral cavity.

Epidemiology

Metastatic cancers to the oral cavity are rare, occurring in about 1% to 3% of cases.[7-9] They are mostly patients aged between 40 and 70 years. Generally, in young patients, metastases are in jaw bones more than in soft tissues. The male-to-female ratio of metastases in oral soft tissues was 2:1, while the distribution in the jawbone was nearly equal by gender.[2] A systematic review conducted by Macedo et al. and published in 2023 found that male patients represented the majority (1.7:1), and most of them were in their sixth decade of life. In 51% of cases, the oral metastatic lesion was the initial indication of malignancy. Furthermore, 60% of them developed metastases to other locations by the time of clinical evaluation.[10] Soft tissues, especially the gingiva, account for 58% of oral cavity metastases; the jaws account for 42%, with the mandible having the highest prevalence (89%). The lungs were the most frequently reported primary site of metastatic lesions in the jaws and oral soft tissues.[7,10]

Pathogenesis

Metastasis refers to the process by which a primary tumor invades surrounding tissues and disseminates cancer cells through lymphatic or blood vessels. As these circulating cancer cells travel throughout the body, they can survive and eventually settle in the microvasculature of target organs, where they extravasate through the walls of blood vessels.

These cancer cells enter and progress toward visible metastases. The tumor microenvironment and/or the functions of the cancer cells themselves support these phases.[2,11] Cancer cells must have specific characteristics that enable them to survive in new environments. In fact, the establishment of a successful metastatic area depends on these cells' ability to maintain distinct microenvironments throughout the metastatic process. Furthermore, angiogenesis and revascularization, which involve creating new blood vessels, are essential for tumor growth.[2,11-13] The formation of the tumor vasculature depends on numerous proangiogenic and antiangiogenic, inflammatory, and coagulation factors.[2,14,15] Additionally, hypoxia within the tumor mass stimulates angiogenesis during the early stages of tumor growth by promoting the up-regulation of specific transcription factors that regulate proangiogenic signals, primarily the vascular endothelial growth factors (VEGFs).[14-17] Considerable evidence suggests that the spread of various types of cancer to distant organs is a controlled, site-specific process rather than an accidental occurence.[2,12] Several studies show that many molecular pathways are involved in the lymphatic and hematogenous dissemination of various malignancies.

The oral region is not a favored site for the initial spread of a cancer from its original site but is usually the result of secondary spread from other metastatic lesions. In fact, it is unclear what causes the metastatic cancers in the jawbones. Bone, especially the one with red marrow, is often regarded as a preferred site for the metastatic process by many primary malignancies, particularly those originating in the lungs, breast, prostate, and kidneys.[2,18] Although jawbones typically contain minimal active marrow, particularly in older adults, remnants of hematopoietic active marrow can still be found in the posterior regions of the mandible. These areas are known to attract metastatic tumor cells.[2] As for the oral soft tissues having a rich complex of capillaries, they can easily capture malignant cells. Additionally, chronic inflammation is associated with various stages of tumorigenesis, such as cellular transformation, promotion, survival, proliferation, invasion, angiogenesis, and metastasis.[4,19]

Clinical features

The clinical features of metastatic cancers to the oral cavity are variable. A comparative overview of the main differences between soft tissue and jawbone metastases is presented in Table 2.

Table 2. Clinical Features: Oral Soft Tissue vs Jawbone Metastases

Feature	Soft tissue metastasis	Jawbone metastasis
Most common site	Gingiva, tongue	Posterior mandible
Growth rate	Rapid	Moderate–rapid
Pain	Variable	Common
Swelling	Exophytic mass	Intraosseous expansion
Ulceration	Frequent	Less frequent
Bleeding	Very common	Occasional
Paresthesia	Rare	Common (“numb chin syndrome”)
Misdiagnosis	Pyogenic lesion, hyperplasia	Osteomyelitis, cyst, periodontitis

Metastatic cancers to the oral cavity can grow fast, causing pain, dysphagia, disfigurement, and intermittent bleeding.

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The majority of them presented as tumors, masses, and swelling, mostly larger than 10 mm in diameter. In the soft tissues, the most commonly involved site is the attached gingiva, preceded by the tongue. The lesions are typically firm and irregular, with or without an ulcerated surface, and they are more often associated with bleeding compared to those in the jaws, which were frequently linked to pain, paresthesia, and sometimes pathological fractures.[8,10] In some cases, metastases are discovered after a recent dental extraction; a painful soft mass extruding from the extraction site is the main symptom.[2]

This schematic illustrates the distribution and key clinical characteristics of oral metastatic lesions, divided into two main categories: soft tissue and jawbone involvement. Soft tissue metastases account for approximately 58% of cases and most commonly affect the gingiva, followed by the tongue and palate. These lesions typically present as rapidly growing exophytic masses with frequent ulceration and bleeding. Jawbone metastases represent approximately 42% of cases, with the posterior mandible being the most commonly involved site, while the maxilla is less frequently affected. Clinically, jawbone lesions are associated with pain, paresthesia (including "numb chin syndrome"), pathological fractures, and radiographic "moth-eaten" radiolucency. This comparison highlights the distinct clinical behavior and diagnostic features of soft tissue versus osseous metastatic involvement in the oral cavity (figure1).

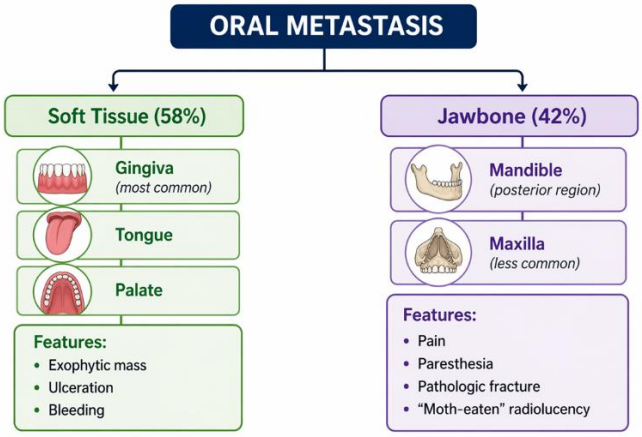

Figure 1. Oral Metastasis Clinical Pattern Map

According to many studies, tooth extraction can serve as a promoting factor in the metastatic process.[8,9,10] Furthermore, the oral metastatic lesion may be the first sign of an undiscovered malignancy at a distant site.[20,21]

Radiological features

Traditional oncology imaging techniques, such as echography, X-ray, CT, and MRI, have been utilized for radiological assessments of cancers, but diagnostic decisions were often limited by low precision. Subsequently, significant advancements in oncologic imaging have revolutionized cancer diagnosis, treatment planning, and monitoring, offering the clinicians valuable insights into tumor characteristics and their responses to therapies. For instance, dual-modality imaging like PET/CT and SPECT/CT combines anatomical, metabolic, and functional information for more accurate disease assessment.[22]

As for the radiographic appearance, metastatic cancers to the oral cavity do not possess a specific one. They can be anything from an osteolytic or opaque lesion with unclear borders to the absence of any signs.[2] The balance between osteoblastic and osteoclastic activity generally determines the characteristics of metastatic bone lesions.[23] Metastases originating from prostate cancer almost always result in the formation of osteoblastic lesions within the bone. In contrast, bone metastases from kidney, lung, or breast cancers tend to be more osteolytic. Furthermore, these lesions may occasionally show up as a single radiolucency of the jawbone that mimics osteomyelitis or an infected cyst. A summary of radiographic characteristics according to primary tumor type is provided in Table 3.

Table 3. Radiographic Characteristics by Primary Tumor Type

Primary tumor	Radiographic pattern	Key diagnostic clue
Prostate	Osteoblastic (radiopaque)	Dense sclerotic bone
Kidney	Osteolytic	"Moth-eaten" destruction
Lung	Osteolytic / mixed	Poorly defined radiolucency
Breast	Mixed pattern	Cortical destruction + expansion
Thyroid	Radiolucent, vascular	Bleeding tendency
Colon	Osteolytic	Aggressive bone loss

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The bone may have a moth-eaten look, which is characterized by numerous tiny, ill-defined holes. The cortical bone of adjacent structures, including the nasal floor, maxillary sinus, and mandibular canal, could be resorbed.[2]

Histological features

The diagnosis of metastatic cancers to the oral cavity is challenging. An incisional biopsy and histopathologic examination are essential to confirm the malignancy of the lesion and potentially its metastatic origin. Furthermore, these lesions present variable histological appearances. In case of a previous tumor history, the microscopic findings of the oral lesion should be compared with those of the primary tumor. However, due to the heterogeneity and sometimes nonspecific features of these lesions, adjunctive techniques are frequently necessary. Special staining aids in identifying specific cellular components, while immunohistochemistry plays a central role in detecting tumor-specific markers and narrowing the primary site. In diagnostically challenging cases, electron microscopy may provide additional ultrastructural detail. [2,24,25]

Table 4 summarizes the integrative approach to histological diagnosis of oral metastatic lesions.

Table 4. Histological Diagnostic Approach for Oral Metastatic Lesions

Diagnostic Method	Purpose	Key Findings / Role	Clinical Relevance
Incisional Biopsy	Initial tissue sampling	Confirms presence of malignant cells	Essential first step in diagnosis
Histopathologic Examination	Microscopic evaluation	Identifies tumor type, differentiation pattern	Helps distinguish primary vs metastatic lesion
Comparison with Primary Tumor	Correlation analysis	Similar morphology with known primary cancer	Strong evidence of metastatic origin
Special Staining	Cellular characterization	Highlights mucin, keratin, or other components	Supports tumor subtype identification
Immunohistochemistry (IHC)	Detection of tumor markers	Expression of CK7, CK20, TTF-1, PSA, etc.	Critical for identifying primary site
Electron Microscopy	Ultrastructural analysis	Detailed cellular architecture	Used in difficult or ambiguous cases

Overall, accurate diagnosis of oral metastatic disease requires a multidisciplinary and multimodal approach, integrating conventional histopathology with advanced diagnostic techniques to ensure precise tumor identification and appropriate clinical management.

Prognosis and management

Metastatic cancers to the oral cavity are usually evidence of a widespread disease and represent a poor prognosis.[26,27] As for the treatment, if the primary tumor has been successfully treated and the patient's medical condition allows, the metastatic lesion should be treated aggressively. Treatment options may include surgical resection, radiation, chemotherapy, or a combination of these methods. However, if the primary tumor has recurred or if there are widespread metastases, the approach to managing the jaw lesion should be more conservative, aiming to relieve the patient's pain while preserving oral function. This approach may include methods such as radiotherapy, chemotherapy, or local surgical excision to reduce the size of the tumor.[2,28]

Stepwise Diagnostic Approach for the Evaluation of Oral Metastatic Lesions

The diagnostic workup of oral metastatic lesions follows a structured, stepwise approach that integrates clinical evaluation, imaging modalities, and histopathological confirmation. Initially, a thorough clinical examination is essential to identify suspicious lesions and assess their morphology, location, and associated symptoms. Radiographic evaluation, including orthopantomogram (OPG) and computed tomography (CT), is then used to detect bone destruction and evaluate the extent of osseous involvement. Magnetic resonance imaging (MRI) provides superior soft tissue contrast and is particularly useful for assessing tumor extension into adjacent anatomical structures.[29,30] Positron emission tomography/computed tomography (PET/CT) plays a critical role in whole-body staging by identifying both the primary tumor and additional metastatic sites. Definitive diagnosis relies on biopsy and

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histopathological examination of the lesion. Subsequently, immunohistochemical analysis is employed to determine the tumor's tissue of origin. In selected cases, molecular markers such as cytokeratin profiles (CK7, CK20), prostate-specific antigen (PSA), and other tumor-specific markers are used to further confirm the primary source of the metastasis.[22, 3] The complete diagnostic pathway is summarized in Table 5.

Table 5. Diagnostic Approach to Oral Metastatic Lesions

Step	Diagnostic tool	Purpose
1	Clinical examination	Identify suspicious lesion
2	Radiography (OPG, CT)	Detect bone destruction
3	MRI	Soft tissue extension
4	PET/CT	Identify primary tumor + metastases
5	Biopsy	Histopathological confirmation
6	Immunohistochemistry	Tumor origin identification
7	Molecular markers	Confirm primary site (CK7, CK20, PSA, etc.)

CONCLUSION

Diagnosing a metastatic lesion in the oral region is challenging, and the prognosis for these lesions is poor; alleviating symptoms is the aim of the therapeutic modality needed. Adequate clinical and histopathological assessments are required for a definitive diagnosis of the lesion and its origin.

Limitations

DECLARATIONS

Ethical Approval

Not applicable.

Consent to Participate

Not applicable.

Competing Interests

The authors declare no conflict of interest.

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CASE REPORT

LACRIMO-AURICULO-DENTO-DIGITAL SYNDROME: A CASE REPORT AND REVIEW OF LITERATURE

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Abstract

Background: Lacrimo-auriculo-dento-digital (LADD) syndrome is a rare autosomal dominant developmental disorder characterized by multisystem anomalies involving the lacrimal apparatus, salivary glands, dentition, auricular structures, and distal limbs. It is associated with pathogenic variants in fibroblast growth factor (FGF) signaling pathway genes, including *FGF10*, *FGFR3*, and *FGFR2*. Clinical expression is highly variable, and severe phenotypes remain uncommon.

Case Presentation: We report a 2-year-old male presenting with congenital xerostomia, feeding difficulties, hypodontia, and rapidly progressive early childhood caries. Clinical examination revealed craniofacial dysmorphism, auricular anomalies, and multiple digital malformations. Ultrasonographic evaluation demonstrated complete absence of the parotid, submandibular, and sublingual glands, consistent with total salivary gland agenesis. Genetic analysis identified a heterozygous de novo missense variant in *FGFR2* (NM_000141.5:c.1991G>A; p.Arg664Gln), classified as likely pathogenic and consistent with LADD syndrome. The patient underwent early preventive and restorative dental management.

Conclusion: This case expands the phenotypic spectrum of LADD syndrome by documenting a rare presentation with complete salivary gland agenesis and a de novo *FGFR2* variant. It highlights the critical role of early diagnosis through integrated clinical, radiological, and genetic assessment, as well as the importance of intensive preventive dental strategies in reducing long-term oral morbidity and improving quality of life.

Keywords: Autosomal dominant disorder, Congenital anomalies, Enamel hypoplasia, Hypodontia, Xerostomia

INTRODUCTION

Lacrimo-auriculo-dento-digital (LADD) syndrome, also known as Levy–Hollister syndrome (OMIM 149730), is a rare autosomal dominant developmental disorder characterized by congenital anomalies affecting the lacrimal system, salivary glands, dentition, ears, and distal limbs [1,2]. Since its initial description, fewer than 150 cases have been reported in the literature, reflecting both its rarity and significant clinical heterogeneity [4,5].

The phenotype of LADD syndrome is highly variable, ranging from isolated glandular hypoplasia to complex multisystem involvement. Core clinical features include lacrimal duct anomalies leading to epiphora, hearing impairment due to auricular malformations, salivary gland hypoplasia or aplasia resulting in xerostomia, dental abnormalities such as hypodontia and enamel defects, and digital malformations including brachydactyly and clinodactyly [3,5,13,18]. Additional systemic findings, including renal, craniofacial, and respiratory anomalies, have also been reported in selected cases [8,9,12].

At the molecular level, LADD syndrome is associated with pathogenic variants in genes involved in fibroblast growth factor (FGF) signaling, particularly *FGF10*, *FGFR3*, and *FGFR2* [16,17,31,32]. These genes play a critical role in epithelial–mesenchymal interactions during embryonic development and are essential for the formation of salivary glands, lacrimal structures, and distal limb tissues. Disruption of this pathway results in impaired organogenesis and the characteristic multisystem phenotype of LADD syndrome [17].

Among the clinical manifestations, salivary gland involvement is of particular importance due to its direct

impact on oral health. Salivary gland hypoplasia or aplasia has been reported in approximately two-thirds of affected individuals and leads to xerostomia, which significantly increases the risk of early-onset dental caries, mucosal disease, and feeding difficulties [19,21,28]. Dental anomalies, including hypodontia, microdontia, enamel hypoplasia, and delayed eruption, are among the most consistent findings, occurring in up to 90% of cases and often representing early diagnostic indicators [5,10,23].

Despite advances in molecular genetics and imaging techniques, reports combining early pediatric presentation, complete salivary gland agenesis, and confirmed molecular findings remain extremely limited. Furthermore, genotype–phenotype correlations in LADD syndrome remain incompletely understood, with significant variability even among patients carrying similar mutations [27,29].

This case report presents a rare and severe phenotype of LADD syndrome characterized by complete salivary gland agenesis, significant dental abnormalities, and a de novo *FGFR2* mutation. The aim is to highlight the diagnostic value of integrating clinical, radiological, and genetic findings, and to emphasize the importance of early recognition and preventive dental management in improving long-term outcomes in affected patients.

CASE REPORT

A 2-year-old male patient presented to our private Oral and Maxillofacial Medicine clinic in Erbil, Kurdistan Region of Iraq, with a chief complaint of persistent oral dryness since birth, accompanied by congenitally missing teeth and multiple dental caries. The patient had been diagnosed with LADD syndrome by a pediatrician within the first month of life.

Systemic physical examination revealed features consistent with LADD syndrome. Head and neck examination demonstrated craniofacial dysmorphism, including a prominent forehead and broad nasal bridge. Ophthalmic evaluation revealed epiblepharon.

External ear examination showed low-set, cup-shaped auricles (Figure 1). On palpation of the parotid and submandibular regions, no discrete glandular enlargement was detected; however, there was an absence of palpable salivary gland bulk and no identifiable submandibular gland outline.

Figure 1. Extraoral craniofacial features of the patient with LADD syndrome.
Lateral profile view showing low-set, cup-shaped auricles. These craniofacial features are consistent with previously reported phenotypic characteristics of LADD syndrome.

On palpation of the parotid and submandibular regions, no discrete glandular enlargement was detected; however, there was an absence of palpable salivary gland bulk and no identifiable submandibular gland outline.

Digital anomalies were observed on physical examination. The right hand showed brachydactyly and nail dysplasia, with mild periungual erythema around the thumb. Additional findings included clinodactyly of the middle finger and symbrachydactyly of the index finger (Figure 2a). Examination of the left hand revealed brachydactyly of the index finger, clinodactyly and symbrachydactyly of the middle finger, along with a hypoplastic thumb and a soft tissue appendage at its base, suggestive of a rudimentary digit or accessory limb remnant (Figure 2b).

Intraoral examination revealed poor oral hygiene, with missing mandibular central incisors and mandibular primary first molars (previously extracted). Stainless steel crowns were present on the bilateral mandibular second primary molars (Figure 3a). The maxillary anterior teeth showed enamel hypoplasia with cervical caries affecting all anterior teeth. Marked xerostomia was evident, with absence of salivary pooling. The tongue appeared dry, erythematous, and depapillated. The lips, particularly the upper lip, were dry and crusted (Figure 3b). The child was uncooperative during intraoral photography, which limited complete photographic documentation.

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Intraoral Findings

Intraoral examination revealed:

- Severe xerostomia with absence of salivary pooling
- Dry, erythematous mucosa and depapillated tongue
- Crusted lips
- Hypodontia and enamel hypoplasia
- Extensive dental caries

These findings are consistent with previous reports linking salivary gland dysfunction to increased caries risk [5,19,20].

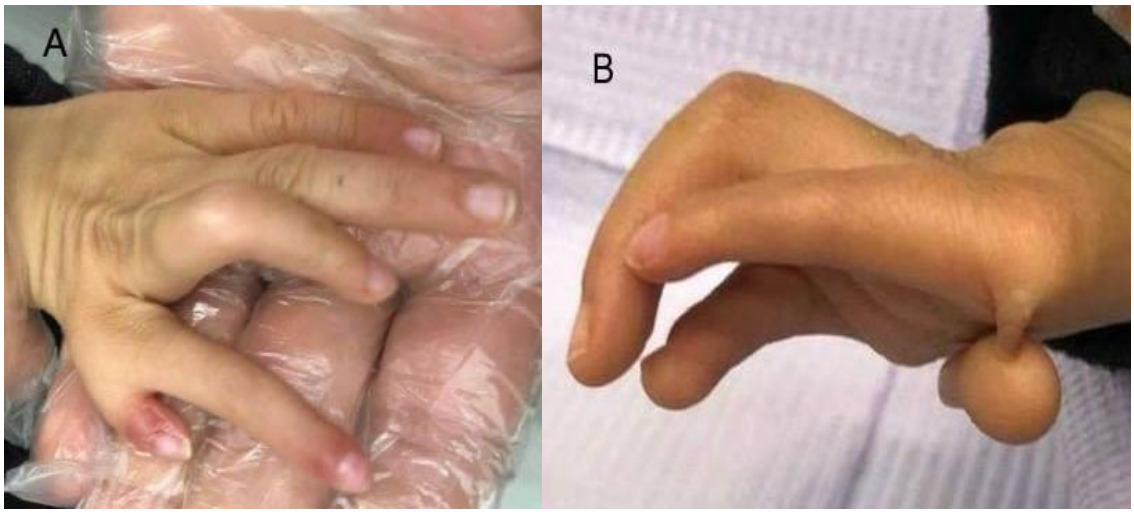

Figure2. (A) Photograph of the right hand showing brachydactyly and nail dysplasia, with mild periungual erythema observed around the thumb. Clinodactyly of the middle finger and symbrachydactyly of the index finger. (B) Photograph of the left hand showing brachydactyly of the index finger, symbrachydactyly and clinodactyly of the middle finger, along with a hypoplastic thumb and a soft tissue appendage at its base.

