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REVIEW ARTICLE

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

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Abstract

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

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

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

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

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

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

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

1.INTRODUCTION

Cleft lip with or without cleft palate (CL/P) is among the most common congenital craniofacial anomalies and remains an important global health concern because of its long-term anatomical, functional, psychosocial, and developmental consequences. Although the most apparent manifestation is disruption of the upper lip, the condition may also affect feeding, speech and language development, dental eruption, maxillofacial growth, nasal function, hearing, facial appearance, and psychosocial well-being. Consequently, contemporary cleft care has progressively shifted from isolated surgical closure of the lip defect toward coordinated, longitudinal, multidisciplinary management extending from infancy through adolescence and, when necessary, adulthood.[1–3,25,26]

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

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

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

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

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

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

The anatomical subunit concept has been particularly influential in contemporary unilateral cleft lip repair because it seeks to position postoperative scars along recognizable facial anatomical boundaries while restoring the relationships between the philtral column, Cupid's bow, vermilion, and nasal base.[16,32]

Comparative investigations indicate that both Fisher-based and modified Millard techniques can provide satisfactory outcomes, although differences may occur in vermilion symmetry and scar characteristics. Thus, surgical technique should be considered as one component of a broader reconstructive strategy.

Timing of primary cleft lip repair remains another important component of treatment planning. The procedure is commonly undertaken during infancy to restore lip function and anatomy, improve facial symmetry, facilitate feeding and psychosocial adaptation, and establish a favorable anatomical foundation for subsequent craniofacial development.[23,35] However, optimal timing may vary according to the patient's general health, cleft severity, nutritional status, associated anomalies, institutional protocols, and availability of multidisciplinary care.

Presurgical infant orthopedic interventions represent another important component of contemporary cleft management. Nasoalveolar molding (NAM) was developed to modify cleft anatomy before primary repair by approximating the alveolar segments, reducing cleft width, improving nasal symmetry, and facilitating surgical closure.[10–14] Although NAM has become established in many specialized cleft programs, its long-term effectiveness remains debated.

Available evidence demonstrates heterogeneity regarding long-term nasolabial aesthetics, dentoalveolar development, midfacial growth, treatment burden, and other clinically important outcomes. More recent evidence suggests that NAM may reduce cleft width in selected patients, whereas the certainty of evidence for long-term aesthetic and functional benefits remains limited. Therefore, NAM should be considered within an individualized multidisciplinary treatment pathway rather than as a universally mandatory intervention.

Primary nasal management has also become increasingly integrated with cleft lip repair. In unilateral and bilateral clefts, nasal deformity is closely related to abnormal positioning of the alar cartilage, nasal base, columella, and surrounding soft tissues.[20–22,33,37]

Contemporary approaches increasingly recognize the lip and nasal components as a coordinated anatomical unit, with the objective of restoring facial relationships and improving symmetry while potentially reducing secondary deformities.

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Assessment of treatment outcomes has consequently evolved from predominantly subjective clinical judgment toward standardized multidimensional evaluation. Nasolabial appearance, lip symmetry, scar quality, nasal morphology, dental and skeletal development, speech, hearing, and patient-reported quality of life may all contribute to the overall assessment of treatment success.[24–26,37–40] Standardized outcome systems and three-dimensional measurements have become increasingly important because they permit more reproducible comparisons between surgical techniques and treatment centers, particularly in the context of substantial intercenter variation in cleft treatment outcomes.[25,39,40]

Three-dimensional imaging has introduced additional opportunities for quantitative evaluation of craniofacial morphology. Conventional two-dimensional photographs remain useful for routine clinical assessment, but three-dimensional surface imaging permits measurement of facial asymmetry, nasal projection, lip dimensions, soft-tissue relationships, and postoperative morphological changes.[27,28] These technologies may improve documentation of growth, treatment outcomes, preoperative planning, and postoperative follow-up.

The expansion of digital workflows has further increased opportunities for individualized cleft care. Three-dimensional facial imaging can be combined with digital morphometric analysis, virtual surgical planning, computer-aided design and manufacturing (CAD/CAM), and three-dimensional printing to create patient-specific treatment simulations and customized devices.[27–31] Such technologies may facilitate anatomical assessment, multidisciplinary communication, and quantitative comparison between planned and achieved surgical outcomes. Digital approaches are particularly promising for longitudinal monitoring of facial morphology during growth.

Artificial intelligence (AI) represents a newer development within this digital transformation. AI-assisted image analysis and automated landmark detection may facilitate objective characterization of craniofacial morphology and identify patterns that are difficult to assess consistently using conventional examination.[30] However, AI should currently be regarded primarily as a decision-support technology rather than a replacement for clinical expertise. Its implementation in cleft care requires sufficiently large and representative datasets, external validation, transparent algorithms, standardized imaging protocols, and careful assessment of bias and reproducibility. Prospective studies are therefore required to establish its clinical value.

Despite major advances in surgical reconstruction, presurgical orthopedics, multidisciplinary care, and digital assessment, important areas of uncertainty remain.

These include the optimal timing and technical design of primary repair, the comparative effectiveness of different cheiloplasty techniques, the indications and long-term benefits of NAM, strategies for prevention and correction of secondary nasal deformity, and the development of standardized outcome measures.[33–35,38–41] Contemporary evidence also demonstrates persistent variation among cleft centers, suggesting that treatment outcomes may depend on institutional protocols, surgical experience, patient characteristics, and access to comprehensive multidisciplinary services.

Accordingly, contemporary cleft lip management should be regarded as a longitudinal and individualized process rather than a single surgical event. The integration of anatomical assessment, refined cheiloplasty techniques, presurgical orthopedic interventions, multidisciplinary rehabilitation, standardized outcome evaluation, and emerging digital technologies provides an increasingly comprehensive framework for pediatric cleft care. The present narrative review therefore aims to critically synthesize current concepts in the management of cleft lip in children, with particular emphasis on embryology and genetics, classification, surgical reconstruction, presurgical orthopedic management, multidisciplinary care, three-dimensional and digital technologies, artificial intelligence-assisted assessment, and future directions toward more precise and patient-specific craniofacial treatment.

1.MATERIALS AND METHODS

1.1 Study Design and Literature Review Approach

The present article was designed as a narrative review to provide an updated and comprehensive analysis of contemporary concepts in the management of cleft lip in children. The review focused on the evolution of treatment strategies, including primary surgical reconstruction, presurgical orthopedic interventions, multidisciplinary care, three-dimensional assessment, digital treatment planning, and emerging artificial intelligence-based technologies.

A narrative review methodology was selected because cleft lip management encompasses a broad range of clinical and scientific domains, including embryology, genetics, classification, surgical reconstruction, nasoalveolar molding, craniofacial growth, functional rehabilitation, aesthetic assessment, quality of life, and digital technologies. The available literature includes historical surgical descriptions, observational studies, comparative clinical investigations, systematic reviews, and multidisciplinary outcome studies. Consequently, narrative synthesis allows these heterogeneous sources to be considered within a common clinical framework rather than restricting the analysis to studies with directly comparable designs or outcomes.[1–6,10–14,23–35]

No systematic review protocol was registered, and no quantitative meta-analysis was performed. The purpose of the present review was to synthesize and critically interpret the available literature concerning contemporary clinical principles and emerging developments in pediatric cleft lip management.

1.2. Literature Search Strategy

A comprehensive literature search was conducted using PubMed/MEDLINE, Scopus, Web of Science, and Google Scholar. Publications published between January 2015 and June 2026 were prioritized to identify recent developments in cleft lip management. In addition, selected earlier publications were included when they represented important contributions to the development of cleft classification, surgical techniques, presurgical orthopedic treatment, outcome assessment, and fundamental principles of cleft care.[7–19,23–25]

The search strategy combined controlled vocabulary and free-text terms related to cleft lip, cleft lip and palate, pediatric craniofacial surgery, primary cheiloplasty, surgical repair, nasoalveolar molding, multidisciplinary care, three-dimensional imaging, digital treatment planning, and artificial intelligence.

The principal search terms included:

“cleft lip”; “cleft lip and palate”; “orofacial cleft”; “children”; “pediatric craniofacial surgery”; “cheiloplasty”; “primary cleft lip repair”; “Millard technique”; “Fisher anatomical subunit repair”; “Tennison-Randall repair”; “Mohler modification”; “nasoalveolar molding”; “NAM”; “multidisciplinary cleft care”; “three-dimensional imaging”; “virtual surgical planning”; “CAD/CAM”; “three-dimensional printing”; “artificial intelligence”; “facial analysis”; “speech outcomes”; “facial growth”; and “quality of life”.
Additional publications were identified by manually screening the reference lists of relevant reviews and major

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clinical investigations. Particular attention was given to studies addressing surgical outcomes, nasolabial appearance, presurgical nasoalveolar molding, long-term treatment outcomes, three-dimensional facial assessment, and quality-of-life measures.[10–14,24–31,38–40]

1.3 Literature Selection and Eligibility Considerations

Literature was selected according to its clinical relevance, scientific contribution, and applicability to contemporary cleft lip management. Priority was given to systematic reviews, clinical investigations, comparative surgical studies, longitudinal cohort studies, multicenter studies, and publications describing standardized outcome assessment. The reviewed literature covered the principal domains of pediatric cleft lip management, including:

1.1.1 embryology, epidemiology, genetics, and environmental risk factors;[1–6]
1.1.2 classification and anatomical assessment of cleft lip and palate;[7–9];
1.1.3 primary cleft lip repair and surgical technique selection;[15–23,32,33,36,37,41];
1.1.4 presurgical nasoalveolar molding and related orthopedic approaches;[10–14];
1.1.5 nasolabial and aesthetic outcome assessment;[24,25,37–40];
1.1.6 multidisciplinary treatment and long-term outcomes;[23,25,26];
1.1.7 three-dimensional facial imaging and digital assessment;[27,28,38];
1.1.8 computer-assisted and digital treatment planning;[29–31];
1.1.9 and emerging applications of artificial intelligence in craniofacial diagnosis and treatment planning.[30]

Studies dealing exclusively with isolated cleft palate without clinically relevant information concerning cleft lip were not considered central to the present review. Duplicate publications, conference abstracts without sufficient methodological information, and non-scientific sources were also excluded. When multiple publications addressed similar clinical questions, greater emphasis was placed on studies with stronger study designs, larger patient cohorts, longitudinal follow-up, objective outcome assessment, or standardized evaluation methods.

1.4 Data Extraction and Narrative Synthesis

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Information from the selected publications was reviewed and organized according to the principal clinical domains of cleft lip management. Extracted information included publication characteristics, patient populations, treatment approaches, surgical techniques, timing of intervention, presurgical interventions, outcome assessment methods, aesthetic and functional outcomes, complications, long-term findings, and reported limitations.

Particular attention was given to evidence concerning the anatomical principles of primary cheiloplasty, including restoration of lip symmetry, orbicularis oris continuity, philtral anatomy, vermilion alignment, and correction of associated nasal deformity.[15–23,32,33,36,37,41]

Evidence concerning presurgical nasoalveolar molding was evaluated with particular consideration of its proposed effects on preoperative anatomical alignment and nasal symmetry, as well as the continuing uncertainty regarding its long-term influence on definitive facial growth and treatment outcomes.[10–14]

For multidisciplinary care, the synthesis considered evidence addressing treatment outcomes, nasolabial appearance, craniofacial development, patient and parent satisfaction, and quality of life.[24–26]

Recent literature concerning three-dimensional imaging, digital workflows, and artificial intelligence was reviewed to assess their potential contribution to objective facial analysis, treatment planning, surgical simulation, and individualized outcome assessment.[27–31,38] Because the included literature demonstrated substantial heterogeneity in patient populations, treatment protocols, surgical techniques, outcome measures, and follow-up duration, the findings were synthesized qualitatively rather than quantitatively. The narrative synthesis was therefore used to identify areas of consistent evidence, areas of controversy, emerging technologies, and remaining research gaps.

1.5 Interpretation of Evidence

As this study was designed as a narrative review, a formal methodological quality assessment and quantitative risk-of-bias analysis were not performed. Nevertheless, the interpretation of the literature considered differences in study design, sample size, follow-up duration, outcome measurement, and methodological rigor. Greater weight was given to longitudinal and multicenter investigations, systematic reviews, comparative studies, and studies using standardized or objective outcome assessment. For example, standardized assessment of nasolabial appearance has been described using structured rating methods, while multicenter studies such as the Eurocleft investigations have demonstrated substantial intercenter variation in treatment protocols and outcomes.[24,25] Evidence derived from retrospective investigations, individual institutional series, or expert-based recommendations was interpreted within the limitations inherent to those study designs.

2 RESULTS

2.4 Epidemiology and Etiological Factors of Cleft Lip

Cleft lip with or without cleft palate (CL/P) remains one of the most common congenital craniofacial anomalies worldwide and represents a complex developmental disorder characterized by considerable variation in clinical presentation, genetic background, and associated functional consequences. The reviewed literature indicates that cleft lip should not be considered a single pathological entity but rather a heterogeneous group of craniofacial developmental disorders resulting from disturbances in facial morphogenesis during early embryonic life. Current evidence supports a multifactorial model in which genetic susceptibility interacts with environmental influences during critical periods of craniofacial development, leading to variable manifestations ranging from minor incomplete defects to complete unilateral or bilateral clefts involving the lip, alveolus, and associated nasal structures.[1–6] Epidemiological investigations have demonstrated significant geographic and population-based differences in the prevalence of cleft lip. The overall incidence of cleft lip with or without cleft palate is generally estimated at approximately 1 per 700 live births; however, reported frequencies vary substantially according to ethnic background, geographical region, socioeconomic conditions, and environmental exposures. Higher prevalence rates have traditionally been described among Asian and Native American populations, whereas lower rates have been observed among populations of African ancestry. These variations support the contribution of both genetic diversity and environmental modifiers to the development of orofacial clefts.[1,5,6] Representative epidemiological and etiological studies are summarized in Table 1.

Table 1. Representative Studies Evaluating Epidemiology and Etiological Factors of Cleft Lip

Study / Source	Study Focus	Principal Findings	Clinical / Etiological Relevance
Genetic association studies	Genetic susceptibility to CL/P	Multiple susceptibility loci and genes contribute to craniofacial development	Supports multifactorial and genetically heterogeneous etiology
IRF6 investigations	IRF6 and cleft susceptibility	IRF6 is strongly associated with syndromic and nonsyndromic clefting	Important for epithelial differentiation and craniofacial development
Genome-wide association studies	Common genetic variants	Associations involving IRF6, MSX1, PAX7, BMP4, VAX1, TP63 and 8q24	Demonstrates involvement of multiple developmental pathways
Epidemiological studies	Population and geographic variation	Prevalence varies according to ancestry, geography and environmental exposure	Supports genetic and environmental contributions
Maternal and environmental studies	Potential modifiable risk factors	Smoking, diabetes, obesity, nutritional disturbances, alcohol and selected medications have been investigated	Suggests interaction between environmental exposure and genetic susceptibility
Epigenetic studies	Gene regulation and environmental interaction	DNA methylation and microRNA mechanisms may modify craniofacial development	Provides emerging mechanistic and preventive perspectives
Syndromic cleft studies	Associated congenital abnormalities	Clefting may occur as part of broader developmental syndromes	Supports genetic assessment and multidisciplinary management

The distribution pattern of cleft lip also demonstrates considerable clinical variability. Unilateral clefts occur more frequently than bilateral defects, with left-sided involvement representing the most common unilateral presentation. The severity of the deformity depends on the extent of failure of fusion between the maxillary and medial nasal prominences and may involve isolated lip discontinuity or extend posteriorly through the alveolar ridge and palate. This phenotypic variability has important implications for surgical planning, functional rehabilitation, and long-term outcome assessment.[1,6]

Advances in molecular genetics have substantially changed the understanding of cleft lip etiology. Contemporary evidence indicates that nonsyndromic cleft lip represents the majority of cases and results from the combined effects of multiple genetic variants interacting with environmental factors rather than from a single causative mutation. Genome-wide association studies and candidate gene analyses have identified several susceptibility loci involved in craniofacial development, epithelial differentiation, cell migration, and tissue remodeling pathways. Among the most consistently reported genetic contributors, IRF6 (interferon regulatory factor 6) represents one of the strongest susceptibility genes associated with both syndromic and nonsyndromic forms of cleft lip. IRF6 plays a critical role in epithelial differentiation and periderm development, processes essential for normal fusion of facial structures during embryogenesis.[2–4]

Other genetic factors implicated in cleft lip susceptibility include MSX1, PAX7, BMP4, VAX1, TP63, and chromosomal regions such as 8q24**,** which have been identified through genome-wide association studies and molecular investigations. These findings have demonstrated that cleft lip development involves multiple biological pathways regulating neural crest cell migration, epithelial adhesion, extracellular matrix formation, and craniofacial patterning. Rather than representing isolated genetic abnormalities, cleft lip is now recognized as a complex developmental condition influenced by the interaction of multiple genetic variants with external factors.[2–4]

Environmental and maternal factors represent another important component of cleft lip pathogenesis. Multiple epidemiological studies have identified maternal smoking, alcohol consumption, diabetes mellitus, obesity, nutritional deficiencies, particularly inadequate folate intake, and exposure to certain teratogenic medications as potential risk factors. However, the strength of these associations varies considerably among populations, suggesting that environmental influences may modify cleft risk differently depending on individual genetic susceptibility and population-specific characteristics.[2,3,6]

Recent research has expanded the concept of cleft lip development through investigation of epigenetic mechanisms. Alterations in DNA methylation patterns, microRNA regulation, and other mechanisms controlling gene expression have been proposed as potential pathways through which environmental exposures influence embryonic craniofacial development. Although the clinical application of epigenetic findings remains limited, these discoveries provide new perspectives regarding disease mechanisms, early risk assessment, and future preventive strategies.[2,3]

An important distinction in clinical evaluation is the differentiation between syndromic and nonsyndromic cleft lip. Syndromic forms occur as part of broader developmental disorders and may involve multiple organ systems, requiring detailed clinical assessment and genetic evaluation. More than 500 syndromes have been reported in association with orofacial clefts, with Van der Woude syndrome, commonly associated with mutations affecting IRF6, representing one of the best-characterized examples. Recognition of syndromic features is essential because it influences genetic counseling, treatment planning, and long-term patient management.[3,6]