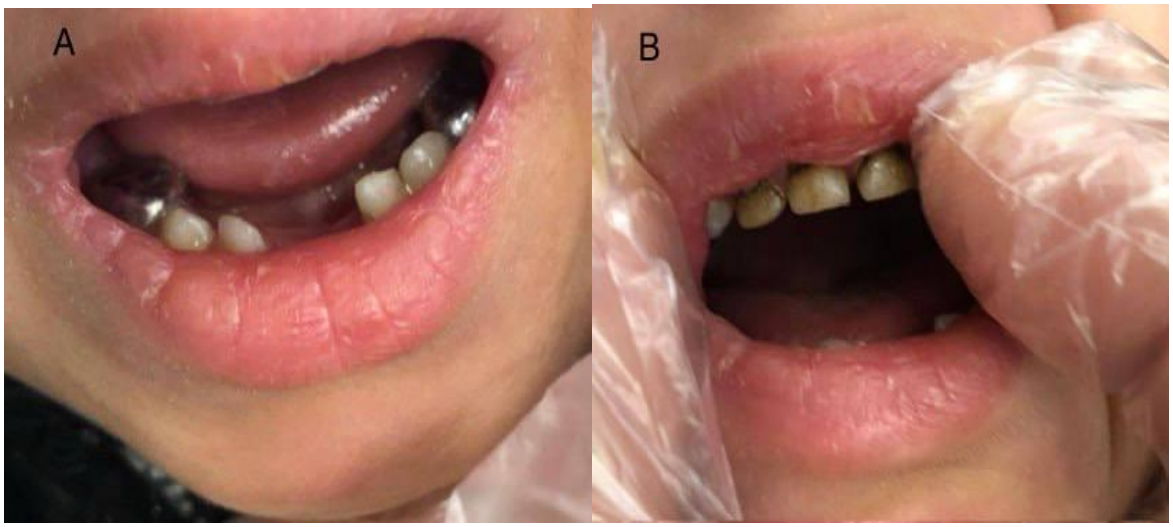

Figure3. Intraoral findings associated with salivary gland aplasia.
(A) Photograph showing missing of mandibular central incisors and primary first molars. Metal crown restorations on mandibular second primary molars bilaterally. (B) The maxillary anterior teeth exhibited enamel hypoplasia accompanied by cervical caries affecting all upper anterior teeth.

Prior to referral, the patient underwent a comprehensive medical evaluation. Investigations included complete blood count (CBC), abdominal and pelvic ultrasonography, neck and major salivary gland imaging, hip joint radiographic assessment, echocardiography, and molecular genetic analysis. All investigations were within normal limits except for neck ultrasonography and genetic testing, which revealed abnormalities consistent with the diagnosis.

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Neck Ultrasound + Doppler:

- Both parotid glands are absent, and no lobes or parotid tissue could be detected in the normal anatomical location. Ectopic parotid tissue can only be identified by isotope scanning.
- Both submandibular and sublingual glands are also absent, and no glandular tissue could be detected in their usual anatomical positions. Ectopic glandular tissue can only be identified by isotope scanning.
- Multiple enlarged cervical lymph nodes (L.N.) are observed on both sides of the lateral neck (anterior and posterior triangles), with the largest located on the right side measuring 15 × 12 mm and on the left side measuring 16 × 10 mm; the remaining nodes are smaller in size. All lymph nodes demonstrate an anechoic texture with normal shape and preserved hilum. These findings suggest post-infectious or inflammatory cervical lymphadenopathy.
- Both thyroid gland lobes and the isthmus are normal in size, with a regular surface and normal texture. No cystic or solid masses are detected. Doppler examination shows normal blood flow. No diffuse parenchymal or focal lesions are observed.

Genetic analysis

Genetic analysis identified a heterozygous mutation in *FGFR2*:
NM_000141.5:c.1991G>A(p.Arg664Gln).
This variant is classified as *likely pathogenic* according to ACMG guidelines and has been associated with LADD syndrome [16,27].
The mutation affects the tyrosine kinase domain, impairing FGF signaling pathways essential for organ development [17]. Parental testing was negative, indicating a de novo mutation, consistent with recent studies reporting sporadic cases [27].

The treatment plan focused on preventive and minimally invasive management. Caregivers were instructed in comprehensive oral hygiene measures, including toothbrushing with a soft-bristled toothbrush and non-foaming fluoride toothpaste. Restoration of carious maxillary anterior teeth was planned using glass ionomer cement or composite resin, depending on the child's cooperation. Monitoring and possible replacement of existing stainless steel crowns were advised as the child grows and occlusion develops. Regular application of topical fluoride varnish was recommended to arrest caries progression and prevent new lesions.

To manage xerostomia, salivary substitutes and oral moisturizing gels were prescribed. The parents were advised to increase the child's water intake and to avoid sugary and acidic foods. Finally, regular dental follow-up every 3 months was scheduled for reassessment, preventive care, and early management of new lesions.

DISCUSSION

Lacrimo-auriculo-dento-digital (LADD) syndrome is a rare autosomal dominant developmental disorder caused by pathogenic variants affecting fibroblast growth factor (FGF) signaling pathways, most commonly involving *FGF10*, *FGFR3*, and less frequently *FGFR2* genes [16,17,31,32]. These genes are essential for epithelial–mesenchymal interactions during embryogenesis, particularly in the development of salivary glands, lacrimal apparatus, dentition, and distal limbs. Disruption of this signaling cascade results in the multisystem developmental abnormalities characteristic of LADD syndrome [17].

In the present case, a heterozygous missense variant in *FGFR2* (NM_000141.5:c.1991G>A; p.Arg664Gln) was identified. Although *FGFR2* is less commonly reported than *FGF10* in LADD syndrome, variants affecting FGFR signaling have been increasingly associated with overlapping phenotypes within FGFR-related developmental disorders [29,31]. The de novo origin of the mutation in this patient is consistent with recent literature reporting sporadic cases of LADD syndrome [16,27]. Taken together, the genetic finding supports the clinical diagnosis but should be interpreted as part of a broader genotype–phenotype correlation rather than a sole diagnostic determinant.

Clinically, the patient exhibited a severe multisystem phenotype involving craniofacial, auricular, digital, dental, and salivary structures. Digital anomalies, including brachydactyly, clinodactyly, and symbrachydactyly, are consistent with previously reported limb manifestations in LADD syndrome and reflect the wide phenotypic variability of FGFR-related disorders [13,18,23].

Although *FGF10* remains the most frequently implicated gene in LADD syndrome, emerging evidence suggests that *FGFR2* variants may also contribute to a broader FGFR-related developmental spectrum with overlapping phenotypes [29,31]. The identified p.Arg664Gln variant, located within the tyrosine kinase domain of *FGFR2*, is predicted to impair downstream FGF signaling, providing a plausible biological mechanism supporting its pathogenic role in the observed phenotype.

The most significant finding in this case was complete absence of all major salivary glands on ultrasonographic examination, resulting in profound congenital xerostomia. While salivary gland hypoplasia or aplasia has been reported in approximately two-

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thirds of LADD cases[19], complete agenesis of parotid, submandibular, and sublingual glands represents an exceptionally rare and severe phenotype [22,28]. Imaging-based evaluation is essential for confirming salivary gland abnormalities and contributes significantly to diagnostic accuracy [22].

Saliva plays a critical role in oral homeostasis, including lubrication, antimicrobial defense, buffering capacity, and enamel remineralization. Its absence leads to xerostomia, increased susceptibility to caries, mucosal irritation, and feeding difficulties [19–21,28]. In this patient, severe early childhood caries and mucosal dryness were direct consequences of complete salivary dysfunction. Dental anomalies such as hypodontia, enamel hypoplasia, and delayed eruption are among the most frequently reported features of LADD syndrome, occurring in up to 90% of cases [5,10,22–25.] These abnormalities may resemble other hereditary enamel defects, complicating early diagnosis [5,23]. However, in the present case, the severity and rapid progression of dental caries were significantly exacerbated by total salivary gland agenesis, demonstrating a synergistic effect between structural dental defects and functional salivary impairment.

Recent studies emphasize the importance of integrating clinical, radiological, and molecular data for accurate diagnosis of LADD syndrome due to its phenotypic overlap with other craniofacial developmental disorders [27–30]. Genetic analysis of FGFR-related pathways continues to expand the known mutation spectrum and highlights the variability of genotype–phenotype expression [29,31].

From a clinical management perspective, early recognition of severe salivary gland dysfunction is critical for preventing rapid oral deterioration. Patients with profound xerostomia require intensive preventive dental care, including frequent topical fluoride applications, strict dietary control, and use of saliva substitutes to improve oral comfort [28,30]. Remineralizing agents such as CPP-ACP may further support enamel stabilization in high-risk patients [28]. Due to the high caries risk, short recall intervals (every 2–3 months) are recommended for early detection and management of new lesions [28,30]. Minimally invasive restorative approaches should be prioritized, and advanced rehabilitation may require treatment under general anesthesia in young children with extensive disease burden [28].

This case highlights the importance of a multidisciplinary approach involving pediatric dentistry, genetics, pediatrics, and radiology in the management of LADD syndrome. Early diagnosis combined with preventive intervention is essential to reduce long-term oral morbidity and improve quality of life in affected patients.

In summary, this report expands the clinical spectrum of LADD syndrome by documenting a rare presentation with complete salivary gland agenesis and a de novo *FGFR2* variant, emphasizing both the phenotypic variability and the importance of early preventive dental management [4,5,27].

DECLARATIONS

Informed Consent

Written informed consent was obtained from the patient's parents for publication of this case report and accompanying images.

Conflict of Interest

The authors declare no conflict of interest.

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REVIEW ARTICLE

NEUROPATHY AFTER DENTAL IMPLANT PLACEMENT: ETIOLOGY, DIAGNOSIS, MANAGEMENT, AND PREVENTION:A SYSTEMATIC REVIEW

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Abstract

Background: Dental implant therapy is a predictable and widely accepted treatment modality for tooth replacement; however, neurosensory disturbances remain a serious and clinically relevant complication. Neuropathy following implant placement may involve the inferior alveolar nerve (IAN), mental nerve, or lingual nerve, leading to temporary or permanent sensory dysfunction.

Objective: This systematic review aims to analyze the etiology, clinical presentation, diagnostic approaches, management strategies, and preventive measures of neuropathy associated with dental implant placement.

Methods:A review of the literature was conducted using PRISMA 2020 principles for transparency. Databases included PubMed, Scopus, Web of Science, and Google Scholar. Studies reporting implant-related nerve injury were included.

Results:A total of 107 records were identified, 61 were excluded, and 46 studies were included in qualitative synthesis. Neuropathy most commonly resulted from mechanical trauma, compression, thermal injury, and postoperative edema. The IAN was the most frequently affected nerve. Early diagnosis using clinical neurosensory testing and cone-beam computed tomography (CBCT) significantly improved outcomes. Most cases were transient neuropraxia, while severe injuries were less frequent.

Conclusion: Prevention through careful planning and anatomical awareness remains the most effective strategy. Early diagnosis and timely intervention significantly improve neurosensory recovery outcomes.

Keywords: Dental implants, neuropathy, inferior alveolar nerve, paresthesia, nerve injury, CBCT

INTRODUCTION

Dental implant therapy has become a predictable and widely accepted treatment modality for the rehabilitation of partially and completely edentulous patients. Long-term studies demonstrate survival rates exceeding 90–95%, confirming implants as a reliable solution in modern oral rehabilitation [1–3]. However, despite continuous improvements in implant design, surface technology, and surgical protocols, complications still occur, particularly when implants are placed in anatomically complex regions such as the posterior mandible [4,5]. Among these complications, neurosensory disturbances represent one of the most clinically significant and distressing outcomes. Implant-associated neuropathy most commonly involves branches of the trigeminal nerve, especially the inferior alveolar nerve (IAN), mental nerve, and lingual nerve [6,7]. These injuries may occur due to direct mechanical trauma, compression from implant proximity, thermal injury during osteotomy, or indirect postoperative effects such as hematoma or edema [8–10].

Recent evidence indicates that neurosensory disturbances following implant surgery are not as rare as previously assumed. A systematic review and meta-analysis reported

transient neurosensory dysfunction rates ranging from 15% to 40% in high-risk mandibular procedures involving nerve manipulation or close proximity [11]. Although most cases resolve within months, a subset of patients may develop persistent neuropathic symptoms, significantly affecting quality of life [12,13].

Clinically, implant-related neuropathy manifests as paresthesia, dysesthesia, hypoesthesia, anesthesia, or neuropathic pain affecting the lower lip, chin, and gingival tissues [14]. In more severe cases, patients may experience burning pain, allodynia, or altered taste sensation when the lingual nerve is involved [15]. These symptoms can appear immediately after surgery or within the first 72 hours, making early detection critical for prognosis [16].

The risk of nerve injury is strongly associated with anatomical factors, particularly in the posterior mandible, where the inferior alveolar nerve runs in close proximity to the implant site [17]. Variations in mandibular canal position, bone resorption patterns, and limited residual bone height further increase surgical risk 1[8]. Advanced imaging techniques, especially cone-beam computed tomography (CBCT), have significantly improved preoperative assessment by enabling three-dimensional visualization of neurovascular structures [19,20].

Despite technological advancements, iatrogenic nerve injury remains a concern in implant dentistry. Studies show that even minor deviations in drilling angulation or implant length selection can result in nerve contact or compression [21]. Seddon's classification remains widely used to describe nerve injury severity: neuropraxia (reversible conduction block), axonotmesis (axonal disruption), and neurotmesis (complete nerve transection) [22]. These categories directly correlate with prognosis and recovery potential, with neuropraxia showing the highest likelihood of full recovery [23].

The management of implant-related neuropathy depends on early recognition and the severity of injury. Conservative approaches include corticosteroids, anti-inflammatory drugs, and neurotrophic vitamins, while pharmacologic agents such as gabapentin and pregabalin are commonly used for neuropathic pain control [24,25]. In cases of mechanical compression or malpositioned implants, early surgical intervention, including implant removal, may prevent irreversible nerve damage [26,27]. Microsurgical nerve repair is reserved for severe or persistent cases [28,29]. Recent advances in implantology emphasize prevention as the most effective strategy. Proper case selection, CBCT-guided planning, the use of surgical guides, and adherence to safety margins (≥2 mm from the mandibular canal) are strongly recommended. Computer-assisted implant placement and digital navigation systems have demonstrated significant reductions in complication rates and are expected to further minimize the incidence of neurosensory complications in implant dentistry [30].

Given the increasing prevalence of implant therapy worldwide, understanding the mechanisms, clinical presentation, and management of neuropathy is essential for clinicians. This review aims to provide an updated, evidence-based synthesis of implant-related nerve injury.

2. MATERIALS AND METHODS

2.1 Study Design and Protocol

This study is a systematic review conducted in accordance with the **PRISMA 2020 Statement**. The methodology was designed to ensure transparency, reproducibility, and methodological rigor.

Due to substantial heterogeneity in study designs, populations, and outcome measures, a quantitative meta-analysis was not performed. Instead, a qualitative synthesis approach was adopted.

No prior protocol registration (e.g., PROSPERO) was performed, which represents a limitation of this review.

2.2 Search Strategy

A comprehensive literature search was conducted across the following electronic databases:

- PubMed
- Scopus
- Web of Science
- Google Scholar

The search strategy combined Medical Subject Headings (MeSH) and free-text keywords using Boolean operators: (dental implant, neuropathy, nerve injury, paresthesia, inferior alveolar nerve, implant complications). Additionally, the reference lists of included studies were manually screened to identify further relevant publications.

2.3 Study Selection (PRISMA Flow Diagram)

Study Selection Process

The study selection process followed PRISMA 2020 guidelines. Two independent reviewers screened titles and abstracts for eligibility. Full-text articles were subsequently assessed. Discrepancies were resolved

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through discussion and consensus.

PRISMA Flow Results

A total of 124 records were identified through database searching. After removal of 17 duplicate records, 107 studies remained for screening. Following title and abstract screening, 61 records were excluded. A total of 46 full-text articles were assessed for eligibility, all of which met the inclusion criteria and were included in the qualitative synthesis.

2.4 Eligibility Criteria

Inclusion Criteria

- English-language publications
- Human clinical studies (prospective, retrospective), systematic reviews, or meta-analyses
- Studies reporting neuropathy or neurosensory complications following dental implant placement

Exclusion Criteria

- Animal or in vitro studies
- Case reports with insufficient clinical data
- Non-peer-reviewed articles
- Studies not directly related to implant-associated neuropathy

2.5 Data Extraction

Data extraction was independently performed by two reviewers using a standardized data collection form. The following variables were extracted:

- Author(s) and year of publication
- Study design
- Sample size
- Nerve involved (inferior alveolar, mental, lingual)
- Type of nerve injury (neuropraxia, axonotmesis, neurotmesis)
- Diagnostic methods (clinical examination, CBCT imaging)
- Treatment approach
- Clinical outcomes

2.6 Risk of Bias Assessment

Methodological quality was assessed using validated tools appropriate to study design:

- Systematic reviews: **AMSTAR 2**
- Observational studies: **Newcastle–Ottawa Scale**
- Clinical trials: **Cochrane Risk of Bias Tool (RoB 2)**

The following domains were evaluated:

- Selection bias
- Performance bias
- Detection bias
- Attrition bias
- Reporting bias

Each study was classified as having low, moderate, or high risk of bias.

2.7 Data Synthesis

Due to heterogeneity in study design and reported outcomes, a qualitative synthesis was performed. Findings were categorized into:

- Etiology of nerve injury
- Clinical presentation
- Diagnostic approaches
- Treatment strategies
- Prognosis

2.8 Ethical Considerations

As this study is based exclusively on previously published data, ethical approval was not required.

3. RESULTS

3.1 Study Selection

A total of 46 full-text articles were assessed for eligibility and included in the qualitative synthesis. No studies were excluded at the full-text stage.

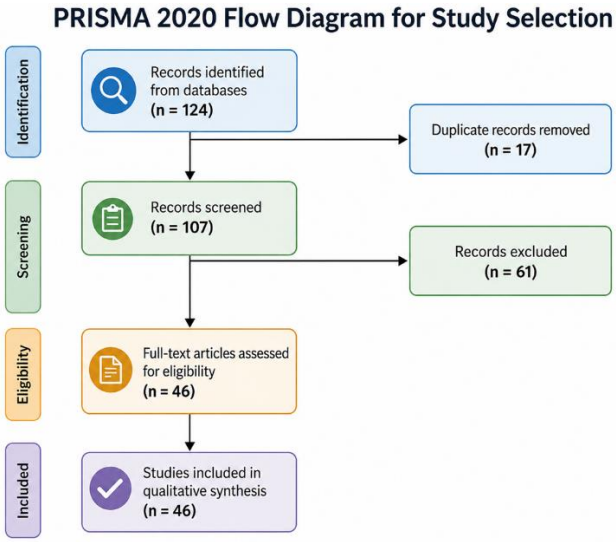

Figure 1. PRISMA Flow Chart

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3.2 Characteristics of Included Studies

A total of **46 studies** were included, comprising:

- Systematic reviews and meta-analyses
- Prospective clinical studies
- Retrospective observational studies
- Clinical trials

Sample sizes ranged from small clinical cohorts (<50 participants) to large-scale systematic reviews (>200 participants).

Table 1. Characteristics of Included Studies

Feature	Description
Total studies	46
Study types	Systematic reviews, meta-analyses, prospective, retrospective, clinical trials
Sample size range	<50 to >200
Main anatomical focus	Posterior mandible
Primary concern	Proximity to inferior alveolar nerve
Imaging modality	CBCT commonly used

3.3 Nerve Involvement

The most frequently affected nerve was the inferior alveolar nerve (IAN), reported in approximately 70–80% of cases.

Table 2. Nerve Involvement and Clinical Presentation

Nerve	Frequency	Clinical Manifestations
Inferior alveolar nerve	Most common (~70–80%)	Lower lip/chin paresthesia, numbness
Mental nerve	Less common	Localized chin sensory deficit
Lingual nerve	Rare	Taste alteration, tongue numbness

Figure 2. Clinical Manifestations

3.4 Types of Nerve Injury

Most studies reported transient neurosensory disturbances, while permanent deficits were less common but clinically significant.

Table 3. Types of Nerve Injury

Type	Severity	Prognosis
Neuropraxia	Mild	Fully reversible in most cases
Axonotmesis	Moderate	Partial recovery over months
Neurotmesis	Severe	Often permanent damage

3.5 Etiology of Neuropathy

The primary causes of implant-related neuropathy identified across studies included: The posterior mandible was consistently identified as the highest-risk anatomical region.

Table 4. Etiology of Implant-Related Neuropathy

Etiological Factor	Description
Mechanical trauma	Direct injury during drilling or implant insertion
Nerve compression	Implant proximity to mandibular canal
Thermal injury	Inadequate irrigation during osteotomy
Postoperative edema	Swelling causing nerve compression
Hematoma	Local pressure effect
Surgical errors	Incorrect angulation or excessive implant length

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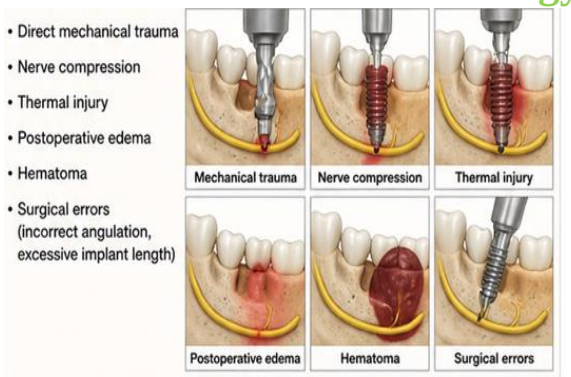

Figure 3. Etiology of Neuropathy

3.6 Diagnostic Methods

All included studies emphasized the importance of early and accurate diagnosis. The most commonly used diagnostic tools were: Several studies highlighted CBCT as the **gold standard** for preoperative planning and postoperative assessment.

Table 5. Diagnostic Methods

Method	Purpose	Notes
Clinical neurosensory testing	Assess sensory function	Light touch, pin-prick, 2-point discrimination
CBCT imaging	Evaluate implant–nerve relation	Gold standard pre/postoperative tool
Patient symptom reporting	Early detection	Paresthesia, pain, numbness
Follow-up examination	Monitor recovery	Serial assessment essential

Figure 4. Thorough preoperative planning with CBCT evolution

3.7 Treatment Approaches

Management strategies varied depending on injury severity (table 6, figure 5):

Table 6. Management Strategies

Approach	Treatment	Indications
Conservative	Observation, corticosteroids, vitamin B	Mild neuropraxia
Pharmacologic	Gabapentin, pregabalin, NSAIDs	Neuropathic pain
Surgical	Implant removal, decompression	Nerve compression
Microsurgery	Nerve repair repair in severe cases	Severe neurotmesis

Early intervention (within 48–72 hours) was consistently associated with better outcomes.

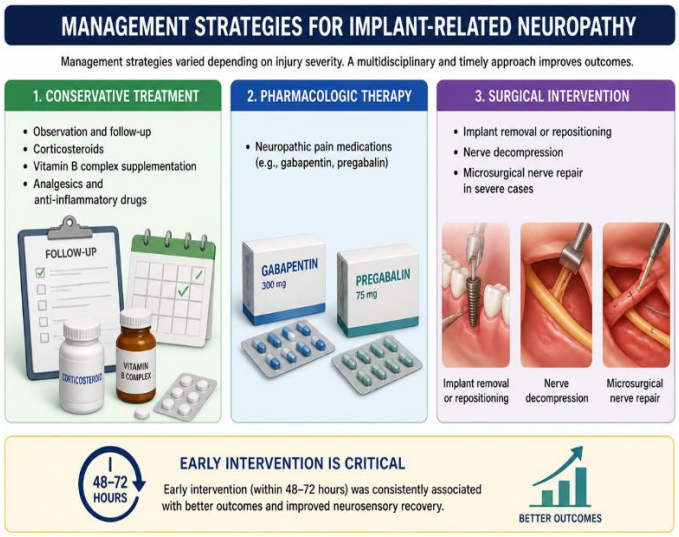

Figure 5. Management Strategies

Clinical Algorithm for Management of Implant-Related Neuropathy

Step 1: Immediate Assessment (0–24 h)

- Evaluate symptoms (paresthesia, numbness)
- Perform neurosensory testing

Step 2: Imaging

- CBCT to assess implant–nerve proximity

Step 3: Early Decision (within 48–72 h)

- If compression suspected → implant removal
- If mild → conservative treatment

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Step 4: Medical Management

- Corticosteroids
- NSAIDs
- Neurotrophic vitamins
- Gabapentin/pregabalin if pain present

Step 5: Follow-up

- Weekly reassessment
- Monitor recovery

Step 6: Advanced Intervention

- Persistent deficit (>3 months) → microsurgical referral

3.8 Clinical Outcomes

The majority of studies reported **favorable outcomes**, particularly in cases of mild injury:

Table 7. Clinical Outcomes

Outcome	Description
Full recovery	Mostly neuropraxia cases
Partial recovery	Axonotmesis cases
Persistent deficit	Delayed diagnosis or severe injury
Key factor	Early intervention improves prognosis

Overall, early diagnosis and appropriate management significantly improved prognosis.

3.9 Risk of Bias Across Studies

The risk of bias assessment revealed:

- Low risk of bias in most systematic reviews and clinical trials
- Moderate risk of bias in retrospective observational studies
- No studies were classified as high risk overall

Common sources of bias included:

- Variability in outcome assessment methods
- Limited follow-up duration in some studies
- Heterogeneity in study design and patient populations

Risk of bias assessment across included studies demonstrating predominantly low to moderate methodological risk, with no studies classified as high risk. Most studies demonstrated low to moderate risk of bias, with higher risk observed in retrospective designs.

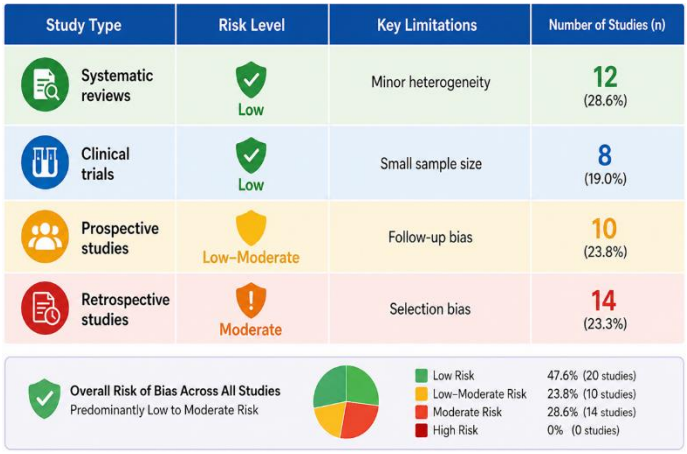

Figure 6. Risk of Bias Summary

Clinical Recommendations

Based on the available evidence, the following clinical recommendations are proposed:

Preoperative Phase

- Perform thorough patient assessment and risk evaluation, particularly in posterior mandibular regions .
- Utilize cone-beam computed tomography (CBCT) for precise three-dimensional visualization of anatomical structures .
- Maintain a minimum safety distance of ≥2 mm from the mandibular canal.
- Consider computer-guided implant surgery in high-risk cases to improve accuracy.

Intraoperative Phase

- Ensure accurate implant positioning and angulation to avoid nerve contact.
- Use controlled drilling techniques with adequate irrigation to prevent thermal injury .
- Avoid excessive implant length or depth in anatomically limited regions.
- Immediately reassess if the patient reports intraoperative pain or altered sensation.

Postoperative Phase

- Conduct early neurosensory evaluation within the first 24–72 hours.
- Monitor for symptoms such as paresthesia, dysesthesia, or anesthesia.

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- Initiate early conservative management, including corticosteroids and neurotrophic support when indicated.
- Consider pharmacologic therapy (e.g., gabapentin, pregabalin) for neuropathic pain.

Management of Complications

- In cases of suspected nerve compression, consider early implant removal or decompression.
- Refer to specialists for microsurgical nerve repair in severe or persistent cases.
- Provide long-term follow-up to monitor recovery and functional outcomes.

Future Clinical Perspective

- Integrate digital workflows, navigation systems, and artificial intelligence to enhance surgical precision and reduce complications.
- Standardize neurosensory testing protocols to improve diagnosis and outcome assessment.
- Emphasize patient-reported outcomes in clinical evaluation, given the significant impact on quality of life.

Neuropathy following dental implant placement remains an uncommon but clinically significant complication, predominantly involving the inferior alveolar nerve due to its anatomical proximity to implant sites. The analysis of 46 studies indicates that most neurosensory disturbances are transient and reversible, particularly in cases of neuropraxia, whereas more severe injuries such as axonotmesis and neurotmesis may result in persistent or permanent deficits.

The findings confirm that mechanical trauma and nerve compression are the primary etiological factors, often associated with implant positioning errors or insufficient safety margins. Despite advances in imaging and digital planning, the risk of nerve injury has not been completely eliminated, emphasizing the importance of clinician expertise and adherence to surgical principles.

Early diagnosis and timely intervention remain critical determinants of prognosis. Evidence consistently demonstrates that management within the first 48–72 hours significantly improves the likelihood of neurosensory recovery. Conservative treatment is effective in most mild cases, while surgical intervention may be required in cases of confirmed nerve compression or severe injury.

Overall, the results highlight that prevention, early recognition, and individualized management strategies are essential to minimize complications and optimize patient outcomes in implant dentistry.

Table 8. Clinical Recommendations

Phase	Recommendations
Preoperative	CBCT planning, ≥2 mm safety distance, risk assessment, guided surgery in high-risk cases
Intraoperative	Accurate angulation, controlled drilling, irrigation, avoid excessive implant length
Postoperative	Early neurosensory testing (24–72h), monitor symptoms, early intervention if changes occur
Complication management	Steroids, neuropathic drugs, implant removal if compression suspected, microsurgical referral if severe
Prevention strategy	Digital planning, navigation systems, AI-assisted implant placement

3.10 Summary of Findings

The analysis of 46 studies indicates that neuropathy following dental implant placement is an uncommon but clinically significant complication, predominantly affecting the inferior alveolar nerve. Most neurosensory disturbances are transient and reversible; however, severe injuries may result in persistent dysfunction. Early diagnosis and timely intervention remain critical determinants of prognosis.

4. DISCUSSION

This systematic review synthesized evidence from 46 studies to provide an updated evaluation of neuropathy associated with dental implant placement. The findings confirm that, despite the high predictability and success rates of implant therapy (31,32), neurosensory complications remain clinically significant, particularly in anatomically complex regions such as the posterior mandible (33,34).

4.1 Principal Findings

The present analysis demonstrates that the inferior alveolar nerve (IAN) is the most frequently affected structure, reflecting its close anatomical relationship to mandibular implant sites [6,18,21,35,36]. The majority of reported nerve injuries were classified as neuropraxia, which is typically transient and associated with favorable recovery. However, more severe forms of injury, including axonotmesis and neurotmesis, were also

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identified and were associated with prolonged or incomplete recovery [22,37].

The primary etiological mechanisms identified were mechanical trauma and nerve compression occurring during osteotomy preparation or implant placement. Additional contributing factors included thermal injury resulting from inadequate irrigation and postoperative inflammatory processes such as edema or hematoma formation [38,39]. These findings are consistent with established pathophysiological models of iatrogenic nerve injury.

4.2 Comparison with Existing Literature

Compared with earlier reports, recent studies suggest an increased detection rate of neurosensory disturbances. This trend likely reflects improved diagnostic awareness and the widespread adoption of advanced imaging modalities, particularly cone-beam computed tomography (CBCT), which allows more accurate visualization of anatomical structures [40].

Despite these technological advancements, implant-related nerve injuries have not been completely eliminated. The findings of this review support the continued recommendation of maintaining a minimum safety distance of at least 2 mm from the mandibular canal [18]. Nevertheless, anatomical variability and surgical technique remain critical determinants of outcome. Even minor deviations in implant angulation or positioning may result in nerve contact or compression [1].

4.3 Clinical Implications

The results of this review highlight several important clinical implications.

First, comprehensive preoperative planning is essential. The use of CBCT imaging and digital workflows should be considered standard practice, particularly in high-risk mandibular regions. Computer-guided implant placement has been shown to improve surgical accuracy and reduce complication rates [41].

Second, early diagnosis of neurosensory disturbances is crucial. Evidence consistently indicates that intervention within 48–72 hours significantly improves the likelihood of recovery. Accordingly, clinicians should implement structured postoperative follow-up protocols incorporating neurosensory testing.

Third, treatment strategies should be individualized based on injury severity. Conservative management is generally appropriate for mild injuries, whereas early surgical intervention, including implant removal or decompression, may be required in cases of confirmed nerve compression [26,36,42,43,45,46]. Pharmacological agents such as gabapentin and pregabalin remain effective for the management of neuropathic pain.

4.4 Risk of Bias and Quality of Evidence

The overall methodological quality of the included studies was assessed as low to moderate risk of bias, supporting the general reliability of the findings. Systematic reviews and clinical trials demonstrated lower risk of bias, whereas retrospective studies were more susceptible to selection and reporting biases.

A key limitation across studies was the lack of standardized neurosensory assessment protocols. This variability limits comparability between studies and precludes robust quantitative synthesis. Future research should prioritize the use of validated and reproducible diagnostic criteria.

4.5 Limitations of the Present Review

This review has several limitations. First, heterogeneity in study design, outcome measures, and follow-up duration prevented the performance of a meta-analysis. Second, variability in the reporting of nerve injury classification and treatment outcomes reduces the generalizability of the findings.

Additionally, the absence of protocol registration may introduce potential methodological bias. Despite these limitations, this review provides a comprehensive and up-to-date synthesis of current evidence on implant-related neuropathy.

4.6 Future Directions

Future research should focus on:

- Well-designed prospective multicenter studies with standardized methodologies
- Development and validation of quantitative neurosensory testing protocols
- Long-term studies evaluating nerve recovery and functional outcomes
- Integration of digital technologies, including navigation systems and artificial intelligence, into implant planning

Furthermore, greater emphasis should be placed on patient-reported outcomes, given the significant impact of neuropathic complications on quality of life.

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CONCLUSION

Within the limitations of this systematic review, neuropathy following dental implant placement remains an uncommon but clinically significant complication, predominantly affecting the inferior alveolar nerve. Most cases are transient and resolve with conservative management; however, severe injuries may result in persistent or permanent dysfunction.

The findings emphasize that prevention through meticulous preoperative planning, early diagnosis, and timely intervention is essential for optimizing clinical outcomes. Continued advancements in imaging, digital technologies, and surgical precision are expected to further reduce the incidence of implant-related nerve injuries.

DECLARATIONS

Conflict of Interest

The author declare no conflict of interest.

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None.

Abbreviations:
IAN = Inferior Alveolar Nerve; MN = Mental Nerve; LN = Lingual Nerve; CBCT = Cone Beam Computed Tomography; NR = Not Reported; SYS = Systematic Review; OBS = Observational Study; TB = Textbook; GD = Guideline; QST = Quantitative Sensory Testing; PRO = Patient-Reported Outcomes.

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REVIEW ARTICLE

PREVENTION STRATEGIES AND TREATMENT OF OBSTRUCTIVE SLEEP APNEA SYNDROME: A NARRATIVE REVIEW

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Abstract

Obstructive sleep apnea (OSA) is a prevalent sleep-related breathing disorder characterized by recurrent episodes of upper airway collapse during sleep, resulting in intermittent hypoxia and sleep fragmentation. Oral and maxillofacial surgeons play a pivotal role in both the prevention and management of OSA through surgical and non-surgical interventions that target craniofacial anatomy.This narrative review critically summarizes current evidence regarding the etiology, diagnostic approaches, preventive strategies, and treatment modalities of OSA within the scope of oral and maxillofacial surgery. Particular emphasis is placed on mandibular advancement devices, orthognathic surgical procedures, and multidisciplinary treatment strategies. Contemporary evidence indicates that maxillomandibular advancement (MMA) is among the most effective surgical interventions, achieving significant reductions in the apnea–hypopnea index (AHI) and substantial improvement in clinical outcomes. Preventive approaches, including early identification of craniofacial risk factors and timely orthodontic intervention, are also addressed. This review underscores the importance of individualized treatment planning and close interdisciplinary collaboration in optimizing patient outcomes. OSA is a multifactorial condition that requires personalized management strategies. Oral and maxillofacial surgery occupies a central position in both preventive and therapeutic pathways, with MMA remaining the gold standard surgical option, while early diagnosis and multidisciplinary care are essential for long-term success.

Keywords: Obstructive sleep apnea, maxillofacial surgery, mandibular advancement, orthognathic surgery, airway management

1.INTRODUCTION

Obstructive sleep apnea (OSA) is a chronic disorder characterized by recurrent episodes of upper airway obstruction during sleep, leading to intermittent hypoxia, sleep fragmentation, and sympathetic activation [1,2]. It is increasingly recognized as a major global health problem due to its association with cardiovascular diseases, metabolic syndrome, and neurocognitive impairment [2,3].

The prevalence of OSA has risen significantly, affecting approximately 10–17% of adult males and 3-9% of females[3]. Despite its high prevalence, a substantial proportion of cases remain undiagnosed, particularly in developing healthcare systems. The burden of untreated OSA includes increased risks of hypertension, stroke, myocardial infarction, and reduced quality of life [2,4].

The pathophysiology of OSA is multifactorial, involving anatomical and neuromuscular components[4]. Anatomical factors include craniofacial abnormalities such as mandibular retrognathia,

maxillary constriction, increased lower facial height, and reduced posterior airway space[5]. These features contribute to airway narrowing and increased collapsibility during sleep. Functional factors include reduced neuromuscular tone of the pharyngeal dilator muscles, particularly during rapid eye movement sleep [4].

Obesity is a major risk factor, contributing to fat deposition around the upper airway and increasing its collapsibility [3,38]. However, craniofacial morphology plays a particularly important role in non-obese patients, emphasizing the relevance of oral and maxillofacial surgery (OMFS) in diagnosis and management [5,6].

OMFS provides unique therapeutic options that directly address the anatomical causes of airway obstruction [6,12]. These include both preventive interventions-such as orthodontic growth modification-and definitive surgical treatments like maxillomandibular advancement (MMA)[13,18]. Preventive strategies have gained increasing attention, particularly in pediatric populations. Early identification of craniofacial abnormalities allows timely intervention using rapid maxillary expansion or functional appliances, which can improve airway dimensions and reduce the risk of developing OSA later in life [18-20].

Treatment of OSA includes both non-surgical and surgical modalities [21]. Continuous positive airway pressure (CPAP) therapy remains the gold standard for moderate-to-severe OSA; however, compliance is often poor [22,31]. Oral appliances, particularly mandibular advancement devices (MADs), are effective alternatives for mild-to-moderate cases [7-10].

Surgical treatment is indicated in patients with anatomical abnormalities or CPAP intolerance [24]. Among surgical options, MMA is considered the most effective, as it enlarges the entire upper airway and provides long-term stability [13,16,42]. Other procedures, such as genioglossus advancement and surgically assisted rapid maxillary expansion (SARME), are used in selected cases [11,17].

Given the complexity of OSA, a multidisciplinary approach involving oral surgeons, orthodontists, sleep specialists, and otolaryngologists is essential for optimal patient outcomes [23].

2. MATERIALS AND METHODS

Study Design

This structured narrative review was conducted to evaluate contemporary prevention strategies and treatment modalities for obstructive sleep apnea (OSA) within the field of oral and maxillofacial surgery (OMFS). The review followed a PRISMA-informed search strategy to enhance transparency, reproducibility, and methodological rigor; however, it was not registered as a systematic review protocol and does not include meta-analysis.

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Literature Search Strategy

A comprehensive electronic literature search was performed in the following databases: PubMed/MEDLINE, Scopus, Web of Science, and Google Scholar.

Google Scholar was used as a supplementary source for citation tracking and identification of additional relevant studies not indexed in primary databases.

The search strategy combined Medical Subject Headings (MeSH) and free-text terms related to obstructive sleep apnea and oral and maxillofacial surgical management. The principal search terms included: “obstructive sleep apnea,” “sleep-disordered breathing,” “oral and maxillofacial surgery,” “maxillomandibular advancement,” “mandibular advancement device,” “orthognathic surgery,” “rapid maxillary expansion,” “drug-induced sleep endoscopy,” “hypoglossal nerve stimulation,” and “airway management.”

Boolean operators (AND/OR) were used to refine and optimize search sensitivity and specificity.

Eligibility Criteria

Inclusion Criteria

Studies were included if they met the following criteria:

- Published in English
- Randomized controlled trials, prospective or retrospective clinical studies, systematic reviews, meta-analyses, or evidence-based clinical guidelines
- Focused on diagnosis, prevention, or management of OSA
- Included adult and/or pediatric populations
- Reported objective sleep-related outcome measures (e.g., apnea-hypopnea index, oxygen saturation, or validated sleep parameters)
- Addressed OMFS-related interventions, including surgical, orthodontic, or airway-focused treatments

Exclusion Criteria

The following were excluded:

- Non-English publications
- Animal or in vitro experimental studies
- Isolated case reports or small case series with limited generalizability
- Studies without objective sleep outcome measures

- Duplicate datasets (most complete or recent version retained)
- Articles not directly relevant to OMFS-based management of OSA

Study Selection Process

All records identified through database searching were imported into a reference management system, and duplicate records were removed prior to screening.

Study selection was performed in two stages:

1. Title and abstract screening
2. Full-text eligibility assessment

Screening was conducted by the author, with repeated verification of eligibility criteria to minimize selection bias and ensure consistency in study inclusion.

Any uncertainties regarding study eligibility were resolved through full-text re-evaluation against predefined criteria.

PRISMA-Informed Flow of Studies

The initial search identified 86 records across all databases:

- PubMed/MEDLINE: n = 41
- Scopus: n = 23
- Web of Science: n = 15
- Google Scholar and manual search: n = 7

After removal of 14 duplicate records, 72 studies were screened based on titles and abstracts. Nineteen studies were excluded due to irrelevance to the review topic.

Fifty-three full-text articles were assessed for eligibility. Of these, 11 studies were excluded due to insufficient clinical outcome data, absence of objective sleep parameters, duplicate patient cohorts, or lack of relevance to OMFS-based interventions. Ultimately, 42 studies were included in the qualitative synthesis.

Data Categorization and Synthesis

Included studies were categorized into the following thematic domains:

- Pathophysiology and risk factors of OSA
- Preventive strategies
- Non-surgical treatment modalities (e.g., CPAP, oral appliances)
- Surgical interventions (e.g., maxillomandibular advancement, orthognathic surgery)
- Emerging technologies and personalized treatment approaches
- Pediatric obstructive sleep apnea management

Data Synthesis

A qualitative narrative synthesis was performed due to heterogeneity in study designs, patient populations, intervention types, and outcome measures. Therefore, meta-analysis was not feasible.

Findings were synthesized descriptively, with emphasis on clinical relevance to oral and maxillofacial surgical practice.

Risk of Bias Assessment

A formal risk-of-bias assessment was not performed due to the narrative nature of the review and the inclusion of heterogeneous study designs (randomized trials, observational studies, and systematic reviews). However, study quality was considered during interpretation, with preference given to higher-level evidence where available.