Overall, current evidence demonstrates that cleft lip results from a complex interaction between embryological processes, genetic susceptibility, and environmental influences. Understanding these mechanisms has clinical relevance beyond etiological classification, as it contributes to improved prenatal counseling, individualized risk assessment, multidisciplinary treatment planning, and the development of future precision-based approaches in craniofacial care.[1–6]

2.5 Classification and Clinical Assessment of Cleft Lip

Accurate classification of cleft lip remains a fundamental component of contemporary cleft care because it provides the basis for diagnosis, communication among multidisciplinary specialists, treatment planning, surgical decision-making, and evaluation of clinical outcomes. The reviewed literature demonstrates that cleft lip represents a highly variable anatomical condition, and therefore classification systems have progressively evolved from simple descriptions of the location and extent of the defect toward more comprehensive approaches incorporating anatomical severity, functional impairment, associated anomalies, and objective three-dimensional morphological analysis.[6–9] Historically, classification systems were primarily based on embryological concepts and anatomical relationships between the cleft defect and the incisive foramen. The classification proposed by Kernahan and Stark introduced a simplified anatomical framework distinguishing involvement of the primary and secondary palate and became one of the most widely recognized systems in cleft surgery.[7]

This concept was further developed through the “striped Y” diagram introduced by Kernahan, which provided a practical visual method for recording the location and extent of cleft involvement.[8]

The modified striped Y classification proposed by Elsahy further refined this approach by improving documentation of anatomical variations and complex cleft patterns.[9] A summary of the principal classification systems and contemporary clinical assessment approaches is presented in Table 2.

Table 2. Classification Systems and Clinical Assessment Approaches in Cleft Lip

Classification / Assessment Approach	Main Characteristics	Clinical Application	Main Advantages	Main Limitations
Kernahan and Stark classification[7]	Embryologically based classification distinguishing primary and secondary palate involvement	Basic anatomical classification and multidisciplinary communication	Simple and historically well established	Limited description of detailed three-dimensional soft-tissue and nasal abnormalities
Kernahan "Striped Y" classification[8]	Symbolic Y-shaped diagram representing anatomical extent	Documentation and visual communication	Easy to record and clinically practical	May not adequately represent complex anatomical variations
Modified "Striped Y" classification[8,9]	Expanded symbolic representation of cleft patterns	Classification of complex cleft configurations	Improves anatomical documentation	Primarily descriptive; limited quantitative assessment
Unilateral cleft lip classification[1,6]	Incomplete or complete involvement with possible alveolar and palatal extension	Surgical planning and assessment of asymmetry	Clinically relevant for operative planning	Does not fully quantify nasal, soft-tissue or skeletal abnormalities
Bilateral cleft lip classification[1,6]	Assessment of prolabium, columella, premaxilla, alveolus and nasal deformity	Planning primary lip and nasal reconstruction	Recognizes greater anatomical complexity	Phenotypic variability may exceed simple categories
Clinical anatomical assessment[6]	Lip height, Cupid's bow, philtral columns, vermilion, orbicularis oris, nasal base, alar position, columella and alveolar segments	Diagnosis, surgical planning and postoperative assessment	Patient-specific and directly treatment relevant	Examiner-dependent and potentially subjective
Syndromic and nonsyndromic assessment[3,6]	Identification of associated congenital abnormalities	Genetic evaluation, counseling and multidisciplinary planning	Identifies patients requiring broader assessment	Requires multidisciplinary expertise
Prenatal two-dimensional ultrasonography[6]	Prenatal visualization of facial structures	Prenatal diagnosis and parental counseling	Widely available and non-invasive	Limited three-dimensional visualization
Three-dimensional prenatal imaging[6]	Three-dimensional visualization of fetal facial structures	Prenatal characterization and counseling	Improved visualization of facial anatomy	Availability and image quality vary
Three-dimensional stereophotogrammetry[27,28]	Radiation-free three-dimensional surface imaging	Facial symmetry, lip/nasal morphology and longitudinal outcomes	Objective and reproducible	Requires specialized equipment and standardized acquisition
Digital morphometric analysis[27–30]	Quantitative facial landmarks, distances, angles and surface morphology	Objective severity and treatment assessment	Reduces observer dependence	Dependent on image quality and landmark reliability
Virtual surgical planning and CAD/CAM[29]	Three-dimensional imaging integrated with computer-assisted planning and digital modeling	Preoperative simulation and customized devices	Improves visualization and multidisciplinary communication	Requires specialized software and expertise
Artificial intelligence-assisted assessment[30]	Automated landmark detection, morphology analysis and pattern recognition	Decision support, classification and outcome assessment	Potential for rapid standardized analysis	Requires large representative datasets and external validation

Although these traditional classification systems remain clinically useful, contemporary cleft management requires a more detailed description of the deformity. Modern evaluation considers not only the presence or absence of a cleft but also its laterality, completeness, alveolar involvement, nasal deformity, soft tissue deficiency, muscle discontinuity, and associated craniofacial abnormalities. This approach is particularly important because two patients with apparently similar cleft types may demonstrate substantially different anatomical challenges requiring individualized surgical strategies.[6–9]

From a clinical perspective, cleft lip is generally categorized according to laterality and severity. Unilateral clefts represent the most common form and result from incomplete fusion between the maxillary and medial nasal prominences on one side. Depending on severity, unilateral clefts may be incomplete, involving only the lip structures, or complete, extending through the alveolus and frequently associated with cleft palate. Bilateral clefts demonstrate greater anatomical complexity because of disruption of the central prolabial segment, altered columellar development, nasal deformity, and possible premaxillary displacement.[1,6]

Clinical assessment begins immediately after birth and requires systematic evaluation of both the cleft deformity and the overall health status of the infant. Initial examination should include assessment of feeding ability, airway function, associated congenital anomalies, nutritional status, and the presence of syndromic characteristics. A detailed facial examination should document the morphology of the upper lip, including Cupid's bow configuration, philtral column development, vermilion continuity, lip height, orbicularis oris muscle continuity, nasal base symmetry, alar position, columellar length, and alveolar segment relationship. These anatomical characteristics directly influence surgical planning and expected postoperative outcomes.[1,6]

The identification of associated anomalies represents an essential component of cleft evaluation. Children with orofacial clefts may present with additional congenital abnormalities affecting multiple organ systems, particularly in syndromic cases. Therefore, comprehensive assessment, including genetic evaluation when indicated, is necessary to differentiate isolated cleft lip from conditions requiring broader medical management.[3,6]

Advances in prenatal diagnosis have significantly influenced contemporary cleft care pathways. Traditional two-dimensional ultrasonography has been progressively supplemented by three-dimensional fetal imaging techniques, allowing improved visualization of facial structures and more accurate prenatal characterization of cleft severity. Early diagnosis facilitates parental counseling, psychological preparation, delivery planning, and timely referral to specialized multidisciplinary cleft teams.[6]

Three-dimensional imaging technologies have further transformed the evaluation of cleft lip by enabling objective and reproducible assessment of facial morphology. Three-dimensional stereophotogrammetry provides accurate measurements of facial symmetry, lip contour, nasal morphology, and postoperative changes without radiation exposure. Compared with conventional two-dimensional photography, three-dimensional analysis reduces observer dependency and allows quantitative evaluation of subtle anatomical differences that may not be detectable through routine clinical assessment.[27,28]

The application of digital workflows has expanded beyond diagnostic assessment toward comprehensive treatment planning. Three-dimensional imaging data can be integrated with computer-assisted planning systems to simulate surgical procedures, evaluate anatomical relationships, and monitor postoperative changes over time. In cleft orthodontics and craniofacial rehabilitation, digital models and CAD/CAM approaches have increasingly supplemented traditional impressions and manual laboratory procedures, improving communication among surgeons, orthodontists, and dental specialists.[29] Artificial intelligence-assisted facial analysis represents an emerging development in cleft classification and outcome prediction. Machine-learning algorithms have demonstrated potential for automated facial landmark detection, severity classification, and quantitative analysis of craniofacial morphology. Although artificial intelligence systems currently function primarily as supportive tools rather than replacements for specialist evaluation, they may contribute to improved standardization, objective assessment, and personalized treatment planning in future cleft care models.[30] Overall, the evolution of cleft lip classification reflects a transition from descriptive anatomical systems toward integrated diagnostic approaches combining clinical examination, genetic assessment, digital imaging, and quantitative facial analysis. Such comprehensive evaluation allows more accurate characterization of individual deformities and supports personalized treatment strategies aimed at optimizing both functional recovery and aesthetic outcomes.[6–9,27–30]

2.6 Contemporary Surgical Management of Cleft Lip

Primary cheiloplasty remains the cornerstone of cleft lip management, with the main objectives of restoring anatomical continuity, re-establishing functional orbicularis oris muscle activity, improving facial symmetry, and achieving an aesthetically acceptable upper lip contour. Contemporary cleft lip surgery has evolved substantially from simple closure of the visible defect toward anatomical reconstruction based on restoration of lip subunits, precise muscle repair, reconstruction of philtral anatomy, accurate vermilion alignment, and preservation of long-term facial growth potential. The principal contemporary surgical techniques and their reconstructive concepts are illustrated in Figure 1.

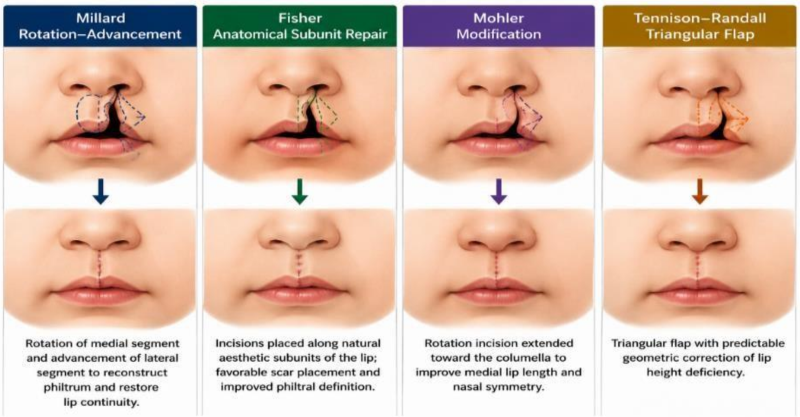

Figure 1. Contemporary Surgical Techniques for Cleft Lip Repair.

Comparison of the principal surgical techniques used for unilateral cleft lip repair, including the Millard rotation–advancement technique, Fisher anatomical subunit repair, Mohler modification, and Tennison–Randall triangular flap technique. Although these procedures differ in incision design and tissue rearrangement principles, all aim to restore orbicularis oris muscle continuity, reconstruct the philtral column, achieve symmetrical Cupid's bow and vermilion alignment, and minimize scar deformity.[15–19] Several surgical techniques have been developed during the last decades, with the Millard rotation–advancement technique, Fisher anatomical subunit repair, Mohler modification, and Tennison–Randall triangular flap technique representing the most commonly reported approaches in contemporary cleft lip surgery. The principal characteristics, surgical principles, advantages, and limitations of these techniques are summarized in Table 3.[15–19]

Table 3. Comparison of Principal Primary Cleft Lip Repair Techniques

Technique	**Key Surgical Principle**	**Main Advantages**	**Potential Limitations / Considerations**
Millard rotation-advancement	Rotation of the medial lip segment with advancement of the lateral segment	Flexible design; permits adjustment of lip height and Cupid's bow; widely used	Scar orientation and vermilion symmetry may vary; technically demanding in severe clefts
Tennison-Randall triangular flap	Triangular lateral lip flap interdigitated with the medial segment	Predictable lengthening and geometric planning	Can create less anatomically aligned scars and requires accurate flap design
Mohler modification	Modified rotation-advancement with extended back-cut and refinement of rotation	Facilitates medial segment rotation and lip height correction	Outcome depends on precise design and tissue availability
Fisher anatomical subunit repair	Repair based on anatomical subunits with scar placement along natural boundaries	Anatomical reconstruction and potentially favorable scar camouflage	Requires detailed anatomical planning and experience
Modified rotation-advancement techniques	Adaptations of established rotation-advancement principles	Allows individualized correction according to cleft morphology	Technique-specific variations complicate direct comparison

Although these techniques differ in their design principles, the fundamental objectives remain consistent: restoration of normal lip anatomy, reconstruction of muscular continuity, preservation of facial landmarks, improvement of vermilion symmetry, and reduction of postoperative scar visibility.[15–19] The Millard rotation–advancement technique remains one of the most widely performed approaches for unilateral cleft lip repair because of its versatility and adaptability to different cleft morphologies. The basic principle involves rotation of the medial lip segment downward to restore vertical lip height and advancement of the lateral segment to close the remaining defect.

This approach allows reconstruction of the philtral column, Cupid's bow, and vermilion border while maintaining natural anatomical relationships.[15,36] Clinical experience accumulated over several decades has demonstrated favorable functional and aesthetic outcomes following Millard repair. However, limitations have also been described, including possible vermilion irregularity, scar asymmetry, and residual distortion in selected cases. These limitations have contributed to the development of alternative techniques focusing on more precise anatomical reconstruction and improved aesthetic predictability.[15,36]

The Fisher anatomical subunit repair introduced a different reconstructive philosophy by emphasizing the aesthetic subunits of the upper lip. Rather than relying primarily on geometric tissue rearrangement, this technique places incisions according to natural anatomical boundaries, particularly the philtral column and facial subunit junctions. The aim is to achieve improved scar camouflage, restoration of philtral definition, and more predictable vermilion reconstruction.[16] Comparative studies evaluating Fisher and modified Millard repairs have demonstrated that both techniques can achieve satisfactory clinical outcomes. Available evidence does not support universal superiority of one approach over another; instead, differences are mainly observed in specific aesthetic parameters, including scar appearance, vermilion contour, and lip symmetry. These findings emphasize that successful cleft lip repair depends primarily on accurate anatomical reconstruction, surgeon experience, appropriate patient selection, and long-term multidisciplinary follow-up rather than the selection of a single operative method.[32,34] The Mohler modification represents an important refinement of the rotation–advancement concept. By extending the rotation incision toward the columellar region, this modification aims to improve medial lip length, enhance philtral reconstruction, and achieve better balance between the repaired lip and adjacent nasal structures.[17,37]

Although favorable results have been reported with the Mohler approach, outcomes remain influenced by cleft severity, tissue characteristics, and surgical technique. Comparative evidence suggests that differences between Mohler, Fisher, and other rotation–advancement modifications are generally related to selected aesthetic characteristics rather than overall functional success.[17,37]

The Tennison–Randall triangular flap technique represents one of the historically important approaches in unilateral cleft lip repair. The technique uses a triangular flap from the lateral lip segment to correct vertical deficiency and improve alignment of the vermilion border. Its predictable geometric principles contributed significantly to the evolution of modern cleft lip reconstruction.[18,19] Despite its historical importance, contemporary practice has increasingly shifted toward anatomical subunit-based approaches because of greater emphasis on scar placement, restoration of natural facial landmarks, and long-term aesthetic outcomes. Nevertheless, the principles introduced by Tennison and Randall remain relevant and continue to influence current surgical concepts.[18,19] The major anatomical objectives of modern cleft lip reconstruction are summarized in Figure 2.

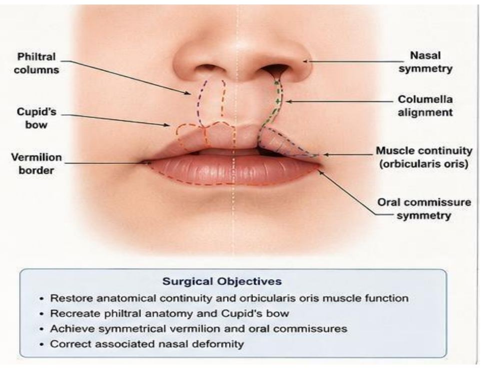

Figure 2. Key Anatomical Goals in Cleft Lip Repair.

Illustration of the principal anatomical objectives of primary cleft lip reconstruction. Modern repair focuses on restoration of the philtral columns, Cupid's bow, vermilion continuity, orbicularis oris muscle integrity, oral commissure symmetry, and balanced soft tissue relationships to optimize functional and aesthetic outcomes.[16,36]

Objective evaluation methods have significantly influenced the assessment of surgical outcomes after cleft lip repair. Traditional assessment based on clinical photographs and expert opinion has progressively been complemented by standardized anthropometric measurements, validated aesthetic scoring systems, three-dimensional facial analysis, scar evaluation, and patient-reported outcome measures.[24,38–40]

Three-dimensional imaging technologies have introduced new possibilities for quantitative assessment of postoperative facial morphology. These methods allow objective evaluation of lip symmetry, facial proportions, and soft tissue changes during growth. Compared with conventional two-dimensional photography, three-dimensional stereophotogrammetry provides improved reproducibility and reduces observer-related variability.[27,28,38] The historical evolution of cleft lip surgery and contemporary approaches to outcome evaluation are summarized in Figures 3 and 4.

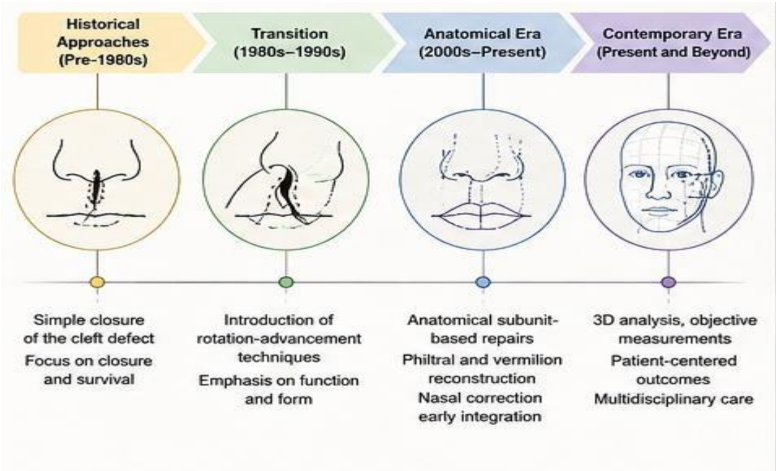

Figure 3. Evolution of Cleft Lip Surgical Approaches.