Ethical Considerations

Ethical approval was not required for this study, as it was based exclusively on previously published literature and did not involve human or animal subjects.

3. RESULTS

3.1 Study Selection and Characteristics

A total of 86 studies were initially identified. After screening and eligibility assessment, 42 high-quality studies were included in the final synthesis.

3.2 Pathophysiology of Obstructive Sleep Apnea

OSA results from a combination of anatomical narrowing and reduced neuromuscular tone of the upper airway during sleep.

Key mechanisms include:

• Posterior displacement of the tongue
• Collapse of the soft palate
• Reduced pharyngeal muscle activity
• Increased airway resistance

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Important risk factors include:

• Obesity
• Mandibular retrognathia
• Maxillary constriction
• Smoking and aging

Craniofacial morphology plays a significant role; patients with retruded mandibles or narrow maxillae exhibit reduced airway dimensions, predisposing them to obstruction.

During sleep, reduced neuromuscular tone of the upper airway leads to posterior displacement of the tongue, collapse of the soft palate, and decreased activity of pharyngeal dilator muscles. These changes result in airway narrowing and increased airway resistance, causing recurrent episodes of apnea and hypopnea. The figure 1 highlights major risk factors, including obesity, mandibular retrognathia, maxillary constriction, smoking, and aging, as well as the role of craniofacial morphology in airway obstruction.

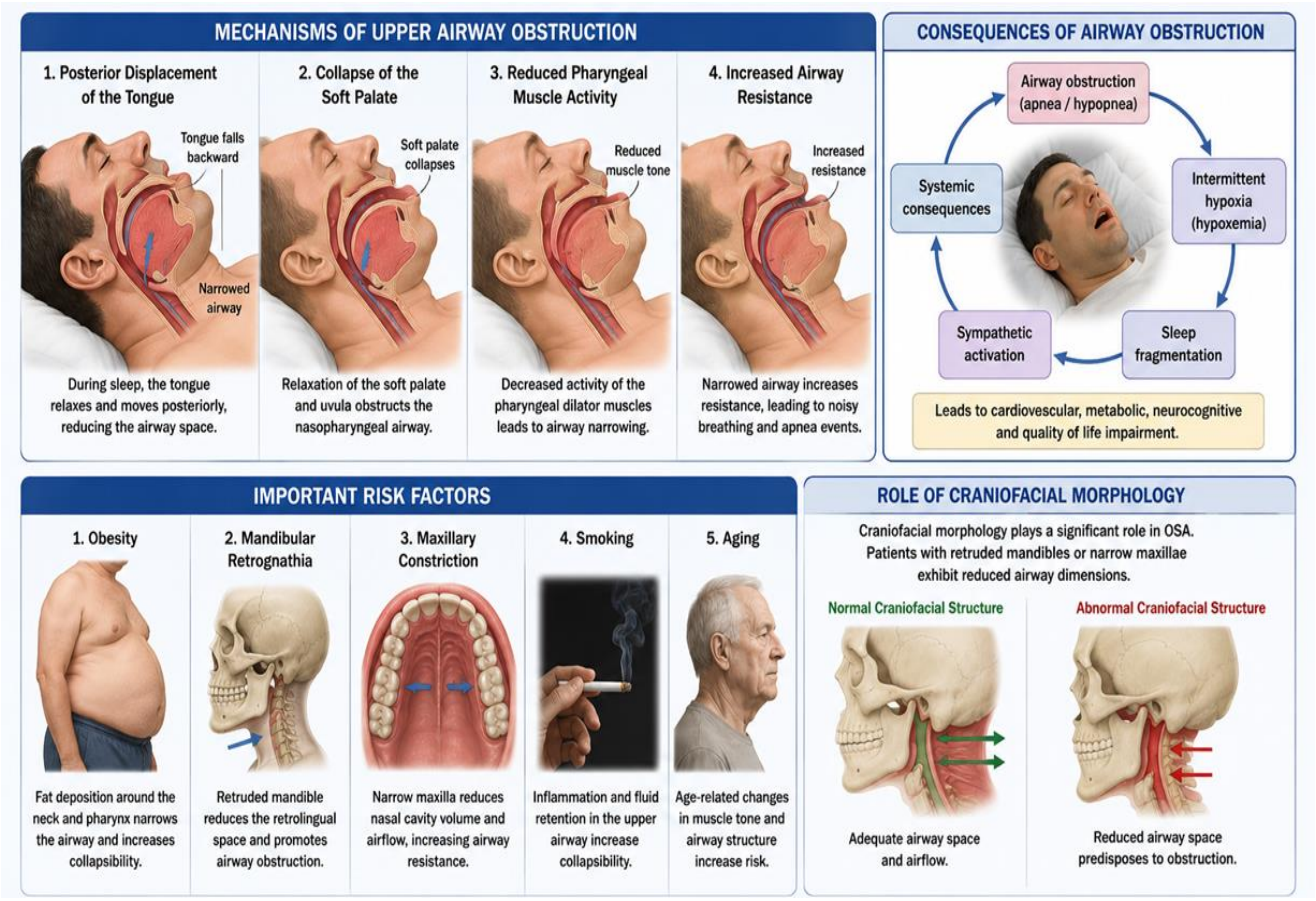

Figure 1. Schematic Illustration of Pathophysiology of Obstructive Sleep Apnea (OSA)

3.3 Drug-Induced Sleep Endoscopy (DISE)

Drug-induced sleep endoscopy (DISE) has emerged as an important diagnostic modality in the evaluation of patients with obstructive sleep apnea. It enables direct, dynamic visualization of upper airway collapse under pharmacologically induced sleep conditions, allowing identification of the specific anatomical sites of obstruction.

In contrast to awake airway examination, DISE provides a more physiologically relevant assessment of upper airway behavior during sleep, which improves diagnostic accuracy and supports individualized surgical planning. The most commonly observed sites of obstruction include the velum (soft palate), oropharyngeal lateral walls, tongue base, and epiglottis. To standardize findings, the VOTE classification (Velum, Oropharynx, Tongue base, Epiglottis) is widely used in clinical practice. Evidence suggests that DISE-guided treatment planning may improve surgical outcomes by enabling more precise patient selection and reducing unnecessary interventions. It is particularly useful in determining candidacy for maxillomandibular advancement, tongue-base procedures, hypoglossal nerve stimulation, and multilevel airway surgery. Overall, DISE has become an important adjunct in OMFS practice, contributing to a more personalized and functionally guided approach to OSA management.

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3.4 Role of Oral and Maxillofacial Surgery in OSA

Oral and maxillofacial surgeons play a central role in the multidisciplinary management of obstructive sleep apnea. Their contribution includes airway evaluation and diagnostic assessment [5,26], fabrication and management of oral appliances [6–10], surgical correction of craniofacial deformities [12–14], and participation in multidisciplinary treatment planning [23]. Surgical intervention is particularly indicated in patients who are unable to tolerate continuous positive airway pressure therapy [22,31], present with craniofacial abnormalities contributing to airway obstruction [5,12], or require definitive anatomical correction through skeletal advancement procedures [13,24].

3.5 Prevention Strategies

Weight Management

Maintenance of healthy body weight is a key preventive strategy, as obesity is one of the most significant risk factors for obstructive sleep apnea. Weight reduction has been shown to improve upper airway patency and reduce the severity of respiratory events during sleep.

Lifestyle Modifications

Avoidance of alcohol, sedatives, and smoking is recommended, as these factors contribute to decreased upper airway muscle tone and worsening of airway collapse during sleep. Regular physical activity may further improve respiratory efficiency and sleep quality.

Sleep Hygiene

Maintaining a consistent sleep schedule and avoiding supine sleeping position are important behavioral strategies. Side-sleeping has been associated with reduced airway collapse in susceptible individuals.

Management of Comorbidities

Effective control of nasal obstruction, allergic conditions, and chronic respiratory diseases may reduce upper airway resistance. Additionally, management of systemic conditions such as diabetes, hypertension, and cardiovascular disease is essential in comprehensive risk reduction.

Oral Appliances in Early or Mild Cases

In selected patients with mild disease or anatomical predisposition, oral appliances may serve a preventive or early-intervention role by maintaining airway patency during sleep [6–10].

Regular Screening

Early identification of high-risk individuals, including obese patients, older adults, males, and those with a positive family history, allows timely intervention and risk reduction strategies [2,3]. Although primarily non-surgical, these preventive measures complement OMFS-based management approaches [18–20].

Overview of preventive strategies for obstructive sleep apnea within oral and maxillofacial practice emphasizes early identification of craniofacial risk factors to enable timely intervention, particularly in pediatric populations. Orthodontic and growth modification approaches, including rapid maxillary expansion (RME) and functional appliances, may improve airway dimensions and support mandibular advancement.

In addition, lifestyle modifications such as weight management, smoking cessation, and sleep position therapy contribute to reducing both the risk and severity of OSA.

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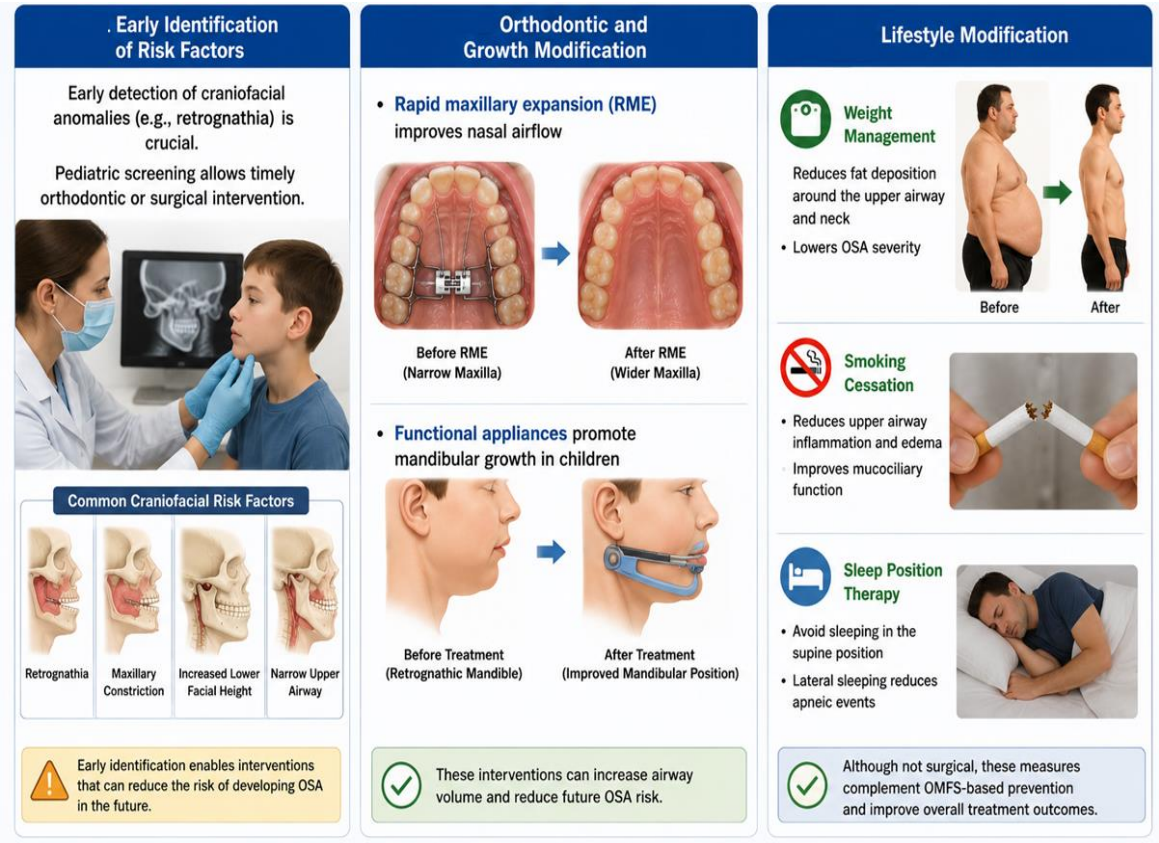

Figure 2. Prevention Strategies for Obstructive Sleep Apnea

3.6 Non-Surgical Treatment Modalities

3.6.1 Continuous Positive Airway Pressure (CPAP)

Continuous positive airway pressure (CPAP) remains the gold standard treatment for moderate-to-severe obstructive sleep apnea; however, long-term adherence is limited in a substantial proportion of patients [22].

3.6.2 Oral Appliance Therapy

Mandibular advancement devices (MADs) are widely used in the management of mild-to-moderate obstructive sleep apnea [7–10]. These devices function by anteriorly repositioning the mandible, thereby increasing upper airway space and reducing the likelihood of tongue collapse during sleep.

Clinical evidence demonstrates that oral appliances significantly reduce the apnea–hypopnea index (AHI) compared with placebo interventions [7,8].

Indications include:

- Mild-to-moderate OSA
- Intolerance to CPAP therapy

Limitations include:

- Temporomandibular joint discomfort
- Dental and occlusal changes
- Variable treatment efficacy across patient populations

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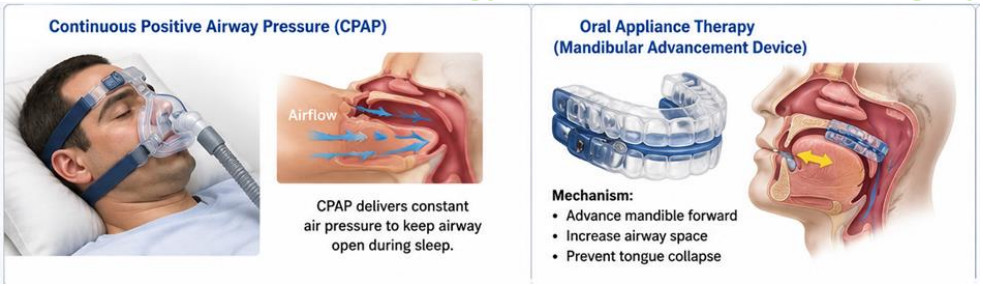

Figure 3. Non-Surgical Treatment Modalities

3.6.3 Hypoglossal Nerve Stimulation (HGNS)

Hypoglossal nerve stimulation (HGNS) is a minimally invasive therapeutic option for selected patients with moderate-to-severe obstructive sleep apnea who are intolerant to continuous positive airway pressure (CPAP) therapy [39,40].

The technique involves implantation of a neurostimulation device that activates the hypoglossal nerve during inspiration, resulting in anterior displacement and stabilization of the tongue, thereby preventing upper airway collapse [41].

Typical selection criteria include:

- Moderate-to-severe OSA
- CPAP intolerance
- Body mass index within recommended limits
- Absence of complete concentric palatal collapse on drug-induced sleep endoscopy (DISE)

Clinical studies have demonstrated significant improvements in apnea–hypopnea index (AHI), oxygen saturation, daytime sleepiness, and overall quality of life following HGNS therapy.

Although HGNS does not replace skeletal advancement surgery in patients with significant craniofacial abnormalities, it represents an important adjunct in multidisciplinary OSA management. Long-term outcome data suggest sustained efficacy and safety, supporting its increasing role in contemporary treatment algorithms for obstructive sleep apnea.

3.7 Surgical Treatment Modalities in Oral and Maxillofacial Surgery (OMFS)

Surgical management of obstructive sleep apnea represents an essential component of oral and maxillofacial practice, particularly in patients with craniofacial skeletal abnormalities or those who fail to respond to non-surgical therapies.

3.7.1 Maxillomandibular Advancement (MMA)

Maxillomandibular advancement (MMA) is widely regarded as the most effective surgical treatment for obstructive sleep apnea [13,16,42]. The procedure involves simultaneous advancement of the maxilla and mandible, resulting in an increase in posterior airway space and reduction of upper airway collapsibility.

Clinical studies have demonstrated significant reductions in the apnea–hypopnea index (AHI), with high surgical success and cure rates reported in selected patient populations [13,42]. Reported success rates in the literature vary but may reach approximately 80–90% in appropriately selected cases [13,19]. Recent meta-analyses further confirm the long-term effectiveness and safety profile of MMA [42].

3.7.2 Mandibular Advancement Surgery

Mandibular advancement procedures are primarily indicated in patients with mandibular retrognathia and skeletal deficiency. These procedures improve upper airway patency by repositioning the mandible anteriorly, resulting in substantial reductions in AHI, with some studies reporting reductions of up to approximately 80% or more in selected cohorts [19]. Improvements in airway stability and respiratory parameters have also been documented [17].

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3.7.3 Genioglossus Advancement

Genioglossus advancement targets the anterior repositioning of the tongue muscle attachment, thereby reducing posterior tongue displacement during sleep. This procedure enhances airway stability and is frequently performed in combination with other surgical interventions in multilevel airway management strategies [36].

3.7.4 Surgically Assisted Rapid Maxillary Expansion (SARME)

Surgically assisted rapid maxillary expansion (SARME) is indicated in adult patients with transverse maxillary deficiency [20.] By increasing maxillary width, SARME improves nasal airflow and contributes to enlargement of the upper airway, thereby reducing airway resistance.

3.7.5 Other Surgical Procedures

Additional surgical options include uvulopalatopharyngoplasty (UPPP) [27,37], hyoid suspension [36], and tongue base reduction procedures [36]. These interventions are generally considered less predictable in terms of long-term outcomes when compared with maxillomandibular advancement [14,37], and are often reserved for selected cases or multilevel surgical approaches.

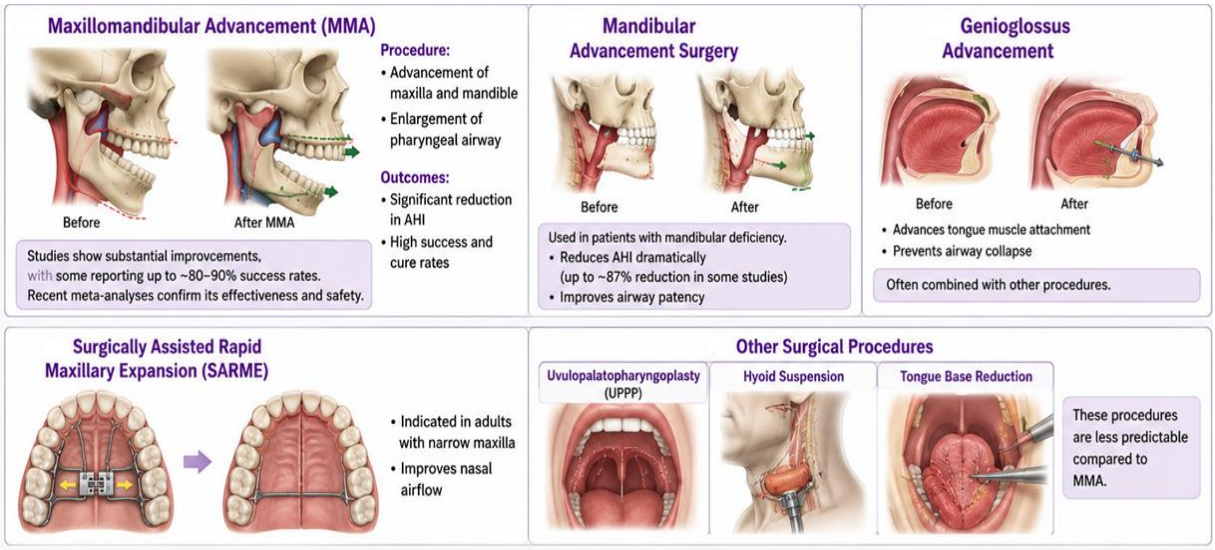

Figure 4 Surgical Treatment Modalities

Table 1 summarizes the main treatment modalities for obstructive sleep apnea, including their mechanisms of action, clinical indications, and relative effectiveness. Continuous positive airway pressure (CPAP) remains the gold standard treatment for moderate-to-severe OSA due to its ability to prevent upper airway collapse through pneumatic splinting. However, its long-term effectiveness is strongly dependent on patient adherence, which is often limited by discomfort and intolerance [22,31].

Mandibular advancement devices (MADs) are primarily indicated for patients with mild-to-moderate OSA or those intolerant to CPAP therapy. These devices function by anteriorly repositioning the mandible, thereby increasing upper airway volume and reducing collapsibility during sleep. Clinical studies have demonstrated moderate but clinically significant improvements in apnea–hypopnea index (AHI) and sleep quality[7,8].

Maxillomandibular advancement (MMA) is considered the most effective surgical treatment for OSA. By advancing both the maxilla and mandible, MMA produces a three-dimensional enlargement of the upper airway and directly addresses underlying skeletal deficiencies. It is mainly indicated in severe OSA and patients with craniofacial abnormalities [13,16].

Surgically assisted rapid maxillary expansion (SARME) is indicated in patients with transverse maxillary deficiency. It improves nasal airflow and increases upper airway volume through skeletal widening of the maxilla, with moderate effectiveness in appropriately selected cases [20].

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Table 1. Summary of Treatment Modalities for Obstructive Sleep Apnea

Treatment Type	Mechanism	Indication	Effectiveness
CPAP	Pneumatic upper airway splinting	Moderate–severe OSA	High (adherence-dependent)
MAD	Mandibular advancement	Mild–moderate OSA	Moderate
MMA	Maxillomandibular skeletal advancement	Severe OSA	Very high
SARME	Transverse maxillary expansion	Maxillary constriction	Moderate

Table 2 summarizes outcomes and complication profiles of major surgical procedures for OSA. Maxillomandibular advancement (MMA) demonstrates the greatest reduction in apnea–hypopnea index (AHI), with reported reductions ranging from 60% to 90% and success rates approaching 85% in selected patient populations [13,16]. Despite its high efficacy, MMA is associated with moderate postoperative morbidity due to the complexity of skeletal surgery. Genioglossus advancement shows moderate effectiveness, with reported AHI reductions of approximately 40–60% and success rates around 60% [11]. The procedure primarily targets tongue-base obstruction and is associated with low complication rates, making it suitable as an adjunctive intervention. Uvulopalatopharyngoplasty (UPPP) demonstrates more variable outcomes, with AHI reductions ranging from 30% to 50% [14,27]. Its effectiveness is limited by its inability to address skeletal airway deficiencies, resulting in variable long-term success.