Overview of the evolution of cleft lip surgery from simple defect closure toward anatomical reconstruction, muscle-based repair, aesthetic subunit restoration, and multidisciplinary patient-centered care. Contemporary management emphasizes restoration of normal anatomy, functional rehabilitation, and long-term evaluation of outcomes.[15,16,38]

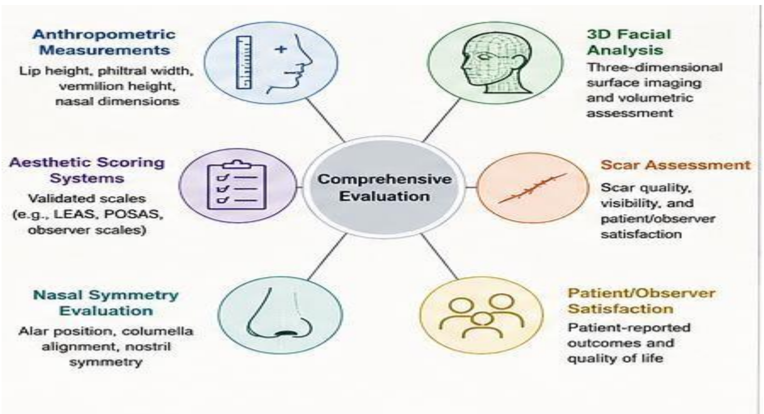

Figure 4. Methods for Evaluation of Surgical Outcomes.

Overall, current evidence indicates that no single surgical technique demonstrates universal superiority for all patients. Successful cleft lip reconstruction depends on individualized surgical planning, accurate anatomical restoration, preservation of functional structures, surgeon expertise, standardized outcome evaluation, and coordinated long-term multidisciplinary care.[16,32,34,36,38–40] The overall evidence synthesized in this review is summarized in Figure 5.

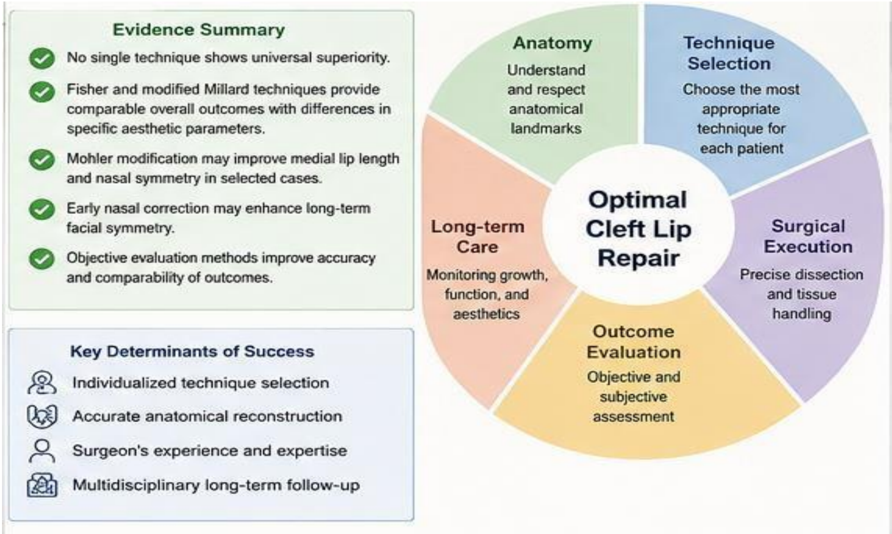

Figure 5. Evidence Summary and Key Determinants of Successful Cleft Lip Repair**.**

Summary of the main determinants influencing outcomes after cleft lip reconstruction. Current evidence indicates that successful results are primarily associated with individualized treatment planning, anatomical precision, surgical expertise, objective postoperative assessment, and long-term multidisciplinary follow-up rather than with a single universally superior technique.[16,32,36,38–40]

2.7 Presurgical Orthopedic Management: Nasoalveolar Molding (NAM)

Presurgical nasoalveolar molding (NAM) has become an important component of contemporary multidisciplinary management of infants born with cleft lip and palate. Unlike surgical repair, which restores anatomical continuity after birth, NAM represents a preparatory orthopedic intervention designed to optimize the cleft anatomy before primary cheiloplasty. The principal objectives of NAM include reduction of the alveolar gap, improvement of maxillary segment alignment, approximation of cleft margins, molding of the displaced nasal cartilage, and reduction of soft tissue tension during primary surgical repair.[10–14]

The reviewed literature demonstrates that NAM is particularly valuable in infants with wide unilateral clefts and bilateral cleft deformities, where significant alveolar separation, nasal asymmetry, and distortion of the surrounding soft tissues may complicate primary reconstruction. By improving the preoperative anatomical conditions, NAM may facilitate surgical closure, enhance nasal symmetry, and contribute to more favorable early aesthetic outcomes.[10,12]

The concept of NAM was introduced by Grayson and colleagues as an extension of traditional presurgical orthopedic treatment. The technique combines intraoral alveolar molding with controlled nasal cartilage shaping through a nasal stent system, allowing simultaneous modification of the alveolar segments, nasal framework, and surrounding soft tissues during the neonatal period. This approach was based on the recognition that neonatal cartilage demonstrates increased plasticity, allowing controlled molding before surgical intervention.[10]

Subsequent clinical studies have evaluated the anatomical effects of NAM and demonstrated improvements in preoperative cleft width, alveolar alignment, and nasal symmetry. Maull et al. investigated the long-term influence of NAM on three-dimensional nasal morphology in unilateral cleft patients and reported favorable changes in nasal shape and symmetry following treatment.[11] Similarly, Barillas et al. demonstrated improved long-term nasal symmetry in unilateral cleft lip and palate patients treated with NAM compared with conventional surgical management without presurgical molding.[12]

The influence of NAM on nasal development has also been investigated through longitudinal studies. Liou and colleagues evaluated progressive changes in nasal symmetry and growth following NAM therapy and reported that early molding may provide measurable improvements in nasal morphology during subsequent development.[13] These findings support the concept that presurgical orthopedic intervention may contribute not only to immediate surgical preparation but also to improved long-term facial symmetry.

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Despite its widespread clinical application, the effectiveness and long-term benefits of NAM remain subjects of ongoing discussion. Although improvements in early nasal and alveolar morphology are consistently reported, evidence regarding its influence on definitive facial growth, maxillary development, and long-term functional outcomes remains limited. Differences in treatment protocols, appliance design, duration of therapy, surgical techniques, and outcome assessment methods contribute to variability among published studies.[14]

Recent technological developments have introduced digital approaches to NAM therapy. Three-dimensional imaging, computer-assisted design, and CAD/CAM technologies have enabled more precise appliance fabrication and improved documentation of treatment progress. Digital workflows may reduce laboratory complexity and improve reproducibility. A recent systematic review and meta-analysis of randomized controlled trials further evaluated digitally versus conventionally fabricated NAM appliances, providing contemporary evidence regarding the effectiveness of digital approaches.[31]

An important limitation of NAM is that successful treatment requires experienced multidisciplinary teams and significant family involvement. The therapy typically requires frequent adjustments, prolonged treatment duration, financial resources, and consistent parental cooperation. Therefore, patient selection and family counseling remain essential components of successful NAM protocols.[14]

Overall, current evidence supports NAM as a valuable presurgical adjunct in infants with cleft lip and palate. Its primary benefit appears to be optimization of the preoperative anatomical environment by improving alveolar alignment and nasal morphology rather than replacing surgical reconstruction. The principal indications, anatomical effects, potential benefits, and limitations of presurgical nasoalveolar molding are summarized in Table 4.[10–14,31]

Table 4. Presurgical Nasoalveolar Molding: Indications, Effects, and Limitations

Domain	Description	Clinical Implication
Primary objective	Approximation of alveolar segments and reduction of cleft width before surgery	May facilitate primary lip repair
Nasal molding	Gradual modification of nasal cartilage and soft-tissue position	May improve preoperative nasal symmetry
Alveolar alignment	Reduction of the separation between alveolar segments	May simplify surgical closure
Timing	Initiated during early infancy and continued until primary repair	Requires early referral and regular follow-up
Potential benefits	Improved presurgical anatomy and reduced cleft width in selected patients	May facilitate surgical reconstruction
Long-term evidence	Evidence for durable aesthetic, dentoalveolar and midfacial benefits remains heterogeneous	Routine universal use is not supported by high-certainty evidence
Treatment burden	Requires repeated appliance adjustment, monitoring and caregiver participation	Access, compliance and socioeconomic factors may affect feasibility
Digital NAM	Digital scans and CAD/CAM approaches can assist appliance design	May improve customization and workflow efficiency

2.8 Primary Nasal Reconstruction During Cleft Lip Repair: Contemporary Concepts, Techniques, and Long-Term Outcomes

Nasal deformity represents one of the most complex and aesthetically significant components of cleft lip and remains a major determinant of long-term facial harmony. The nasal abnormalities associated with cleft lip are not limited to external appearance but reflect a three-dimensional disturbance involving cartilage, soft tissues, and underlying skeletal structures. Typical characteristics include lateral displacement of the alar base, flattening and malposition of the lower lateral cartilage on the cleft side, shortening of the columella, deviation of the nasal tip, widened or asymmetric nostrils, and altered relationship between the nose, upper lip, and maxillary structures. The severity of nasal deformity is closely associated with cleft type, extent of tissue deficiency, and degree of disruption of normal anatomical relationships.

Historically, correction of cleft-associated nasal deformity was frequently postponed until adolescence, when facial growth was considered sufficiently complete. However, contemporary concepts of cleft care have progressively shifted toward early nasal reconstruction performed simultaneously with primary cheiloplasty. This change in philosophy is based on improved understanding of neonatal cartilage characteristics, the potential for early remodeling, and the recognition that untreated nasal cartilage displacement may contribute to persistent asymmetry during facial growth.[20–22] Primary nasal reconstruction during cleft lip repair aims to restore the position and shape of the lower lateral cartilage, improve alar base symmetry, correct nasal floor deformity, and establish a more balanced nasal framework while preserving future growth potential. Modern approaches range from limited soft tissue repositioning and nasal molding techniques to more comprehensive primary rhinoplasty maneuvers involving cartilage repositioning, suspension techniques, and refinement of the nasal base. The principles of contemporary primary nasal reconstruction are illustrated in Figure 6.

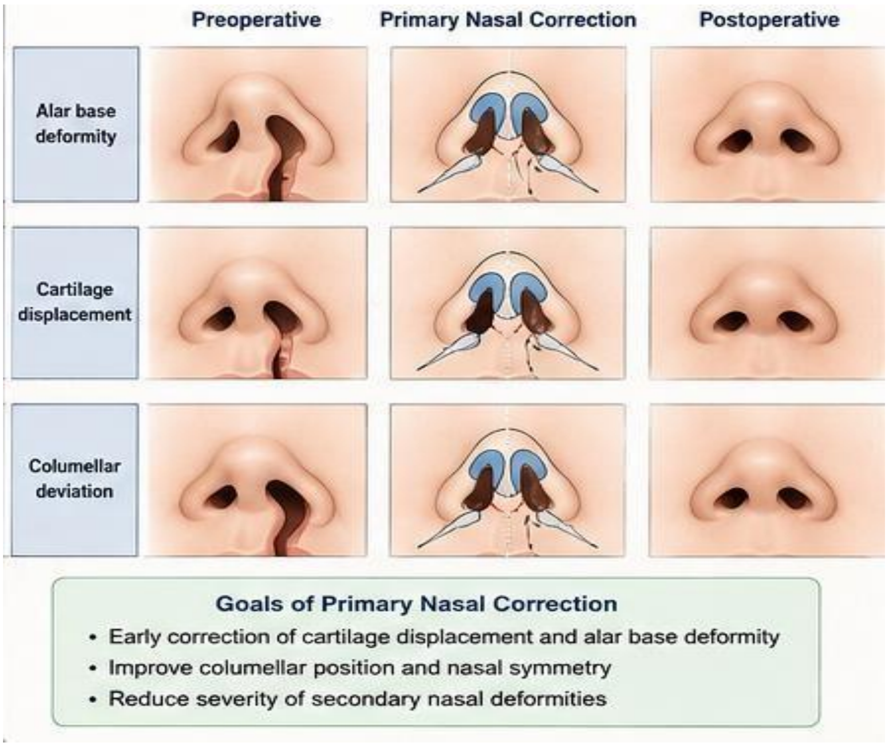

Figure 6. Principles of Primary Nasal Reconstruction During Cleft Lip Repair.

Illustration demonstrating the major components of primary nasal correction, including repositioning of the cleft-side lower lateral cartilage, correction of alar base displacement, restoration of columellar alignment, improvement of nostril symmetry, and integration of nasal reconstruction with primary cleft lip repair.

The concept of simultaneous nasal correction has been strongly influenced by the work of Salyer, McComb, Mulliken, and other pioneers who emphasized that correction of nasal deformity should be considered an integral component of primary cleft reconstruction rather than a separate secondary procedure. Early approaches demonstrated that careful manipulation of nasal soft tissues and cartilage could improve nasal appearance without compromising subsequent facial development. Contemporary protocols increasingly incorporate primary nasal correction as part of anatomical reconstruction of the cleft deformity, particularly in patients with significant nasal asymmetry or bilateral cleft involvement.[33,20–22]

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The literature demonstrates that several principles are consistently associated with favorable outcomes. These include accurate repositioning of displaced cartilage structures, preservation of vascular supply, avoidance of excessive tissue tension, restoration of nasal base symmetry, and coordinated management of the lip–nose complex. Mulliken emphasized the importance of anatomical reconstruction of the nasal deformity during primary repair, particularly in bilateral cleft lip where columellar shortening, prolabial deficiency, and nasal tip distortion represent major reconstructive challenges.[20] Despite increasing acceptance of primary nasal correction, the optimal extent and timing of intervention remain debated. Some surgeons advocate limited primary correction to minimize potential interference with nasal growth, whereas others support more comprehensive early reconstruction based on evidence that neonatal cartilage demonstrates significant adaptability. Current evidence suggests that appropriately performed primary nasal correction can improve early and intermediate nasal symmetry without necessarily compromising subsequent growth, although long-term evidence remains heterogeneous.[21,22,33]

A major advancement in the evaluation of cleft nasal outcomes has been the introduction of objective assessment methods. Traditional evaluation based on clinical photography and subjective expert grading has gradually been complemented by anthropometric measurements, three-dimensional stereophotogrammetry, and digital facial analysis. These approaches allow quantitative assessment of nasal width, nostril symmetry, alar position, columellar deviation, and changes occurring during growth. Three-dimensional evaluation has become increasingly important because cleft nasal deformity represents a complex spatial abnormality that cannot be fully characterized using two-dimensional measurements alone.[27,28,38] The management of cleft nasal deformity should also be considered within the broader context of multidisciplinary rehabilitation. The relationship between the nose, upper lip, alveolus, and maxilla requires coordinated planning between cleft surgeons, orthodontists, pediatric dentists, and other specialists. Primary nasal reconstruction should therefore be individualized according to cleft morphology, associated deformities, patient age, and long-term functional and aesthetic goals.[34,35] Current evidence does not support a single universally superior technique for primary nasal reconstruction. Instead, successful outcomes appear to depend on anatomical understanding, appropriate surgical timing, preservation of nasal growth potential, surgeon experience, and standardized long-term evaluation. The principal contemporary approaches, anatomical objectives, potential benefits, and limitations of primary nasal management during cleft lip repair are summarized in Table 5.[20–22,33–35,38]

Table 5. Contemporary Approaches to Primary Nasal Management in Cleft Lip

Approach	**Principal Objective**	**Potential Benefits**	**Important Considerations**
Primary nasal correction	Correct alar, nasal base and soft-tissue asymmetry during primary cheiloplasty	Improved early facial symmetry and nasal contour	Requires careful preservation of growth potential
Alar cartilage repositioning	Reorient displaced alar cartilage	Improves nostril shape and alar symmetry	Technique must account for abnormal cartilage anatomy
Nasal base correction	Improve relationship between nasal floor, alar base and lip	May improve nasolabial symmetry	Overcorrection should be avoided
Columellar management	Address columellar shortening or deviation, particularly in bilateral clefts	May improve nasal projection and symmetry	More complex in severe bilateral deformity
Integrated lip–nose repair	Treat lip and nasal deformities as a coordinated anatomical unit	Provides comprehensive primary reconstruction	Requires individualized surgical planning
Three-dimensional assessment	Quantitative evaluation of nasal morphology before and after surgery	Improves objective outcome assessment	Requires standardized imaging protocols

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2.9 Postoperative Outcomes, Complications, and Long-Term Results After Cleft Lip Repair

Evaluation of outcomes after cleft lip repair has progressively evolved from a simple assessment of wound healing and anatomical closure toward a multidimensional analysis incorporating functional recovery, facial aesthetics, psychosocial adaptation, and patient satisfaction. The reviewed literature emphasizes that the success of cleft lip reconstruction cannot be determined solely by the immediate postoperative appearance, because facial growth, nasal development, dental maturation, and psychosocial factors continue to influence treatment outcomes throughout childhood and adolescence.

The primary objectives of cleft lip repair include restoration of anatomical continuity, reconstruction of the orbicularis oris muscle, improvement of upper lip symmetry, preservation of facial growth potential, acceptable scar quality, and harmonious integration of the reconstructed lip and nose with the developing craniofacial structures. Contemporary outcome studies increasingly support the use of combined clinician-based assessments and patient-reported outcome measures because objective anatomical correction does not always correspond directly with patient satisfaction or perceived facial improvement.

Functional Outcomes After Primary Cleft Lip Repair

Functional restoration remains a fundamental objective of cleft lip reconstruction. Accurate reconstruction of the orbicularis oris muscle and restoration of muscular continuity contribute to improved lip competence, oral function, and facial animation. Modern anatomical repair techniques emphasize precise muscle alignment rather than simple closure of the mucocutaneous defect, resulting in improved functional integration of the reconstructed lip.

Although cleft lip has a less direct influence on speech development than cleft palate, alterations in lip morphology, maxillary development, and dental relationships may affect feeding efficiency, articulation patterns, and overall oral function. Therefore, long-term follow-up within specialized cleft teams remains essential to identify functional limitations and provide coordinated interventions when required.[1,35]

Aesthetic Outcomes and Objective Evaluation

Aesthetic assessment after cleft lip repair remains complex because facial appearance is influenced by multiple interacting factors, including surgical technique, scar maturation, nasal growth, maxillary development, and individual biological variability. Historically, evaluation relied primarily on subjective assessment of standardized clinical photographs. However, contemporary approaches increasingly incorporate validated scoring systems, anthropometric measurements, and three-dimensional facial analysis.