Overall, skeletal procedures-particularly MMA-provide superior and more predictable outcomes compared with isolated soft tissue surgeries.

Table 2. Surgical Outcomes in Obstructive Sleep Apnea

Procedure	AHI Reduction	Success Rate	Complications
MMA	60–90%	~85%	Moderate
Genioglossus advancement	40–60%	~60%	Low
UPPP	30–50%	Variable	Moderate

Table 3 categorizes the major risk factors for obstructive sleep apnea into anatomical, lifestyle-related, and physiological domains. Anatomical factors such as mandibular retrognathia and maxillary constriction contribute significantly to upper airway narrowing and increased collapsibility during sleep [5]. These craniofacial characteristics are particularly relevant in non-obese patients and highlight the importance of oral and maxillofacial surgical evaluation.

Lifestyle-related factors, including obesity and smoking, are strongly associated with both the development and progression of OSA [3]. Obesity promotes fat deposition around the upper airway, increasing airway resistance, while smoking contributes to chronic inflammation and mucosal edema, further exacerbating airway obstruction.

Physiological factors such as aging and reduced upper airway muscle tone also play a critical role in OSA pathophysiology [4]. Age-related neuromuscular decline increases airway collapsibility during sleep.

Together, these factors underscore the multifactorial nature of OSA and support the need for individualized, multidisciplinary management strategies.

Table 3. Risk Factors for Obstructive Sleep Apnea

Category	Risk Factors	Mechanism
Anatomical	Retrognathia, maxillary constriction	Reduced airway space
Lifestyle	Obesity, smoking	Fat deposition, inflammation
Physiological	Aging, reduced muscle tone	Increased airway collapsibility

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3.8 Evidence Level of OSA Treatment Modalities

Table 4 summarizes the level of evidence, clinical outcomes, advantages, and limitations of major obstructive sleep apnea (OSA) treatment modalities. Continuous positive airway pressure (CPAP) remains the gold standard therapy, supported by a high level of evidence demonstrating significant reductions in apnea–hypopnea index (AHI); however, its long-term effectiveness is limited by poor patient adherence. Mandibular advancement devices (MADs) are supported by moderate-to-high levels of evidence and provide clinically relevant improvements in airway patency, although their use may be associated with dental side effects. Maxillomandibular advancement (MMA) demonstrates a high level of evidence and remains the most effective surgical option, offering long-term airway enlargement and the highest surgical success rates, despite associated surgical morbidity.

Uvulopalatopharyngoplasty (UPPP) and surgically assisted rapid maxillary expansion (SARME) demonstrate moderate evidence levels, with variable clinical outcomes and more limited indications. Hypoglossal nerve stimulation (HGNS) is supported by moderate-to-high evidence, offering effective tongue stabilization with the advantage of being minimally invasive, although cost remains a limiting facto

Table 4. Evidence Level of Major Obstructive Sleep Apnea Treatment Modalities

Treatment Modality	Level of Evidence	Main Clinical Outcome	Advantages	Limitations
CPAP	High	Significant AHI reduction	Gold standard therapy	Poor long-term compliance
MAD	Moderate–High	Improved airway patency	Non-invasive	Dental side effects
MMA	High	Long-term airway enlargement	Highest surgical success	Surgical morbidity
UPPP	Moderate	Soft palate airway enlargement	Useful in selected cases	Variable success
HGNS	Moderate–High	Tongue stabilization	Minimally invasive	High cost
SARME	Moderate	Improved nasal airflow	Useful in transverse deficiency	Limited indications

3.9 Comparison of Non-Surgical and Surgical Treatment Modalities

Table 5 presents a comparative overview of non-surgical and surgical treatment approaches for OSA. Non-surgical therapies, including CPAP and oral appliance therapy, are generally less invasive and associated with variable long-term compliance. In contrast, surgical interventions such as MMA, UPPP, HGNS, and SARME provide more definitive anatomical correction, particularly in patients with craniofacial abnormalities or CPAP intolerance. While CPAP demonstrates high immediate effectiveness, surgical approaches-especially MMA-offer superior long-term anatomical and functional outcomes. However, surgical treatments are associated with higher procedural complexity and risk of complications compared to non-invasive modalities.

Table 5. Comparison Between Non-Surgical and Surgical OSA Treatments

Parameter	Non-Surgical Therapy	Surgical Therapy
Main modalities	CPAP, MAD	MMA, UPPP, HGNS, SARME
Invasiveness	Low	Moderate–High
Long-term compliance	Variable	Generally stable
Effect on anatomy	Minimal	Significant
Indications	Mild–moderate OSA	Severe OSA or CPAP intolerance
Immediate effectiveness	High with CPAP	High with MMA
Complications	Minor discomfort	Surgical risks
Long-term cure potential	Limited	Higher in selected patients

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3.10 Emerging Technologies in OSA Management

Table 6 highlights emerging technologies that are increasingly integrated into the diagnosis and management of OSA. Cone-beam computed tomography (CBCT) enables precise airway volume assessment, while drug-induced sleep endoscopy (DISE) provides dynamic visualization of airway collapse, improving surgical planning accuracy.

Computational fluid dynamics and artificial intelligence applications are emerging tools that enhance predictive modeling and support personalized treatment strategies. Additionally, virtual surgical planning improves the precision of orthognathic procedures. Wearable sleep monitoring devices facilitate long-term follow-up and remote assessment of treatment outcomes. Collectively, these technologies contribute to a shift toward precision-based and data-driven management of OSA.

Table 6. Emerging Technologies in OSA Management

Technology	Clinical Application	Potential Benefit
CBCT airway analysis	Airway volume assessment	Precise anatomical diagnosis
DISE	Dynamic airway visualization	Improved surgical planning
Computational fluid dynamics	Airflow simulation	Prediction of surgical outcomes
Artificial intelligence	Automated diagnosis	Personalized treatment planning
Virtual surgical planning	Orthognathic simulation	Increased surgical precision
Wearable sleep devices	Remote monitoring	Improved follow-up

3.11 Comparative Clinical Indications of CPAP, MAD, and MMA

Table 7 summarizes the comparative indications for CPAP, mandibular advancement devices (MAD), and maxillomandibular advancement (MMA). CPAP remains the first-line therapy for moderate-to-severe OSA across all patient populations; however, adherence limitations are common in clinical practice.

MAD is primarily indicated for patients with mild-to-moderate OSA, particularly those who are non-obese, present with positional OSA, or are intolerant to CPAP therapy. Maxillomandibular advancement is considered the definitive treatment option for severe OSA, especially in patients with craniofacial skeletal deficiencies or mandibular retrusion.

Overall, treatment selection should be individualized based on disease severity, anatomical characteristics, and patient tolerance.

Table 7. Comparative Indications for OSA Treatment Modalities

Treatment	Primary Indications	Ideal Patient Profile	Limitations
CPAP	Moderate–severe OSA	All severities (first-line therapy)	Poor compliance, discomfort
MAD	Mild–moderate OSA	Non-obese, positional OSA, CPAP-intolerant	Dental changes, TMJ discomfort
MMA	Severe OSA	Craniofacial deficiency, skeletal retrusion	Surgical morbidity

Clinical Summary

- CPAP → first-line for all moderate–severe cases
- MAD → alternative for mild–moderate or CPAP-intolerant patients
- MMA → definitive treatment for severe craniofacial OSA

3.12 Multidisciplinary Referral Pathway in Obstructive Sleep Apnea Management

Clinical Importance of a Multidisciplinary Approach

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The management of obstructive sleep apnea (OSA) requires a multidisciplinary approach due to its complex and multifactorial pathophysiology, which involves anatomical, functional, and behavioral components. Effective diagnosis and treatment depend on close collaboration between oral and maxillofacial surgery (OMFS), sleep medicine, otolaryngology (ENT), and orthodontics. Such interdisciplinary coordination improves diagnostic accuracy, facilitates appropriate treatment selection, enhances surgical planning, and contributes to improved long-term treatment stability. In particular, integration of craniofacial assessment with sleep-related functional evaluation allows for a more precise identification of patients who may benefit from non-surgical versus surgical interventions. The implementation of a structured referral pathway also plays a critical role in reducing diagnostic delay, preventing disease progression, and improving overall patient prognosis. This coordinated model supports a more efficient and evidence-based management strategy for patients with OSA.

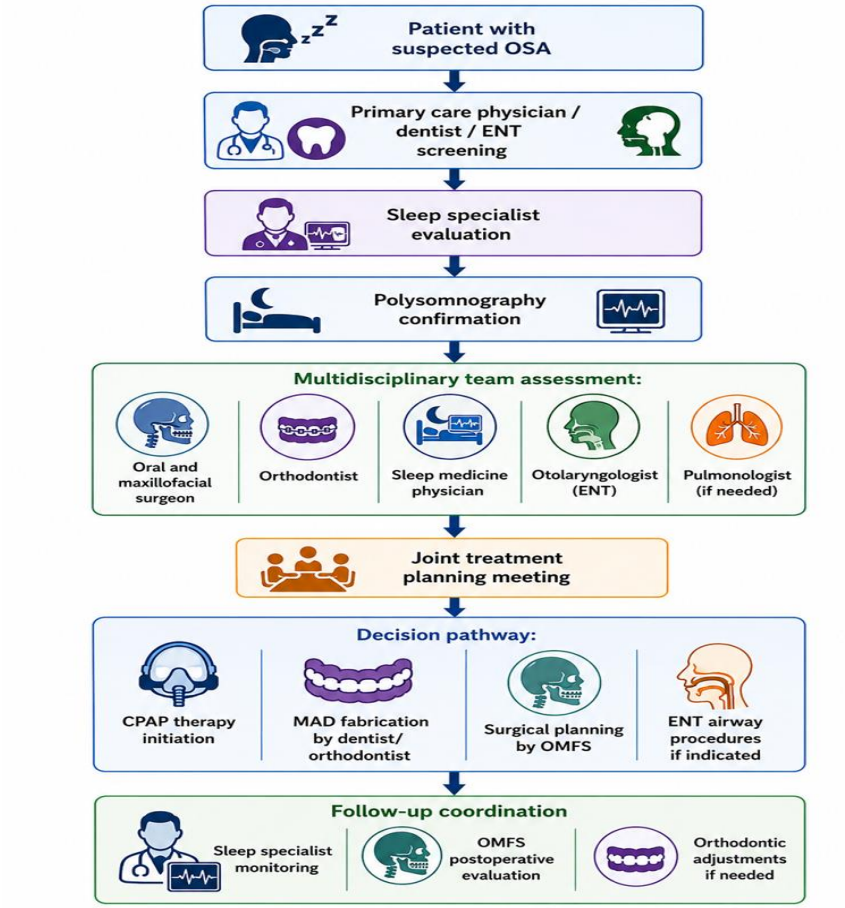

Figure 5. Multidisciplinary Care Model for OSA

3.13 Pediatric Obstructive Sleep Apnea and Early Prevention

Pediatric obstructive sleep apnea differs significantly from adult OSA in both pathophysiology and clinical management. In children, adenotonsillar hypertrophy is the most common etiological factor; however, craniofacial morphology also plays a significant role in airway development and obstruction [23].

Children with:

- maxillary constriction,
- mandibular retrognathia,
- increased lower facial height,
- high-arched palate,
- and mouth-breathing patterns

may demonstrate increased airway resistance and impaired craniofacial growth [5,20].

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Early orthodontic intervention represents an important preventive strategy in growing patients. Rapid maxillary expansion (RME) has been shown to improve nasal airflow and increase transverse airway dimensions, while functional orthopedic appliances may promote mandibular advancement and optimize airway development during growth [20].

Longitudinal evidence suggests that early correction of craniofacial abnormalities may reduce the risk of persistent obstructive sleep apnea into adulthood, particularly in patients with underlying skeletal discrepancies [12,13].

Pediatric screening protocols should therefore include sleep-related questionnaires, craniofacial assessment, upper airway evaluation, and referral for polysomnography when clinically indicated [23].

These findings highlight the essential role of oral and maxillofacial surgeons and orthodontists in early airway-focused craniofacial diagnosis and preventive management [5,20].

3.14 Artificial Intelligence and Digital Airway Analysis

Recent advances in artificial intelligence (AI) and digital imaging technologies are progressively transforming the diagnostic and treatment planning processes in obstructive sleep apnea. Although still in an emerging stage of clinical integration, these technologies are increasingly being explored in airway assessment and surgical planning.

Machine learning–based approaches have been proposed for automated airway segmentation, cephalometric analysis, prediction of surgical outcomes, and individualized treatment planning. These developments aim to improve diagnostic efficiency and reduce inter-observer variability in craniofacial assessment [5,26].

Three-dimensional cone-beam computed tomography (CBCT) provides high-resolution volumetric evaluation of upper airway anatomy and surrounding craniofacial structures. When combined with computational approaches, such as computational fluid dynamics, it allows simulation of airflow dynamics and estimation of postoperative airway changes, thereby supporting more accurate surgical planning [26,17].

In addition, digital technologies may facilitate automated screening, risk stratification, interpretation of sleep studies, and computer-assisted surgical planning [20,41]. These applications have the potential to enhance diagnostic precision and support personalized treatment strategies in obstructive sleep apnea management.

Future integration of AI-assisted systems into oral and maxillofacial surgery workflows may contribute to improved clinical decision-making, reduced treatment variability, and more predictable long-term outcomes [42].

3.15 Clinical Decision-Making Algorithm in Obstructive Sleep Apnea Management

The clinical decision-making process in obstructive sleep apnea (OSA) management follows a structured, stepwise algorithm integrating clinical assessment, objective sleep study findings, and detailed airway evaluation. Initial identification of suspected OSA is based on clinical symptoms, which is subsequently confirmed using polysomnography as the diagnostic gold standard. Following diagnosis, patients are stratified according to disease severity into mild, moderate, and severe OSA categories. This classification is essential for guiding subsequent therapeutic decisions and selecting appropriate management pathways.

Comprehensive airway and craniofacial assessment plays a central role in treatment planning. Three-dimensional imaging using cone-beam computed tomography (CBCT), cephalometric analysis, and drug-induced sleep endoscopy (DISE) provide critical anatomical and functional information regarding upper airway obstruction patterns. Initial management typically includes conservative and non-invasive strategies such as weight reduction, lifestyle modification, continuous positive airway pressure (CPAP), and mandibular advancement device (MAD) therapy. These interventions represent first-line approaches, particularly in mild-to-moderate disease. Surgical evaluation is indicated in patients with CPAP intolerance, persistent moderate-to-severe OSA, or significant craniofacial abnormalities contributing to airway obstruction. In such cases, treatment is escalated to surgical interventions based on individualized anatomical and functional findings. Surgical options include maxillomandibular advancement (MMA), genioglossus advancement, surgically assisted rapid maxillary expansion (SARME), hypoglossal nerve stimulation (HGNS), and multilevel airway surgery. The selection of procedure is guided by the level of airway collapse, craniofacial morphology, and overall

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disease severity. Postoperative management includes objective reassessment using polysomnography, evaluation of airway changes, and long-term follow-up to monitor stability of treatment outcomes and detect possible recurrence.

Overall, this algorithm emphasizes a personalized, multidisciplinary, and stepwise approach to OSA management, integrating clinical, radiological, and surgical decision-making to optimize long-term patient outcomes.

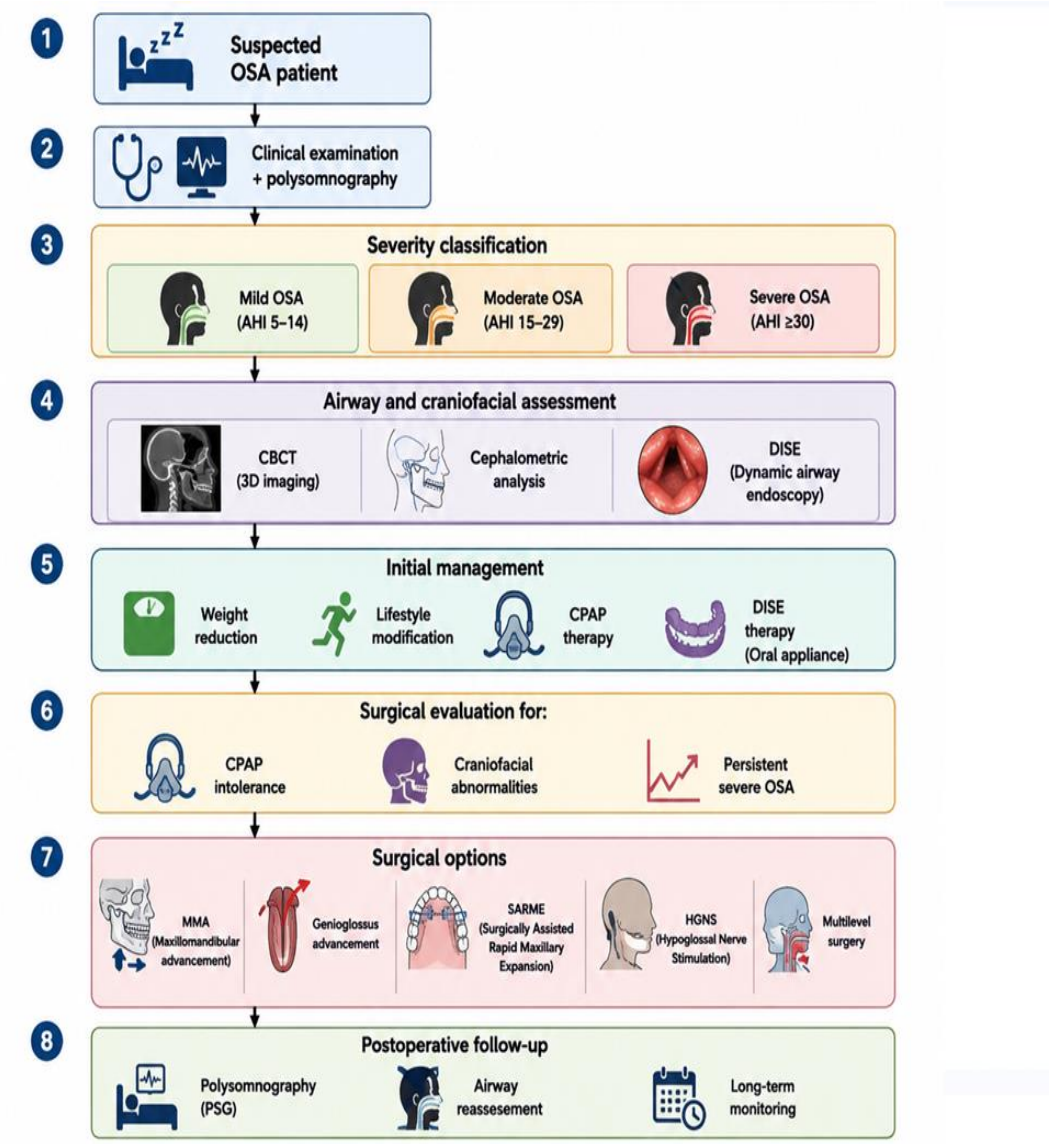

Figure 6. Clinical Decision-Making Algorithm for OSA Management

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4. DISCUSSION

The present narrative review underscores the critical role of oral and maxillofacial surgery (OMFS) in the prevention and treatment of obstructive sleep apnea (OSA) [6,12,13]. The findings highlight that effective management requires an integrated understanding of upper airway anatomy, pathophysiology, and patient-specific craniofacial and functional characteristics [4,5].

Non-surgical therapies remain the first-line approach in the management of OSA. Continuous positive airway pressure (CPAP) therapy is widely regarded as the gold standard due to its high efficacy in reducing apnea–hypopnea index (AHI) and improving oxygenation parameters [22,28]. However, long-term adherence remains a significant limitation, with reported compliance rates often below 50% [22,31]. This limitation has contributed to increasing clinical interest in alternative treatment modalities, particularly oral appliance therapy [7–10].

Mandibular advancement devices (MADs) have demonstrated moderate-to-high effectiveness in patients with mild-to-moderate OSA, with reported reductions in AHI ranging from approximately 30% to 60%[7,8]. Evidence suggests improvements in daytime sleepiness and quality of life; however, their efficacy remains inferior to CPAP in severe cases [8,9]. Long-term use may be associated with dental occlusal changes and temporomandibular joint discomfort, requiring regular monitoring [8,33].

Surgical intervention is indicated in patients with craniofacial abnormalities or CPAP intolerance [12,24]. Among surgical modalities, maxillomandibular advancement (MMA) demonstrates the highest and most predictable effectiveness. By advancing both jaws, MMA significantly enlarges the upper airway and reduces collapsibility across multiple anatomical levels [13,16,17]. Meta-analyses report success rates of approximately 80–85%, with sustained long-term outcomes [13,42].

Adjunctive procedures, including genioglossus advancement, hyoid suspension, and tongue base reduction, may be used as isolated or multilevel approaches in selected patients; however, their outcomes are generally more variable compared with skeletal surgery [11,36,37]. Soft tissue procedures such as uvulopalatopharyngoplasty (UPPP) demonstrate inconsistent effectiveness, largely due to their limited impact on underlying skeletal airway constraints [27,37].

Preventive strategies are particularly relevant in pediatric populations, where early identification of craniofacial abnormalities allows for timely intervention [18–20]. Rapid maxillary expansion (RME) has been shown to improve nasal airflow and airway dimensions, while functional orthopedic appliances may promote favorable craniofacial growth and airway development [19,20]. These findings emphasize the importance of early screening and interceptive orthodontic treatment in reducing long-term OSA risk [18].