Common parameters used for postoperative evaluation include:

- Cupid's bow symmetry;
- philtral column reconstruction;
- vermilion border continuity;
- lip height and projection;
- scar quality and visibility;
- nasal base symmetry;
- nostril shape and position.

The Asher-McDade nasolabial aesthetic rating system has been widely used for standardized evaluation of cleft-related facial appearance and remains an important reference tool in clinical research.[24] More recent studies have demonstrated that three-dimensional stereophotogrammetry provides additional quantitative information regarding facial symmetry and postoperative morphological changes, reducing observer dependency and improving reproducibility.[27,38–40] Comparative studies evaluating different surgical approaches indicate that modern anatomical repair techniques generally achieve favorable aesthetic outcomes. However, available evidence suggests that differences between techniques are often smaller than the influence of surgeon experience, quality of anatomical reconstruction, postoperative management, and long-term facial growth patterns.[32,34] The principal domains, assessment methods, and outcome measures used for evaluating patients after cleft lip repair are summarized in Table 6.[24,27,38–40]

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Table 6. Multidimensional Assessment of Outcomes After Cleft Lip Repair

Outcome Domain	Representative Measures	Clinical Relevance
Lip symmetry	Cupid's bow symmetry, lip height, vermilion alignment	Assesses restoration of lip anatomy
Scar quality	Scar width, visibility, hypertrophy and contour	Important aesthetic and patient-centered outcome
Nasal morphology	Alar symmetry, nasal width, projection and nostril shape	Evaluates primary nasal reconstruction
Facial growth	Maxillary and midfacial development	Important for long-term craniofacial outcome
Dental development	Dental eruption, alignment and occlusion	Reflects dentoalveolar consequences of clefting and treatment
Speech	Articulation, resonance and velopharyngeal function when relevant	Assesses functional rehabilitation
Hearing	Audiological status and middle-ear function	Important because of associated otologic problems
Patient-reported outcomes	Satisfaction, appearance perception and quality of life	Captures outcomes not fully represented by clinical measurements
Three-dimensional morphometry	Landmark distances, angles, asymmetry indices and surface measurements	Provides objective and reproducible assessment

Postoperative Complications and Secondary Procedures

Despite significant advances in surgical techniques, postoperative complications and secondary deformities remain important considerations in cleft lip management. Reported complications include hypertrophic or widened scars, vermilion irregularities, residual lip asymmetry, whistle deformity, Cupid's bow distortion, and persistent nasal asymmetry.

The frequency and severity of secondary deformities depend on multiple factors, including cleft severity, surgical technique, timing of repair, tissue characteristics, and duration of follow-up. Secondary procedures may include scar revision, lip revision, secondary rhinoplasty, orthodontic treatment, and alveolar reconstruction when indicated.

Current evidence indicates that meticulous primary reconstruction based on restoration of anatomical subunits and functional muscle continuity reduces the severity of secondary deformities. Nevertheless, cleft patients require prolonged surveillance because craniofacial growth may reveal residual asymmetry or functional limitations that become clinically significant later in development.[34,35]

Patient-Reported Outcomes and Quality of Life

Modern cleft care increasingly recognizes patient perception and psychosocial well-being as essential components of treatment success. Although surgical outcomes have traditionally been evaluated by clinicians, contemporary research highlights the importance of understanding how patients perceive facial appearance, function, and social integration.

2.10 Quality-of-life studies demonstrate that successful cleft treatment extends beyond anatomical reconstruction and includes improvement in confidence, communication, social participation, and psychological adaptation. Patient-reported outcome measures are therefore increasingly incorporated into clinical studies to provide a more comprehensive assessment of treatment effectiveness.[26] Overall, current evidence indicates that primary cleft lip repair performed within specialized multidisciplinary programs provides reliable improvement in facial appearance and function. However, long-term follow-up remains essential because growth-related changes, secondary deformities, and psychosocial factors continue to influence final outcomes throughout childhood and adolescence.

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Multidisciplinary Management of Children with Cleft Lip

Contemporary management of children with cleft lip has evolved from isolated surgical correction toward a comprehensive, lifelong rehabilitation model based on multidisciplinary care. The reviewed literature consistently demonstrates that cleft lip represents a complex craniofacial condition involving anatomical reconstruction, facial growth, dental development, speech and hearing function, nutritional status, and psychosocial adaptation. Consequently, optimal outcomes cannot be achieved through surgery alone but require coordinated collaboration among specialists throughout childhood and adolescence.

The establishment of multidisciplinary cleft teams has substantially improved treatment consistency and long-term outcomes. Modern cleft programs integrate the expertise of cleft surgeons, orthodontists, pediatric dentists, speech-language pathologists, otolaryngologists, geneticists, psychologists, nurses, and imaging specialists. This coordinated approach allows individualized treatment planning according to cleft severity, associated anomalies, developmental stage, and patient-specific functional requirements.[1,25,35]

Role of the Cleft Team in Early Childhood Management

The multidisciplinary pathway begins immediately after birth, when early assessment focuses on feeding ability, nutritional status, associated congenital anomalies, and parental counseling. Infants with cleft lip, particularly those with associated palatal involvement, may experience impaired oral seal and reduced feeding efficiency. Early intervention by pediatricians, specialized nurses, and feeding specialists helps establish adequate nutrition and supports normal growth during the preoperative period. Family-centered counseling represents an essential component of early cleft care. Parents require clear information regarding surgical timing, expected treatment stages, long-term prognosis, and the need for prolonged multidisciplinary follow-up. Evidence from international cleft programs indicates that effective communication between healthcare providers and families contributes to improved treatment adherence and psychosocial adaptation.[25,26]

Coordination Between Surgical and Orthodontic Management

Close collaboration between cleft surgeons and orthodontists is fundamental for achieving stable functional and aesthetic outcomes. Orthodontic evaluation begins early, particularly in patients with alveolar involvement, maxillary segment displacement, or complex cleft morphology. Presurgical orthopedic interventions, including nasoalveolar molding (NAM), are integrated into many treatment protocols to optimize soft tissue and alveolar relationships before primary repair.[10–14] During later stages of development, orthodontic treatment addresses dentofacial abnormalities associated with cleft formation, including maxillary deficiency, dental crowding, crossbite, tooth eruption disturbances, and preparation for alveolar bone grafting when indicated. The timing of orthodontic intervention must be coordinated with surgical procedures to achieve predictable long-term facial and occlusal outcomes.

Speech, Hearing, and Functional Rehabilitation

Although isolated cleft lip has a limited direct influence on speech compared with cleft palate, many children with combined cleft lip and palate experience speech-related difficulties due to velopharyngeal dysfunction, hearing impairment, and altered craniofacial development. Speech-language specialists play a critical role in early evaluation, monitoring of language development, and implementation of individualized rehabilitation strategies. Otolaryngological assessment is also an important component of long-term cleft care. Children with cleft conditions have an increased prevalence of middle ear dysfunction and conductive hearing loss related to impaired Eustachian tube function. Early identification and management of hearing abnormalities are essential for normal speech development, learning ability, and social integration.[25,35]

Dental and Oral Health Management

Dental care represents another essential component of multidisciplinary cleft rehabilitation. Children with cleft lip frequently present with dental abnormalities, including missing or malformed teeth, delayed eruption, enamel defects, and malposition of permanent teeth, particularly adjacent to the cleft region.

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Pediatric dentists contribute to preventive care, oral hygiene education, management of dental disease, and coordination of treatment before orthodontic and surgical procedures. Maintaining optimal oral health is particularly important before alveolar reconstruction and orthodontic correction because dental infection and poor hygiene may negatively influence treatment outcomes.

Psychosocial Support and Patient-Centered Care

Contemporary cleft care increasingly recognizes psychosocial well-being as an important determinant of treatment success. Facial differences may influence self-esteem, social interaction, emotional development, and quality of life, particularly during school years and adolescence.