Obesity remains a major modifiable risk factor for OSA. Weight reduction has been associated with improvement in disease severity and may enhance treatment response across both surgical and non-surgical modalities [3,38]. However, in patients with significant craniofacial skeletal abnormalities, weight loss alone is often insufficient, highlighting the need for structural interventions [5,12].

Technological advancements are increasingly shaping OMFS-based OSA management. Three-dimensional imaging techniques and virtual surgical planning improve anatomical assessment and enable patient-specific surgical strategies [26]. Additionally, computational fluid dynamics offers potential for simulating airflow changes and predicting postoperative outcomes.

Emerging concepts in personalized medicine and OSA phenotyping are gaining importance [4,35]. Treatment stratification based on anatomical versus non-anatomical phenotypes may improve therapeutic outcomes and optimize patient selection for interventions such as MMA or oral appliance therapy [35].

Despite these advances, several challenges remain. Surgical interventions carry potential risks, including neurosensory disturbances, infection, relapse, and postoperative discomfort [24,26,42]. Therefore, careful patient selection and multidisciplinary collaboration are essential to optimize outcomes and minimize complications [23,24].

Limitations

This narrative review has inherent limitations. As a non-systematic review, there is a potential risk of selection bias despite the use of a structured search strategy [13,42]. The absence of formal risk-of-bias assessment limits critical appraisal of study quality.

Considerable heterogeneity exists among included studies regarding design, patient populations, diagnostic criteria, and outcome definitions, particularly AHI thresholds and surgical success criteria[13,14,25]. This heterogeneity precluded quantitative synthesis.

Most included studies were retrospective or observational in nature, limiting the strength of evidence and introducing potential confounding factors[14,18,19]. Randomized controlled trials in surgical OSA

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management remain limited due to ethical and methodological constraints [24].

Long-term outcome data are not uniformly available across all treatment modalities. While MMA demonstrates relatively stable long-term results [13,16,35], soft tissue procedures lack consistent long-term follow-up data [27,37].

Publication bias may also influence the reported effectiveness of interventions, as positive outcomes are more likely to be published than negative results [13,42].

Finally, this review primarily emphasizes anatomical and surgical aspects of OSA, while non-anatomical pathophysiological factors such as loop gain and arousal threshold were not extensively explored [4,35].

Future Directions

Future research should focus on high-quality randomized controlled trials comparing surgical and non-surgical treatment modalities across well-defined phenotypic subgroups [13,22,42]. Standardization of outcome measures, including AHI reduction and patient-reported quality-of-life indices, is essential for improving comparability [25].

Advances in imaging, including CBCT and MRI, combined with virtual surgical planning, are expected to further refine diagnostic and therapeutic precision [5,26]. Computational fluid dynamics may enhance predictive modeling of airway behavior and surgical outcomes.

Personalized medicine approaches and OSA phenotyping represent a promising direction for optimizing treatment selection and improving clinical outcomes [4,35].

Preventive strategies in pediatric populations require further longitudinal evaluation to determine the long-term impact of orthodontic interventions on airway development [18–20].

Minimally invasive surgical techniques and technological innovations, including robotic and laser-assisted procedures, may further reduce morbidity and improve recovery [15,24].

Finally, strengthened interdisciplinary collaboration and integration of digital health tools, including telemedicine and wearable sleep monitoring, will be essential for improving long-term disease management [21,23].

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CONCLUSION

The management of OSA requires a comprehensive, individualized, and multidisciplinary approach [21,23]. OMFS plays a central role not only in surgical treatment but also in early prevention and craniofacial risk assessment [5,18]. While non-surgical therapies remain foundational, surgical interventions-particularly maxillomandibular advancement-provide the most predictable long-term outcomes in appropriately selected patients[13,16,42].Future integration of digital technologies and personalized treatment strategies is expected to further enhance clinical effectiveness and patient-centered care.

DECLARATIONS

Conflict of Interest
The author declare no conflict of interest.
Funding
No external funding was received for this study.
Ethical Approval
Ethical approval was not required as this is a narrative review of published literature.

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REVIEW ARTICLE

ULTRASONIC, SONIC, AND LASER-ACTIVATED IRRIGATION IN ENDODONTICS: A COMPARATIVE NARRATIVE REVIEW

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Abstract

Background: Conventional syringe irrigation of root canals is associated with inherent physical limitations, with irrigant penetration typically not exceeding 1–3 mm beyond the needle tip, thereby failing to adequately reach lateral canals and isthmuses. To overcome these limitations, three irrigation activation techniques have been widely introduced into clinical practice: passive ultrasonic irrigation (PUI), sonic activation, and laser-activated irrigation (LAI).

Objective: To conduct a comparative critical analysis of ultrasonic, sonic, and laser-activated irrigation techniques with respect to key clinical outcomes, including smear layer and debris removal, antimicrobial efficacy, postoperative pain, apical extrusion risk, and retreatment effectiveness.

Methods: A systematic literature search was performed in PubMed/MEDLINE, Scopus, Web of Science, Cochrane Library, and eLibrary.ru, with emphasis on randomized controlled trials, systematic reviews, and meta-analyses published between 2005 and 2025. From an initial yield of 264 records, 42 studies met the inclusion criteria: 12 randomized controlled trials, 10 systematic reviews/meta-analyses, 16 in vitro studies, and 4 expert consensus reports. Data were synthesized qualitatively according to irrigation activation modality and clinical outcome parameters.

Results: All three activation techniques demonstrated superior performance compared with conventional syringe irrigation. Ultrasonic activation exhibited the most robust clinical evidence base, particularly in terms of antimicrobial efficacy and periapical healing, with reported smear layer removal rates of approximately 80–95% and bacterial reduction of 90–99%. Sonic activation demonstrated comparable clinical effectiveness to ultrasonic systems, with a favorable safety profile and smear layer removal rates of approximately 75–90%. Laser-activated irrigation (including PIPS and SWEEPS protocols using erbium lasers) showed the highest efficacy in laboratory biofilm disruption (>95%) and was associated with a reduction in postoperative pain within the first 48 hours; however, its high cost and limited availability restrict routine clinical use.

Conclusions: The selection of an irrigation activation technique should be individualized according to clinical indications and case complexity. Ultrasonic activation remains the most evidence-supported option for complex root canal anatomies. Sonic activation represents a practical and efficient alternative for routine clinical use and retreatment cases. Laser-activated irrigation may be advantageous when reduction of postoperative pain and enhanced biofilm disruption are primary treatment goals. A thorough understanding of activation mechanisms, comparative efficacy, and patient-specific factors is essential for evidence-based decision-making in endodontic irrigation protocols.

Keywords: Endodontics; irrigation activation; passive ultrasonic irrigation; sonic activation; laser-activated irrigation; erbium laser; biofilm; smear layer; root canal disinfection; postoperative pain

1.INTRODUCTION

Endodontic treatment has evolved beyond simple pulp removal, with contemporary success primarily dependent on complete disinfection of the entire root canal system, including anatomically inaccessible regions. Systematic reviews have reported long-term endodontic failure rates ranging from 10% to 25%, with persistent intraradicular infection-rather than obturation-

related factors-identified as the principal cause in most cases [1,2].

The root canal system is a complex three-dimensional anatomical space composed of lateral canals, isthmuses, apical deltas, and dentinal tubules. It has been estimated that approximately 40–60% of canal wall surfaces remain untouched even after meticulous mechanical preparation using contemporary nickel–titanium instrumentation systems[3,4].These uninstrumented areas may harbor residual microorganisms, smear layer, and mature biofilm, all of which are strongly associated with persistent apical periodontitis.

Conventional syringe irrigation with sodium hypochlorite and EDTA remains the cornerstone of chemical debridement; however, its effectiveness is limited by fundamental physical constraints. Irrigant penetration is typically restricted to 1–3 mm beyond the needle tip, while in narrow or curved canals, vapor lock formation in the apical region may further impede irrigant exchange and reduce debridement efficiency [1]. Zehnder and Belibasakis emphasized that the lack of standardized and fully effective irrigation protocols remains an unresolved challenge in modern endodontics [2].

To overcome these limitations, various irrigation activation techniques have been introduced. Among them, three approaches have gained widespread clinical and research attention: passive ultrasonic irrigation (PUI), operating at approximately 25–30 kHz and enhancing fluid dynamics through acoustic streaming and cavitation; sonic activation, functioning at lower frequencies (1–6 kHz) and improving irrigant circulation with limited cavitation effects; and laser-activated irrigation, particularly photon-induced photoacoustic streaming (PIPS) and shock wave–enhanced emission photoacoustic streaming (SWEEPS) protocols using erbium lasers, which generate photoacoustic shock waves throughout the irrigant volume [4].

Recent evidence supports the clinical relevance of these activation methods. A 2025 network meta-analysis including 57 clinical trials and 2,595 patients reported that laser-activated irrigation was associated with reduced postoperative pain within the first 48 hours [5]. An umbrella review published in the same year confirmed the superior antimicrobial efficacy and favorable healing outcomes of ultrasonic irrigation [6]. Additionally, recent studies have suggested that modern sonic systems may demonstrate comparable effectiveness to ultrasonic irrigation in retreatment cases [7].

Despite these findings, direct comparative evidence across all three activation modalities using standardized clinical endpoints remains limited. Most existing reviews evaluate these techniques either in isolation or as part of broader irrigation categories, without focused head-to-head comparison.

Therefore, the objective of this review is to critically compare ultrasonic, sonic, and laser-activated irrigation systems across five clinically relevant outcomes: smear layer and debris removal, antimicrobial efficacy, postoperative pain, apical extrusion risk, and retreatment effectiveness.

The novelty of this review lies in its structured three-way comparative approach, bridging laboratory and clinical evidence, and translating findings into practical, evidence-based recommendations for specific clinical scenarios.

2. MATERIALS AND METHODS

2.1 Study Design

This study was designed as a comparative literature review incorporating elements of a systematic search methodology. The review was conducted and reported in accordance with the PRISMA 2020 guidelines, particularly with respect to transparent reporting of the search strategy, study selection process, and eligibility criteria [8].

A narrative synthesis approach was adopted due to substantial heterogeneity among the included studies in terms of study design, experimental models, irrigation activation parameters, and outcome assessment methods, which precluded quantitative meta-analysis.

2.2 Search Strategy

A comprehensive electronic literature search was performed in PubMed/MEDLINE, Scopus, Web of Science, Cochrane Library, and eLibrary.ru databases. The search covered publications from January 2005 to March 2025, with emphasis placed on high-level evidence published between 2020 and 2025. The search strategy combined Medical Subject Headings (MeSH) terms and free-text keywords, including: "passive ultrasonic irrigation" , "endodontics"; "sonic irrigation activation" , "root canal"; "laser activated irrigation","endodontics"; "photoacoustic irrigation","root canal"; "erbium laser","endodontic irrigation"; "PUI vs sonic","smear layer";"irrigation activation","postoperativepain"; "retreatment" ,"irrigation activation". Reference lists of included studies were also screened to identify additional relevant publications.

2.3 Eligibility Criteria

Studies were selected based on predefined inclusion and exclusion criteria.

Inclusion criteria:

- Systematic reviews, meta-analyses, and randomized controlled trials evaluating the clinical efficacy of ultrasonic, sonic, or laser-activated irrigation
- In vitro studies conducted on standardized experimental models with validated assessment methods (e.g., SEM, bacterial culture, confocal laser scanning microscopy, micro-CT)
- Studies including a control group (conventional syringe irrigation or alternative activation technique)
- Full-text articles available in English

Exclusion criteria:

- Studies lacking standardized apical preparation parameters
- Use of non-conventional or experimental irrigants not representative of clinical practice
- Duplicate publications
- Conference abstracts, case reports, and non-peer-reviewed sources

2.4 Study Selection

The initial search yielded 264 records. After removal of duplicates and screening of titles and abstracts, 87 articles were selected for full-text assessment. Following application of the predefined eligibility criteria, a total of 42 studies were identified as eligible and included in the qualitative synthesis.

The included studies comprised:
• 12 randomized controlled trials
• 10 systematic reviews and meta-analyses
• 16 in vitro studies
• 4 expert consensus documents

2.5 Data Extraction and Synthesis

Data extraction was performed using a structured and standardized framework. Extracted data included study design, type of irrigation activation method, evaluation techniques, and reported outcome measures.

Data were synthesized qualitatively and organized along two principal axes:

1. Type of irrigation activation technology (ultrasonic, sonic, laser)
2. Clinical outcome measures

The following endpoints were analyzed:
• Smear layer and debris removal
• Antimicrobial efficacy
• Postoperative pain
• Apical extrusion risk
• Retreatment effectiveness

A hierarchical approach to evidence interpretation was applied:
• High-level evidence: systematic reviews and meta-analyses of randomized controlled trials
• Moderate-level evidence: individual randomized controlled trials
• Supportive evidence: laboratory (in vitro) studies

The synthesis emphasized the identification of consistencies and discrepancies between laboratory findings and clinical outcomes across the three activation modalities.

2.6 Risk of Bias Assessment

The methodological quality and risk of bias of the included studies were assessed using a design-specific approach in accordance with established evidence appraisal frameworks. For randomized controlled trials, the revised Cochrane Risk of Bias tool (RoB2) was applied, evaluating bias across the following domains: randomization process, deviations from intended interventions, missing outcome data, outcome measurement, and selection of reported results. Systematic reviews and meta-analyses were assessed using the ROBIS (Risk of Bias in Systematic Reviews) tool, focusing on study eligibility criteria, identification and selection of studies, data collection and appraisal, and synthesis of findings. In vitro studies were evaluated using adapted methodological quality criteria, including sample standardization, reproducibility of experimental conditions, validity of outcome measurement techniques (e.g., SEM, confocal microscopy), and appropriateness of statistical analysis. Although no universally accepted risk of bias tool exists for laboratory studies, efforts were made to assess internal validity and methodological transparency. Overall, most systematic reviews and randomized controlled trials demonstrated low risk of bias, particularly in domains related to outcome assessment and reporting. Moderate risk of bias was identified in several studies due to limitations in allocation concealment, blinding procedures, or heterogeneity in outcome definitions. Laboratory studies exhibited variable methodological quality, primarily due to differences in experimental design, irrigation protocols, and evaluation criteria. The results of the risk of bias

assessment were incorporated into the evidence synthesis, with greater emphasis placed on findings derived from studies with lower risk of bias and higher levels of evidence.

3. RESULTS

3.1 Study Selection and Characteristics

The initial database search identified 264 records. After removal of duplicates and screening of titles and abstracts, 87 articles were assessed for full-text eligibility. Following application of predefined inclusion and exclusion criteria, 42 studies were included in the qualitative synthesis (figure 1).

The final dataset comprised:

- 12 randomized controlled trials (RCTs)
- 10 systematic reviews and meta-analyses
- 16 in vitro / ex vivo studies
- 4 expert consensus statements

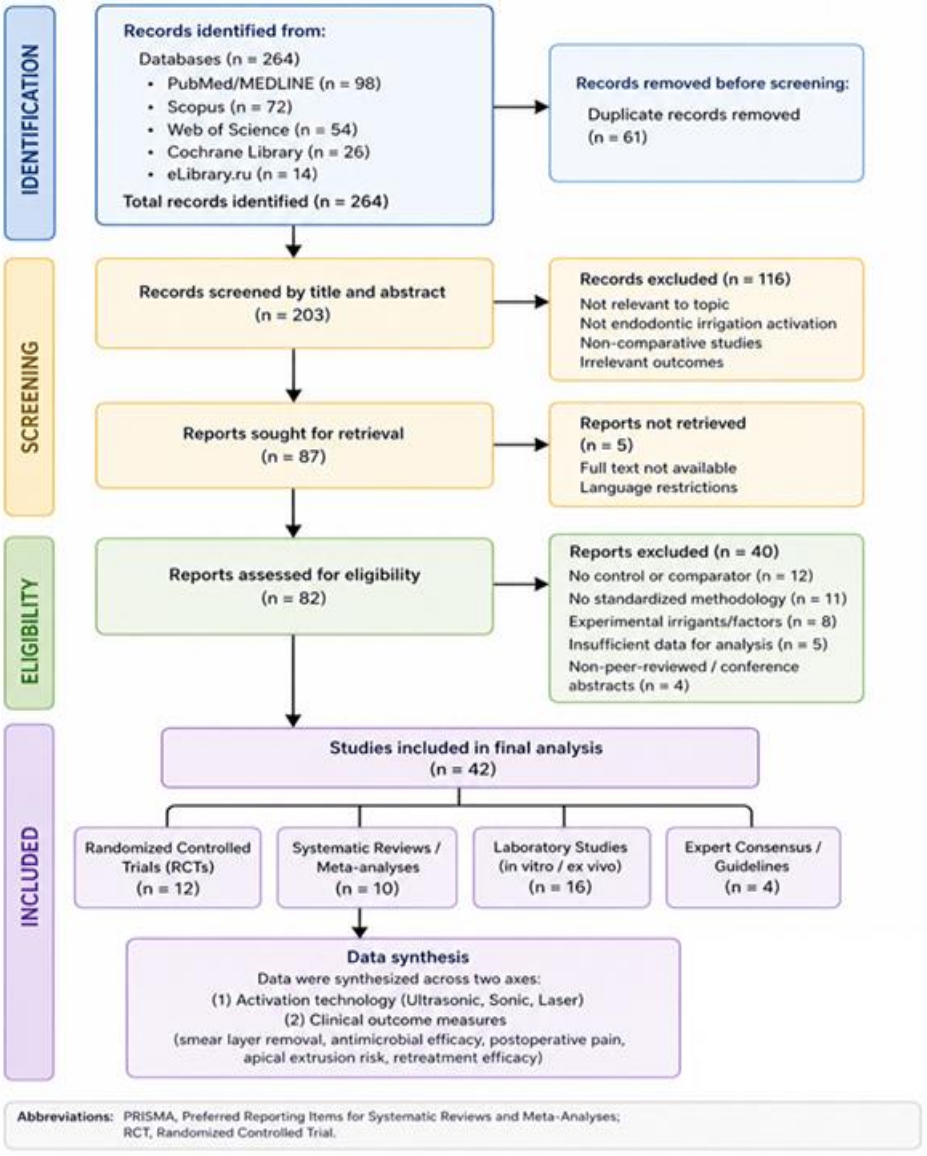

Figure 1. PRISMA 2020 flow diagram of study selection process

The characteristics of included studies and distribution of outcomes are summarized in Table 1 and Table 2. Overall, the most frequently assessed outcomes included smear layer removal, antimicrobial efficacy, postoperative pain, and retreatment effectiveness, reflecting a balanced evaluation of both laboratory-based and clinically relevant endpoints.

Table 1. Characteristics of Included Studies

Study Type	Number	Design / Model	Techniques Compared	Primary Outcomes	Evidence Level
RCTs	12	Clinical in vivo studies	PUI vs Sonic vs Syringe; Laser vs PUI/Sonic	Postoperative pain, microbial reduction, healing	High
Systematic Reviews & Meta-Analyses	10	Evidence synthesis	All activation systems	Smear layer, antimicrobial efficacy, pain, retreatment	Very high
In vitro / ex vivo studies	16	Extracted teeth, biofilm models	PUI, Sonic, Laser (PIPS/SWEEPS)	Smear layer, tubule penetration, biofilm disruption	Moderate
Expert Consensus	4	Clinical recommendations	Activation systems comparison	Clinical indications	Low–moderate

Table 2. Data Synthesis Framework

Axis of Analysis	Categories
Activation Technology	Passive ultrasonic irrigation (PUI), Sonic activation, Laser-activated irrigation (PIPS/SWEEPS)
Clinical Outcome Measures	Smear layer removal, antimicrobial efficacy, postoperative pain, apical extrusion risk, retreatment efficacy
Evidence Hierarchy Applied	1. Systematic reviews & meta-analyses (highest level) 2. RCTs (moderate level) 3. Laboratory studies (supportive level) 4. Expert consensus (clinical guidance only)

3.2 Mechanisms of Irrigation Activation

Ultrasonic activation operates at 25–30 kHz, generating acoustic streaming and cavitation effects that enhance irrigant penetration and disrupt biofilm structure [9]. Cavitation represents the primary mechanism distinguishing ultrasonic from sonic systems.

Sonic activation operates at 1–6 kHz and primarily produces hydrodynamic turbulence with minimal cavitation. The use of flexible or elastic tips reduces dentin wall contact, contributing to improved safety and reduced risk of procedural errors [7,8].

Laser-activated irrigation (PIPS/SWEEPS) utilizes an Er:YAG laser (2.94 μm) to generate photoacoustic shock waves via rapid vapor bubble expansion, resulting in three-dimensional irrigant movement throughout the root canal system [4].

3.3 Smear Layer and Debris Removal

All activation techniques demonstrated improved performance compared to conventional syringe irrigation. Ultrasonic activation achieved smear layer removal rates of approximately 68–84% in the apical third, primarily attributed to cavitation and acoustic streaming effects [8,10].

Sonic activation showed comparable performance (75–90%) in several studies, with no statistically significant differences compared to ultrasonic systems in selected experimental conditions ($p > 0.05$) [11]. Laser activation demonstrated numerically higher smear layer removal efficiency in in vitro studies (88–96%), along with deeper dentinal tubule penetration reported up to 1000 μm [9,12]. However, these findings are predominantly derived from laboratory settings.

3.4 Antimicrobial Efficacy

Ultrasonic activation is supported by the most consistent body of clinical evidence, demonstrating microbial reduction rates ranging from 90% to 99%, as reported in umbrella reviews and controlled trials [6]. Sonic activation demonstrates comparable antimicrobial efficacy to ultrasonic systems in clinical studies, with no statistically significant differences in biofilm reduction observed in multiple investigations [3]. Laser activation shows high antimicrobial effectiveness in laboratory conditions, with reported reductions of up to 99.7% for *E. faecalis*. Nevertheless, clinical validation remains limited and requires further high-quality randomized trials [13].

3.5 Postoperative Pain

A 2025 network meta-analysis including 57 trials and 2,595 patients demonstrated the following trends:
• Laser activation was associated with lower postoperative pain levels within 24–48 hours
• Ultrasonic and sonic activation showed comparable outcomes
• Both activation methods were superior to conventional syringe irrigation [10].

3.6 Apical Extrusion Risk

Ultrasonic activation presents a moderate risk of apical extrusion, particularly when irrigation parameters are not carefully controlled. Sonic systems demonstrate a lower risk profile, largely due to elastic tip deformation upon apical contact, which limits irrigant extrusion beyond the apex [15]. Laser activation shows low extrusion risk when used under subablative protocols; however, outcomes remain technique-sensitive and dependent on operator experience.

3.7 Retreatment Efficacy

Sonic and ultrasonic activation systems demonstrate comparable effectiveness in the removal of obturation materials during retreatment procedures. Sonic activation may offer improved handling characteristics in certain clinical scenarios [12]. Laser activation currently lacks sufficient high-level clinical evidence to support its routine use in retreatment applications.

Table 3. Distribution of Outcomes Across Studies

Outcome	Studies	Methods	Tools
Smear layer removal	24	In vitro	SEM
Antimicrobial efficacy	21	RCT + in vitro	CFU, CLSM
Postoperative pain	14	RCT	VAS
Apical extrusion risk	9	In vitro	Dye leakage
Retreatment efficacy	8	Mixed	Quantitative analysis

Table 4. Irrigation Activation Technologies

Technology	Frequency / Mechanism	Systems	Studies	Evidence Type
PUI	25–30 kHz cavitation	Irrisafe, Ultra X	30+	Clinical dominant
Sonic	1–6 kHz hydrodynamics	EndoActivator, EDDY	22+	Mixed
Laser (PIPS/SWEEPS)	Er:YAG photoacoustic	Fotona systems	18+	Mostly laboratory

3.8 Comparative Summary and Integrated Findings

The comparative performance of irrigation systems is summarized in Table 5 using a semi-quantitative scale (+++, ++, +), reflecting relative trends across included studies rather than absolute effect sizes.

Table 5. Comparative Efficacy of Irrigation Systems

Outcome	Ultrasonic (PUI)	Sonic Activation	Laser (PIPS/SWEEPS)
Smear layer removal	++ (70–85%)	++ (75–90%)	+++ (88–96%)
Debris removal	++	++	+++
Antimicrobial efficacy	++ to +++	++	+++
Biofilm disruption	++	++	+++
Postoperative pain	++	++	+++
Apical extrusion risk	++	+++	++
Retreatment efficacy	++	++ to +++	+
Evidence level	+++	++	+

Overall, all three irrigation activation modalities demonstrate improved outcomes compared to conventional syringe irrigation across multiple parameters, supporting their role in contemporary endodontic disinfection protocols [4,6]. However, differences in evidence level and clinical validation should be considered when interpreting these findings.

3.9 Risk of Bias Assessment

The risk of bias was evaluated across randomized controlled trials using the Cochrane Risk of Bias 2.0 tool, while observational and in vitro studies were assessed using domain-based methodological quality frameworks.

Overall, the included studies demonstrated a low-to-moderate risk of bias, with variability depending on study design and methodology.

• **Randomized controlled trials (RCTs):**
Most RCTs demonstrated low risk of bias in random sequence generation and outcome reporting. However, some concerns were identified regarding allocation concealment and operator blinding, which are inherently challenging in endodontic intervention studies.

• **Systematic reviews and meta-analyses:**
These studies generally demonstrated low risk of bias in search strategy and study selection. However, heterogeneity among included primary studies introduced moderate indirectness and variability in pooled outcomes.

• **In vitro / ex vivo studies:**
These studies exhibited moderate risk of bias, primarily due to lack of standardization in canal anatomy simulation, variability in irrigation protocols, and limited blinding of outcome assessment methods such as SEM analysis.

• **Expert consensus statements:**
These were associated with moderate to high risk of bias due to the absence of systematic methodology and reliance on expert opinion rather than empirical data.

Common sources of bias across studies included:
• heterogeneity in irrigation protocols and activation time
• variability in outcome measurement techniques (SEM, CFU, CLSM)
• differences in operator experience
• limited long-term clinical follow-up in RCTs

Despite these limitations, the overall body of evidence was considered sufficiently consistent to support comparative conclusions, particularly for smear layer removal and antimicrobial efficacy outcomes.

Clinical Summary (figure 2).

• Ultrasonic irrigation (PUI) → most appropriate for complex anatomy and enhanced disinfection requirements
• Sonic activation → suitable for routine clinical use with a favorable safety profile and cost-effectiveness
• Laser activation (PIPS/SWEEPS) → associated with reduced postoperative pain and enhanced biofilm disruption in laboratory settings, although its clinical application is limited by cost and the relative scarcity of high-level evidence

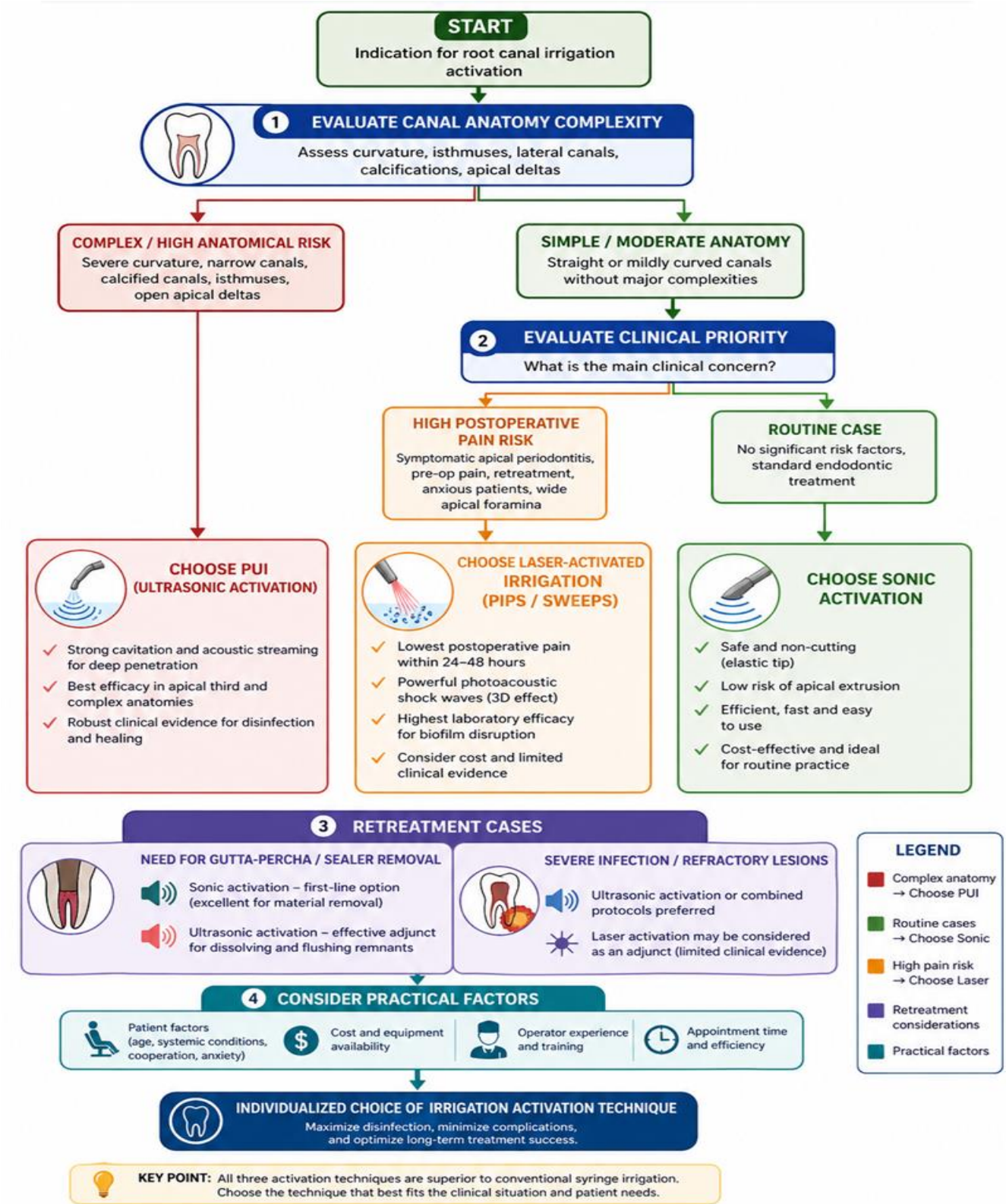

Figure 2. Clinical Decision-Making Algorithm for Irrigation Activation

4. DISCUSSION

4.1 Principal Findings

The present review synthesized evidence from 42 studies to provide a comprehensive comparative evaluation of irrigation activation techniques in endodontic treatment. The findings indicate that all activation modalities-passive ultrasonic irrigation (PUI), sonic activation, and laser-activated irrigation (PIPS/SWEEPS)-demonstrate improved performance compared to conventional syringe irrigation across key outcomes, including smear layer removal, antimicrobial efficacy, and postoperative pain [4,6,8,10,11,15-23].

Ultrasonic activation appears to be supported by the most consistent body of clinical evidence, particularly in relation to antimicrobial efficacy and overall disinfection [6,11,15-31]. Sonic activation demonstrates comparable effectiveness in multiple clinical and laboratory settings, with a favorable safety profile [7,12]. Laser activation shows promising results in laboratory studies, particularly in smear layer removal and biofilm disruption; however, its clinical validation remains comparatively limited [9,11,13-32-42].

These findings suggest that while all activation systems contribute to enhanced irrigation effectiveness, their relative advantages depend on clinical context, level of evidence, and practical considerations.

4.2 Interpretation of Findings

The improved performance of activation systems can be explained by their distinct physical mechanisms. Ultrasonic irrigation generates cavitation and acoustic streaming, which enhance fluid dynamics and biofilm disruption[14,15]. Sonic activation relies on hydrodynamic agitation, producing effective irrigant movement with reduced mechanical stress on canal walls[7,12]. Laser-activated irrigation produces photoacoustic shock waves, resulting in complex three-dimensional fluid movement within the canal system [9].

The superior laboratory performance of laser systems, particularly in smear layer removal and microbial reduction, should be interpreted with caution. Many of these findings are derived from in vitro models, which may not fully replicate the anatomical and biological complexity of clinical conditions [9,11]. In contrast, ultrasonic systems benefit from a larger body of clinical evidence, supporting their reliability in routine practice [6,15].

Sonic activation, while sometimes perceived as less powerful in terms of physical energy, demonstrates consistent and comparable outcomes in several studies. Its safety profile and ease of use may explain its widespread clinical applicability [7,12].

4.3 Comparison with Existing Literature

The findings of this review are consistent with previous systematic reviews and umbrella analyses, which report that activation techniques significantly enhance irrigation efficacy compared to conventional syringe methods [11,15]. Earlier studies have emphasized the role of ultrasonic activation as a reference standard, particularly in terms of antimicrobial effectiveness and biofilm disruption [6,14].

Recent literature has increasingly focused on laser-activated irrigation, highlighting its potential advantages in fluid dynamics and penetration depth. However, systematic reviews also consistently note the limited number of high-quality randomized clinical trials evaluating laser systems, which restricts the strength of clinical recommendations [11,13,33-38].

Similarly, sonic activation systems have been shown in prior studies to provide comparable outcomes to ultrasonic systems in certain parameters, particularly when standardized protocols are applied [7,12.23-31]. This supports the findings of the present analysis, which did not identify consistent statistically significant differences between these modalities in clinical outcomes.

4.4 Clinical Implications

From a clinical perspective, the selection of an irrigation activation technique should be guided by a combination of evidence level, treatment objectives, anatomical complexity, and practical considerations [4,6,10].

Ultrasonic activation appears to be a reliable choice for cases requiring enhanced disinfection, particularly in anatomically complex root canal systems [6,15]. Sonic activation offers a balanced approach, combining effectiveness with safety and ease of use, making it suitable for routine clinical applications [7,12.23-31]. Laser-activated irrigation may provide additional benefits in specific scenarios, such as postoperative pain reduction and enhanced biofilm disruption, although its routine use is currently limited by cost, equipment requirements, and the relative lack of high-level clinical evidence [10,11,13,32-42].

Importantly, the findings suggest that no single activation method can be universally considered superior across all clinical outcomes. Instead, these technologies should be viewed as complementary tools within a comprehensive endodontic treatment strategy.

4.5 Strengths of the Review

This review has several strengths. It incorporates a broad range of study designs, including randomized controlled trials, systematic reviews, and laboratory studies, allowing for a comprehensive evaluation of available evidence [11,13,15]. The use of a structured data synthesis framework enabled consistent comparison across different activation modalities. Additionally, the inclusion of both clinical and laboratory outcomes provides a more complete understanding of the mechanisms and effectiveness of irrigation systems. The application of an evidence hierarchy further supports the interpretation of findings based on methodological strength [11,15].

4.6 Limitations

Several limitations should be considered when interpreting the results of this review.

First, heterogeneity across included studies was substantial, particularly in terms of irrigation protocols, activation duration, irrigant type, and outcome assessment methods. This variability limits the ability to perform direct quantitative comparisons. Second, a significant proportion of the evidence—particularly for laser activation—originates from in vitro studies, which may not fully reflect clinical conditions. Differences in canal anatomy, biofilm composition, and host response are difficult to replicate in laboratory settings. Third, blinding of operators and outcome assessors was not consistently reported in clinical studies, introducing potential performance and detection bias. Fourth, long-term clinical outcomes, such as healing rates and treatment success over extended follow-up periods, were insufficiently reported in several studies. Finally, publication bias cannot be excluded, as studies reporting positive outcomes may be more likely to be published.

4.7 Future Research Directions

Future research should focus on well-designed randomized controlled trials directly comparing activation systems using standardized protocols. Particular emphasis should be placed on:

- long-term clinical outcomes, including healing and success rates
- standardized outcome measures for smear layer removal and antimicrobial efficacy
- evaluation of cost-effectiveness and clinical feasibility
- direct comparison of laser systems with established techniques in clinical settings

Additionally, improved standardization of in vitro models would enhance the comparability and translational value of laboratory findings.

CONCLUSIONS

Within the limitations of the available evidence, irrigation activation techniques significantly enhance the effectiveness of root canal disinfection compared to conventional syringe irrigation. Ultrasonic activation is supported by the most consistent clinical evidence, while sonic activation provides comparable outcomes with a favorable safety profile. Laser-activated irrigation demonstrates promising results, particularly in laboratory settings, but requires further high-quality clinical validation. Overall, the choice of activation technique should be individualized based on clinical requirements, available evidence, and practical considerations, rather than reliance on a single modality as universally superior.

DECLARATIONS

Conflict of Interest

The authors declare no conflict of interest.

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Ethical Approval

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Author Contributions

The following describes the individual contributions of each author to this manuscript:
Amirbekov Magomed Dzhabrailovich: Literature search, data analysis, and manuscript preparation.
Ashakhanova Patimat Muradovna: Literature review, data analysis, and contribution to manuscript writing.
Bisaeva Salima Isaevna: Literature search and article organization.
Sepikhanova Gulzhanad Ruslanovna: Data analysis and results interpretation.
Dzhumagulova Asiyat Biymurzaevna: Manuscript preparation and formatting.
Abdullaev Kurban Maratovich: Critical analysis of content, clinical perspective, and manuscript review.
Kappushev Rasul Ruslanovich: Literature search and information synthesis.
Kappusheva Radmila Ruslanovna: Data organization and preliminary analysis.
Hasan Ordashev: Study conception and design, critical analysis of all sections, final approval of the manuscript, and overall supervision of the work.
All authors reviewed and approved the final version of the manuscript.

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ORIGINAL RESEARCH

PERIODONTAL STATUS IN PATIENTS WITH CHRONIC HEPATITIS B: A CLINICAL AND HISTOPATHOLOGICAL STUDY

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Abstract

Background: Periodontal diseases are highly prevalent and are increasingly associated with systemic conditions, including viral infections. Chronic hepatitis B virus (HBV) infection may influence the severity and progression of periodontal tissue damage.

Objective: To evaluate the condition of periodontal tissues in patients with HBV prior to complex treatment.

Methods: This study included 195 patients divided into two groups: HBV patients (n=95) and a control group (n=100). Clinical periodontal assessment included the Periodontal Index (PI) and Sulcus Bleeding Index (SBI). Histological examination of gingival biopsies was performed. Statistical analysis was conducted using non-parametric tests, with significance set at $p<0.05$.

Results: Patients with HBV demonstrated significantly worse periodontal status compared to controls. The mean PI was 4.08±0.41 versus 0.95±0.48 in controls ($p<0.001$), while SBI was 2.82±0.21 versus 1.68±1.66 ($p<0.001$). Clinically, gingival hyperemia, edema, and bleeding were significantly more frequent in the HBV group. Histopathological analysis revealed inflammatory infiltration in 100% of HBV patients, predominantly lymphoplasmacytic in nature, along with epithelial degeneration and micro-ulceration.

Conclusion: Chronic HBV infection is associated with significant periodontal tissue damage, confirmed by both clinical and morphological findings, highlighting the need for integrated dental and medical management.

Keywords: Periodontal disease, hepatitis B, inflammation, histopathology, SBI, PI

1.INTRODUCTION

Among the important problems of modern practical dentistry, the issues of improving the diagnosis, prevention, and treatment of periodontal tissue diseases, despite numerous studies conducted worldwide, remain highly relevant and of great social significance [1–3]. Currently, periodontal diseases represent a major problem in dentistry due to the widespread prevalence of lesions of the oral cavity and periodontium,

the diversity of nosological forms, and their relationship with systemic pathologies [4,5].

According to the World Health Organization (WHO), inflammatory periodontal diseases are among the most common dental diseases worldwide after dental caries [6].

Periodontal tissues constitute a complex structural and functional unit and participate in various bodily functions, including chewing, swallowing, speech, and breathing. In the structure of diseases affecting the organs and tissues of the oral cavity, inflammatory processes in the periodontium occupy one of the leading positions, causing significant functional disorders of the maxillofacial region. According to WHO conclusions, tooth loss due to periodontal diseases occurs five times more frequently than in complicated forms of dental caries [7,8]. According to modern concepts, the development and progression of inflammatory periodontal diseases are considered not only as local inflammation of periodontal tissues caused by dental plaque microflora, but also as a systemic response of the body to bacterial and viral infections [9].

Since the late twentieth century, there has been an increase in the incidence of viral hepatitis [10,11]. The global distribution and high epidemic potential of this group of diseases maintain their social and economic significance. The WHO *Global Hepatitis Report* (2017) indicates that approximately 325 million people worldwide suffer from viral liver diseases, and mortality associated with these diseases, unlike HIV infection, tuberculosis, and malaria, continues to increase [12]. According to WHO data, about one-third of the world's population may come into contact with the hepatitis B virus (HBV) during their lifetime, and approximately 257 million people are chronically infected with hepatitis B [13].

The etiology of many chronic liver diseases remains unclear; however, even liver cirrhosis of viral etiology, which should be regarded as the final (stage IV) stage of chronic viral hepatitis, is often mistakenly not considered a consequence of infectious pathology [14].

Among medical specialties, certain professions are at particularly high risk of HBV infection, including workers in hemodialysis centers and clinical laboratories, obstetricians-gynecologists, surgeons, and dentists. Among dentists, the incidence of HBV infection is reported to be 1.7 times higher than among other groups of healthcare workers [15].

Many authors have reported a high frequency and diverse clinical presentation of lesions of the oral cavity, particularly periodontal tissues, in diseases of the gastrointestinal tract [16–18]. As a result of diseases of the digestive system, the functional activity of the salivary glands, as well as the composition and properties of saliva, undergo changes. This leads to disruption of the dynamic balance between demineralization and remineralization processes and contributes to the development and progression of dental caries.

Comorbid conditions have become increasingly common in recent years and represent one of the factors that significantly complicate the management of patients with periodontitis due to the potentially mutually aggravating course of these diseases [19,20]. For example, inflammatory periodontal diseases may necessitate postponement of antiviral therapy for HBV, thereby accelerating the progression of liver damage [21-23].

When determining management strategies and selecting appropriate therapy in patients with mild to moderate periodontitis in the presence of chronic infections, it is essential to consider that more frequent and prolonged exacerbations of periodontitis in patients with comorbid pathology are mainly associated with the infectious component. At the same time, unfavorable features of the disease course are linked to endogenous intoxication, immune system disorders, imbalance in lipid peroxidation processes, excessive infectious load, activation of pro-inflammatory cytokines in periodontal pockets, and suppression of the local immune response. When developing a plan for long-term follow-up of patients with periodontitis associated with chronic infections, a differentiated approach is required. This approach should include the development of long-term treatment and rehabilitation programs, taking into account the severity of the pathology and the unfavorable nature of the pathological process in periodontal tissues. Monitoring of such patients should be carried out with the involvement of infectious disease specialists and include additional laboratory and instrumental diagnostic methods. The duration of follow-up in each case should be determined individually based on the course of periodontitis [18,20].

Thus, periodontal tissue diseases in the presence of concomitant systemic conditions represent one of the most complex problems in dentistry due to difficulties in diagnosis and treatment [24]. Lesions of the oral mucosa may aggravate the course of the underlying disease and determine the specifics of therapeutic measures [25,26]. Accurate and timely assessment of periodontal tissue condition, as well as the selection of modern and rational treatment approaches, remain highly relevant issues in contemporary dentistry [4].

The aim of this study was to assess the condition of periodontal tissues in patients with viral hepatitis B prior to complex treatment.

MATERIAL AND METHODS

Study Design and Population

This observational comparative study included 195 patients examined between 2022 and 2024. Participants were divided into two groups: HBV group (n = 95) and control group (n = 100).

Ethical Considerations

The study protocol was approved by the Ethics Committee of Yerevan State Medical University. Written informed consent was obtained from all participants.

Inclusion Criteria

- Confirmed HBV diagnosis
- Presence of periodontal lesions
- Age between 21 and 57 years

In addition to the underlying disease, patients with HBV had oral cavity lesions. The age of the patients ranged from 27 to 54 years, and they were hospitalized in the infectious diseases clinic of the "Mikaelyan Institute of Surgery" of Yerevan State Medical University (Yerevan, Armenia) during the period 2022–2024. The control group included 100 individuals without HBV who had periodontal tissue damage and who applied to the Stomatology Scientific and Educational Clinical Center No. 1 of Yerevan State Medical University and the "Orthodent" dental clinic during the same period. Their age ranged from 21 to 57 years.

Clinical and laboratory diagnostic methods

The final diagnosis of HBV was established based on the detection of hepatitis B virus surface antigen (HBsAg) in blood serum using enzyme-linked immunosorbent assay (ELISA) and detection of hepatitis B virus DNA using polymerase chain reaction (PCR). The patients underwent traditional clinical and laboratory examination methods, including general blood and urine tests, as well as biochemical blood tests: determination of total bilirubin and its fractions, alanine aminotransferase (ALT), aspartate aminotransferase (AST), alkaline phosphatase (ALP), gamma-glutamyl transferase (GGT), total protein and its fractions, and coagulogram. All patients underwent stomatological status assessment according to previously developed criteria, which included evaluation of the condition of the marginal and alveolar parts of the gingiva and the dento-periodontal complex. An index assessment of the condition of the periodontal tissues was also performed using the periodontal index (PI) according to Russell [27], and the gingival sulcus bleeding index (SBI) according to Mühlemann and Son was determined [28].

Morphological study: The material for morphological studies consisted of biopsy tissue samples excised from the mucous membrane in the area of direct localization of the pathological process in all patients with HBV infection. According to the standard histological protocol, the tissue samples were fixed in 10% neutral formalin, dehydrated, and embedded in paraffin. A series of sections with a thickness of 4 µm were stained with hematoxylin–eosin for general assessment of the condition of the examined tissues [29]. Histological micropreparations were studied using a ZEISS Primo Star trinocular microscope (ZEISS Microscopy, Germany) at magnifications of ×100 and ×400. Microphotographs were obtained using a ZEISS Axiocam ERc 5s (Carl ZEISS Microscopy, Germany). All features were examined in accordance with international standards, WHO recommendations, and recognized research methods [30].

Statistical analysis: Descriptive analysis (mean ± SD for continuous variables and frequencies/proportions for categorical variables) was performed for all variables of interest. Differences between the two groups were evaluated using the chi-square test or Fisher's exact test for categorical variables and the Wilcoxon signed-rank test for continuous variables. Spearman correlation analysis was performed to determine relationships between continuous variables. A p-value of < 0.05 was considered statistically significant, and < 0.001 was considered highly significant. Analyses were conducted using Excel 2013 and R software, as well as the VassarStats program to calculate odds ratios (OR) and 95% confidence intervals (CI).

RESULTS

The study included 95 patients with HBV, including 71 men (74.7%) and 24 women (25.3%). The control group consisted of 100 individuals without HBV with periodontal tissue damage: 62 men (62.0%) and 38 women (38.0%). The mean age in the group of patients with HBV was 40.17 ± 13.48 years, and in the control group it was 37.99 ± 16.66 years. During the assessment of stomatological status, patient complaints and data from clinical examination of the oral cavity were taken into account, including evaluation of the condition of the marginal and alveolar parts of the gingiva, the dento-periodontal complex, as well as periodontal indices PI and SBI before and after complex treatment. Table 1 presents the data of the clinical examination of the condition of the marginal and alveolar parts of the gingiva before complex treatment.

Table 1. Clinical examination of marginal and alveolar gingiva in HBV and control groups

Variable	Control group (n = 100)	HBV group (n = 95)	p-value
Hyperemia			
Absent	99 (99.0%)	32 (33.7%)	<0.001
Present	1 (1.0%)	63 (66.3%)	
Cyanosis			
Absent	75 (75.0%)	65 (68.4%)	>0.05
Present	25 (25.0%)	30 (31.6%)	
Edema			
Absent	87 (87.0%)	32 (33.7%)	<0.001
Present	13 (13.0%)	63 (66.3%)	
Bleeding			
Absent	89 (89.0%)	24 (25.3%)	<0.001
Present	11 (11.0%)	71 (74.7%)	
Epithelial desquamation			
Absent	100 (100%)	91 (95.8%)	>0.05
Present	0 (0%)	4 (4.2%)	

An objective examination of the oral cavity revealed a number of pathological changes in the gingiva. In patients with HBV, hyperemia and edema of the gingiva were detected in 66.3% (63) of cases, which is statistically significantly higher compared to the control group ($p < 0.001$), where these symptoms were observed in 1% and 13% of examined individuals, respectively. Cyanosis of the gingiva was observed in 31.6% of cases ($p > 0.308$). Gingival bleeding was observed in 74.7% of the examined patients with HBV, which is significantly higher-approximately 7 times-compared with the control group ($p < 0.001$). Desquamation of the gingival epithelium, resembling the clinical picture of desquamative gingivitis, was observed in 4.2% (4) of cases, which was not statistically different from the control group ($p > 0.454$), where this symptom was not observed. The condition of the dento-periodontal complex in patients with HBV is presented in Table 2.

Table 2. Condition of the dento-periodontal complex in HBV and control groups

Variable	Control group (n = 100)	HBV group (n = 95)	p-value
Subgingival dental plaque			
Absent	61 (61.0%)	28 (29.5%)	<0.001
Present	39 (39.0%)	67 (70.5%)	
Tooth mobility (Grade I)			
Absent	71 (71.0%)	73 (76.8%)	>0.05
Present	29 (29.0%)	22 (23.2%)	
Tooth mobility (Grade II)			
Absent	93 (93.0%)	46 (48.4%)	<0.001
Present	7 (7.0%)	49 (51.6%)	
Tooth mobility (Grade III)			
Absent	95 (95.0%)	92 (96.8%)	>0.05
Present	5 (5.0%)	3 (3.2%)	
Periodontal pockets >3.5 mm			
Absent	61 (61.0%)	12 (12.6%)	<0.001
Present	39 (39.0%)	83 (87.4%)	
Purulent discharge			
Absent	91 (91.0%)	55 (57.9%)	<0.001
Present	9 (9.0%)	40 (42.1%)	

Subgingival dental deposits, identified on the lingual and vestibular surfaces of the central incisors and canines of the lower jaw, as well as on the buccal surfaces of the upper premolars and molars, were detected in 70.5% (67) of cases in the HBV group, whereas in the control group they were detected in 39% (39) of patients, which is statistically significant ($p < 0.001$).

When analyzing the data on pathological tooth mobility of grades I and III in patients with HBV and in the control group, no statistically significant differences were found ($p > 1$). Grade II pathological tooth mobility in patients with HBV was detected in 51.6% (49) of cases, which is statistically significantly higher compared to the control group ($p < 0.001$), where this finding was observed in 7% (7) of patients. The presence of periodontal pockets (PP) > 3.5 mm was observed in 87.4% (83) of patients, and purulent discharge from PP was observed in 42.1% (40) of patients. Both indicators showed a high level of statistical significance ($p < 0.001$).

To assess the degree of periodontal damage in patients with HBV, periodontal indices were determined to evaluate inflammatory changes in the periodontium: the Periodontal Index (PI) according to Russell and the Sulcus Bleeding Index (SBI) according to Mühlemann and Son (Table 3).

Table 3. Periodontal indices (mean ± SD)

Index	Control group	HBV group	p-value
PI (Periodontal Index)	0.95 ± 0.48	4.08 ± 0.41	<0.001
SBI (Sulcus Bleeding Index)	1.68 ± 1.66	2.82 ± 0.21	<0.005

∗ p-value: comparison between HBV and control group

In patients with HBV, the periodontal index values differed significantly from those of the control group. The PI value averaged 4.08 ± 0.41 points, which is 4.3 times higher than in the control group (Fig. 1), and the SBI value averaged 2.82 ± 0.21 points, which is 1.68 times higher than in the control group (Fig. 2). The differences were statistically significant with a high degree of reliability ($p < 0.005$).

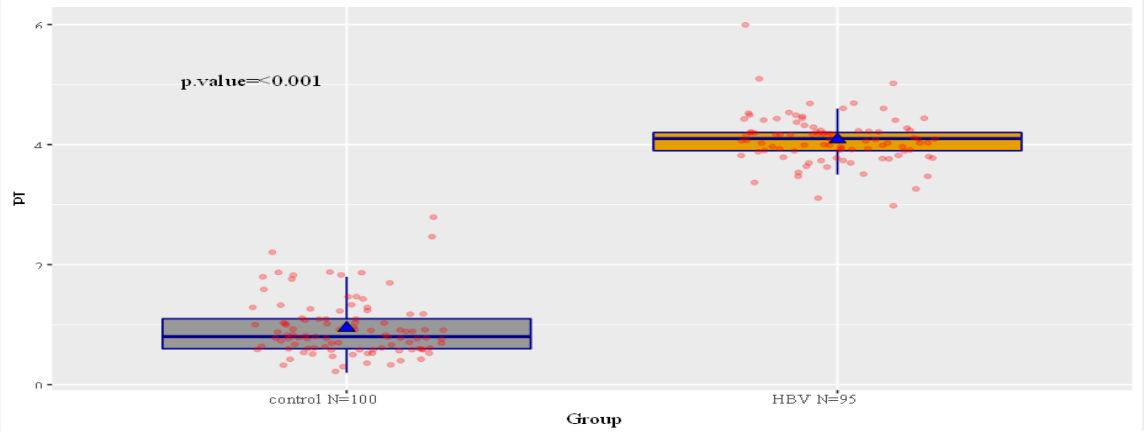

Figure 1. PI index value in patients with HBV and in the control group

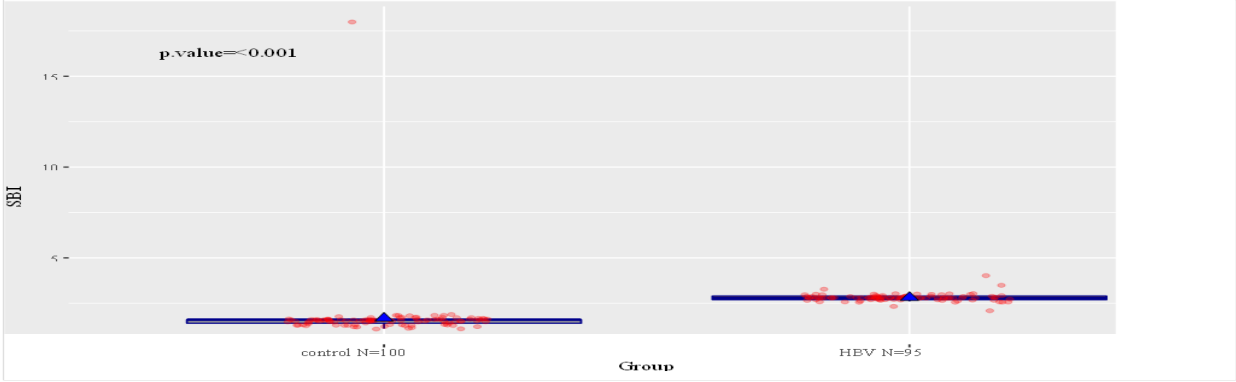

Figure 2. SBI index score in patients with HBV and in the control group

Pathohistological Study

Pathological changes in the oral cavity were localized in the alveolar bone region, namely in the area of the gingiva and the transitional fold. The results of the histological study showed that patients with HBV had combinations of pathohistological signs that manifested as inflammatory infiltration with circulatory disturbances, gingival ulceration with fibrinous deposits, dystrophic changes in the squamous epithelium, and, in isolated cases, sequestration of the jaw bone was observed. A comparative analysis of these pathomorphological changes demonstrated that lymphoplasmacytic infiltration of the gingival tissue was detected with a high degree of statistical significance ($p < 0.001$). Signs of inflammation of the gingival tissue were observed in biopsy samples in 100% of patients with HBV in the form of pronounced inflammatory cellular infiltration, which was predominantly productive in nature ($p < 0.001$). The inflammatory infiltrate was mainly represented by lymphocytes and plasma cells, reflecting pronounced chronic inflammation (Fig. 3).

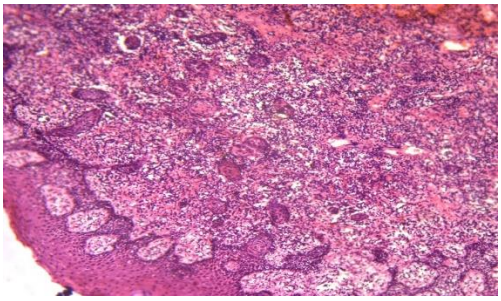

Figure 3. Lymphoplasmacytic infiltration of gingival tissue in a patient with HBV (hematoxylin–eosin staining, ×100)

Morphological examination of the gingiva revealed damage to epithelial cells, including the appearance of vacuoles in their cytoplasm, i.e., vacuolar degeneration progressing to ballooning dystrophy, as well as cell death and desquamation of the epithelium with the formation of micro-erosions. These changes were often detected only by microscopic examination and were observed in 75% of cases. Erosions or micro-ulcers were covered with fibrinous deposits in 25% of cases in patients with HBV (Fig. 4).

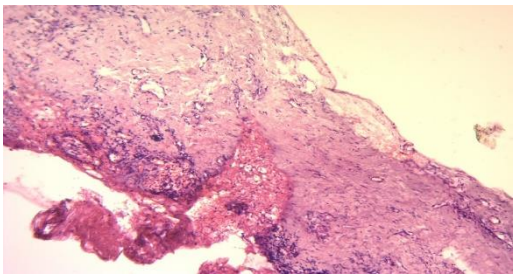

Figure 4. Micro-erosions of the gingival tissue covered with fibrin deposits. Superficial ulcers of the oral mucosa are covered with fibrin deposits (hematoxylin–eosin staining, ×100).

In isolated patients, fragments of necrotic bone tissue were identified, most likely due to sequestration of the jaw bone in HBV (Fig. 5).

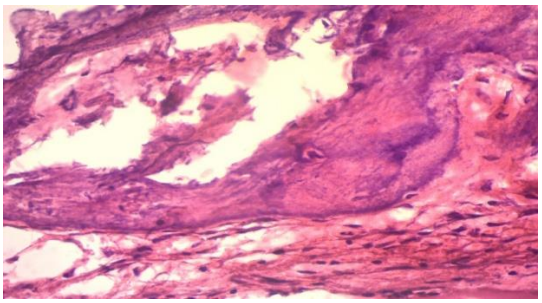

Figure 5. Fragments of necrotic bone tissue in HBV (hematoxylin–eosin staining, ×400).

Thus, numerous morphological signs can be conditionally divided into those that indicate the severity and activity of inflammation and those associated with a long-term chronic course of inflammation in periodontal tissues.

4. DISCUSSION

There is practically no pathology that does not affect the condition of the oral mucosa. At the same time, the similarity of clinical manifestations in the oral cavity among diseases of different etiology and pathogenesis contributes to difficulties in establishing a definitive diagnosis[31,32]. Many researchers consider the periodontium as an integral part of the whole organism and recognize the close pathogenetic relationship between periodontal diseases and somatic pathology. Patients with periodontitis who have concomitant and background diseases require special attention, both in the diagnosis of combined pathology and in treatment and prevention [21]. Lesions of the periodontal system aggravate the course of diseases and serve as an important addition to the overall clinical picture of hepatitis and HIV infection [33–35]. Viral liver lesions occupy an important place in assessing the dental health status of patients [36]. At the same time, dentists and physicians of other specialties do not pay sufficient attention to the condition of the oral cavity in liver diseases [37]. The experience of dentists working in infectious disease departments has shown that the effectiveness of diagnosis and treatment of oral mucosal lesions depends on the earliest possible examination of admitted patients [38]. Dental care for patients, even with an established diagnosis of viral hepatitis, is mainly provided upon request due to acute pain. There are very few developments in dental management strategies for patients with hepatitis. Even in countries with a high level of dental services, sufficient experience in this area has not yet been accumulated [39,40].

In a comparative study of the criteria selected to characterize the condition of various parts of the periodontium in viral hepatitis B compared with the control group, it was established that in the latter (except for isolated cases), periodontal lesions are practically not observed. According to the results of our study, pathognomonic symptoms of periodontal lesions in viral hepatitis B were reliably identified [41].

The data on the condition of the marginal and alveolar parts of the gingiva in patients with HBV are of particular interest. When comparing patients with viral hepatitis B to the control group, hyperemia, edema, and bleeding were more frequently observed in the HBV group. Based on the above, it can be reliably concluded that the marginal and alveolar parts of the gingiva are more frequently affected in HBV. It should be noted that, according to Fedeli U. et al. (2017), who studied the characteristics of periodontal damage in patients with chronic liver diseases of viral etiology, more severe dystrophic and inflammatory changes in periodontal tissues are observed in chronic hepatitis and liver cirrhosis caused by hepatitis B virus compared to those caused by hepatitis C virus [42]. Our data indicate that it is difficult to draw a definitive conclusion regarding the comparative severity of periodontal damage in HBV, since we did not conduct a comparative analysis with other viral hepatitis groups.

There are few studies in the available literature that have investigated and systematized the symptoms of periodontal damage in HBV, especially early manifestations of the disease. The reliability of the frequency of occurrence of specific symptoms has also not been sufficiently studied. Some authors even report contradictory findings regarding the relationship between periodontal tissue lesions and viral hepatitis. In our opinion, such discrepancies may be related to methodological limitations of previous studies. For example, Nagao Y. et al. (2014) investigated periodontal tissue lesions in patients with chronic hepatitis (HBV – 20 patients, HCV – 23 patients) and liver cirrhosis caused by HBV (15 patients) or HCV (16 patients). Based on descriptive analysis of a small sample size, the authors concluded that there was no association between chronic HBV or HCV and the frequency or nature of periodontal lesions [21]. However, given the limited sample size and the absence of robust statistical analysis, the reliability of these conclusions is questionable.

There are also isolated studies that describe only a few individual signs in small patient samples. No comprehensive comparative analysis of these signs in patients with viral hepatitis B has been conducted. In our opinion, this is important, as patient management protocols and treatment strategies may differ significantly. It should be noted that the literature contains several review articles addressing this issue, which describe in detail the epidemiological data and pathophysiological mechanisms of extrahepatic manifestations in viral hepatitis and HIV infection [43–46]. However, there is a lack of original research studies in this area. Therefore, we attempted to analyze and compare the available data reported in the literature.

Pakfetrat A. et al. (2015) examined 110 HIV-positive patients, some of whom also had HBV infection, to assess the prevalence of oral lesions. The authors identified severe periodontitis in 27.3% of patients [47]. As noted above, in our study, periodontitis was detected more frequently in patients with viral hepatitis B. In addition, we evaluated individual symptoms of periodontal damage, most of which demonstrated a high frequency of occurrence.

Azatyan V.Yu. et al. (2021) investigated pathomorphological changes in the oral mucosa in patients with HBV, HCV, and HIV infections; however, no detailed study of periodontal tissues was conducted to

allow comparison with our findings [48].

The problem of liver diseases of viral etiology remains highly relevant due to their widespread distribution. The global prevalence and high epidemic potential of these diseases maintain their significant social and economic burden. Pathologies caused by HBV are most commonly observed in young, working-age individuals, leading to disability and relatively high mortality rates. Therefore, the study of periodontal tissue condition in viral hepatitis B, including the features of pathomorphological changes and their comparative assessment with control group data, is highly relevant and justified the conduct of this study.

One limitation of this study is that patients were recruited from a single clinic in Yerevan, although this clinic is one of the largest in the Republic of Armenia.

Another limitation of the present study is the reduced sample size available for cytokine analysis in oral fluid, as only 18 patients in the HBV group and 30 individuals in the HBV-negative group consented to participate. This may limit the statistical power of immunological comparisons and should be taken into account when interpreting cytokine-related findings.

CONCLUSION

Thus, viral hepatitis B contributes to damage of the periodontal tissues. Pathomorphological examination indicates the nature of periodontal tissue damage, which manifests as inflammatory infiltration, circulatory disturbances, and ulceration of the gingival tissue.

List of Abbreviations and Designation

ALT - Alanine aminotransferase
ALP- Alkaline phosphatase
AST - Aspartate aminotransferase
CI - Confidence Intervals
DNA - Deoxyribonucleic acid
ELLISA - Enzyme-linked immunosorbent assay
GGT -ɤ-glutamyl transferase
HBsAg - Detection of hepatitis B virus surface antigen
HBV – Hepatit B Virus
OR - Odds Ratio
PCR - Polymerase chain reaction
PI - Periodontal index according to Russell
PP - Pathological pockets
RA – Republic of Armenia
SBI - Gingival sulcus bleeding index according to Miihlemann and Son
SD - Standard deviation
WHO - World Health Organization

DECLARATIONS

Conflict of Interest

The authors declare no conflict of interest.

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No external funding was received for this study.

Ethical Approval

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.

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