Psychological assessment and counseling have therefore become integrated components of specialized cleft programs. Patient-reported outcome measures demonstrate that successful rehabilitation involves not only restoration of facial anatomy but also improvement in confidence, social participation, and overall quality of life.[26]

Future Perspectives in Integrated Cleft Care

Recent technological developments have further enhanced multidisciplinary collaboration. Three-dimensional facial imaging, digital treatment planning, computer-assisted surgical simulation, and artificial intelligence-based analysis provide new opportunities for objective diagnosis, individualized planning, and longitudinal assessment of treatment outcomes.[27–30]

The principal specialists involved in contemporary cleft care and their respective roles across the different stages of childhood and adolescent rehabilitation are summarized in Table 7.[1,25,26,35]

Table 7. Multidisciplinary Components of Contemporary Cleft Care

Specialty / Professional	Principal Role	Timing / Focus
Cleft / plastic / maxillofacial surgeon	Primary lip and nasal repair; secondary reconstruction when indicated	Infancy through adolescence/adulthood as required
Orthodontist	Growth modification, dentoalveolar alignment and preparation for later treatment	Childhood through adolescence
Pediatric dentist	Dental prevention, caries control and eruption monitoring	Early childhood onward
Speech-language specialist	Speech and language assessment and therapy	Infancy/childhood and as clinically indicated
Otolaryngologist / audiologist	Hearing assessment, middle-ear disease and airway evaluation	Throughout childhood
Geneticist	Assessment of syndromic features, counseling and testing	At diagnosis and when indicated
Psychologist / mental health professional	Psychosocial assessment and support	Throughout development as needed
Nursing / feeding specialists	Feeding support, caregiver education and nutritional monitoring	Neonatal period and early infancy
Radiology / imaging specialists	Three-dimensional imaging and quantitative assessment	Preoperative planning and longitudinal follow-up

2.10 Digital Technologies and Artificial Intelligence in Cleft Lip Management

The integration of digital technologies into cleft lip management represents one of the most important developments in contemporary craniofacial care. Over the last decade, cleft treatment has progressively moved from conventional two-dimensional clinical evaluation toward individualized, three-dimensional, and data-driven approaches. The reviewed literature demonstrates that digital technologies have influenced multiple stages of cleft care, including diagnosis, anatomical assessment, presurgical planning, surgical simulation, orthodontic management, and postoperative outcome

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evaluation. Unlike traditional photographic documentation, modern digital platforms allow objective quantification of facial morphology and provide reproducible measurements of complex three-dimensional structures. These innovations have improved communication among members of multidisciplinary cleft teams and have facilitated more individualized treatment planning according to the specific anatomical characteristics of each patient.

Three-Dimensional Facial Imaging and Morphometric Assessment

Three-dimensional (3D) facial imaging has become an increasingly valuable tool in the evaluation of children with cleft lip and associated craniofacial deformities. Conventional two-dimensional photography provides important clinical information; however, it is limited by differences in head position, lighting conditions, and observer interpretation. In contrast, three-dimensional stereophotogrammetry enables non-invasive acquisition of facial surface data and allows quantitative assessment of facial symmetry, lip morphology, nasal contour, soft tissue volume, and postoperative changes without exposure to radiation.

Heike et al. emphasized that three-dimensional imaging has significantly expanded the possibilities for craniofacial research and clinical monitoring by providing objective measurements of facial growth and treatment outcomes. This technology allows longitudinal evaluation of changes occurring during childhood development and facilitates comparison of different surgical strategies using standardized morphological parameters.[27]

Comparative studies evaluating different three-dimensional surface imaging systems have demonstrated high accuracy and reproducibility for facial analysis. Tzou et al. reported that modern stereophotogrammetry systems provide reliable assessment of craniofacial soft tissues and represent a valuable alternative to conventional anthropometric evaluation.[28]

In cleft lip management, 3D imaging enables assessment of parameters such as facial asymmetry, nasal deviation, nostril shape, lip height, vermilion contour, and differences between cleft and non-cleft sides. These measurements are particularly important because postoperative evaluation increasingly requires objective assessment rather than relying exclusively on subjective aesthetic judgment.

Three-dimensional models also improve communication within multidisciplinary teams. Surgeons, orthodontists, and families can visualize anatomical abnormalities, treatment objectives, and expected surgical outcomes using patient-specific digital representations. This approach contributes to more informed decision-making and improves coordination between different specialists involved in long-term cleft rehabilitation.

Virtual Surgical Planning and Computer-Assisted Treatment

Virtual surgical planning (VSP) has become an important component of modern craniofacial surgery and has gradually expanded into cleft care. Initially developed for complex maxillofacial reconstruction, VSP is now increasingly applied in patients requiring secondary correction, severe alveolar deformity management, and orthognathic procedures. Digital planning allows integration of clinical examination, three-dimensional facial imaging, and anatomical datasets to simulate surgical interventions before treatment. Surgeons can evaluate anatomical relationships, analyze tissue deficiencies, and plan individualized procedures based on patient-specific morphology. The use of computer-assisted workflows has also improved communication between specialists. Orthodontists, surgeons, and restorative teams can simultaneously evaluate digital models and coordinate treatment sequences, particularly in patients requiring multiple surgical and orthodontic interventions.

Digital orthodontic workflows and CAD/CAM technologies have introduced new possibilities for cleft and craniofacial treatment planning, appliance fabrication, and interdisciplinary collaboration.[29] These approaches may reduce dependence on conventional impressions and manual laboratory procedures while improving reproducibility and efficiency.

Three-Dimensional Printing and Customized Devices

Additive manufacturing technologies have further expanded the role of digital approaches in cleft care. Three-dimensional printing enables production of patient-specific anatomical models, surgical simulation tools, orthodontic appliances, and educational materials. In presurgical orthopedic management, digital workflows combining intraoral

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scanning, computer-aided design, and three-dimensional printing have emerged as alternatives to conventional appliance fabrication techniques. These methods may reduce laboratory processing time, improve manufacturing accuracy, and increase patient comfort while maintaining comparable clinical effectiveness. Velickovic et al. evaluated digitally versus conventionally fabricated nasoalveolar molding appliances in a systematic review and meta-analysis of randomized controlled trials and provided contemporary evidence regarding the comparative effectiveness of these approaches.[31] Although digital fabrication technologies remain under continuous development, current evidence suggests that they represent an important step toward personalized cleft care. Their integration with three-dimensional imaging and virtual planning may allow more predictable and patient-specific therapeutic strategies.

Artificial Intelligence Applications in Cleft Care

Artificial intelligence (AI) represents one of the most rapidly developing areas in craniofacial medicine. Current applications of AI in cleft lip management are primarily focused on automated facial analysis, anatomical landmark identification, severity classification, and prediction of treatment outcomes. Machine-learning and deep-learning algorithms have demonstrated the ability to analyze large numbers of facial images and identify morphological characteristics associated with craniofacial deformities. These technologies may reduce observer variability and provide standardized quantitative evaluation of facial structures. Harrison et al. reviewed emerging applications of artificial intelligence in pediatric craniofacial surgery and emphasized the potential role of AI-based systems in automated landmark detection, morphological analysis, classification, and individualized treatment planning.[30]

In cleft care, AI-assisted analysis may support clinicians by providing objective measurements that complement traditional clinical assessment. Another promising application involves prediction of postoperative outcomes. By integrating preoperative facial morphology, three-dimensional imaging data, surgical parameters, and patient characteristics, machine-learning models may eventually assist in estimating expected postoperative appearance and selecting the most appropriate treatment strategy.

However, current evidence indicates that AI should be considered a decision-support technology rather than a replacement for clinical expertise. Several limitations remain, including insufficiently large datasets, differences between imaging systems, limited external validation, ethical concerns, and the need for integration into existing multidisciplinary workflows. Future clinical implementation will require prospective studies evaluating the accuracy, reliability, generalizability, and clinical relevance of AI-based systems before routine adoption in cleft care.

Future Perspectives of Digital Cleft Care

The future of cleft lip management is expected to involve increasingly integrated digital workflows combining three-dimensional imaging, artificial intelligence, virtual surgical planning, additive manufacturing, and personalized treatment strategies. Digital transformation has the potential to improve early diagnosis, optimize surgical planning, standardize postoperative assessment, and facilitate long-term monitoring of facial growth. Furthermore, integration of digital technologies into multidisciplinary cleft teams may enhance communication between specialists and improve patient-centered care. Nevertheless, digital technologies should be viewed as complementary tools that enhance established principles of cleft management rather than replace clinical judgment and surgical expertise. The success of future digital approaches will depend on validation through high-quality clinical studies, standardized outcome measurements, and effective integration into comprehensive multidisciplinary treatment pathways. Overall, current evidence supports the expanding role of digital technologies and artificial intelligence as important components of contemporary cleft lip management. These innovations provide opportunities for more accurate diagnosis, individualized surgical planning, and objective evaluation of long-term outcomes, while maintaining the fundamental principles of anatomical reconstruction and multidisciplinary rehabilitation. The principal digital technologies, artificial intelligence applications, clinical purposes, potential benefits, and current limitations are summarized in Table 8.[27–31]

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Table 8. Digital and Artificial Intelligence Applications in Contemporary Cleft Lip Management

Technology	Current / Potential Application	Potential Clinical Value	Key Limitations
Three-dimensional facial imaging	Surface capture and quantitative facial morphology	Objective assessment of symmetry and treatment outcomes	Equipment cost and standardized acquisition requirements
Digital morphometric analysis	Automated or semi-automated landmark and measurement analysis	Improved reproducibility and longitudinal comparison	Landmarking and protocol variability
Virtual surgical planning	Three-dimensional simulation of surgical changes	Improved preoperative planning and team communication	Requires specialized software and expertise
CAD/CAM	Digital design of patient-specific devices and models	Customized treatment and workflow efficiency	Technical and financial requirements
Three-dimensional printing	Production of anatomical models and customized devices	Facilitates planning, education and individualized care	Material, accuracy and workflow considerations
Artificial intelligence	Automated landmark detection, classification and pattern recognition	Potential decision support and standardized assessment	Requires large datasets, validation and bias assessment
AI-assisted outcome prediction	Prediction of postoperative morphology or treatment response	Potential for personalized treatment planning	Currently requires stronger prospective clinical validation
Digital longitudinal monitoring	Repeated three-dimensional assessment during growth	Quantitative monitoring of facial development	Requires standardized repeated imaging

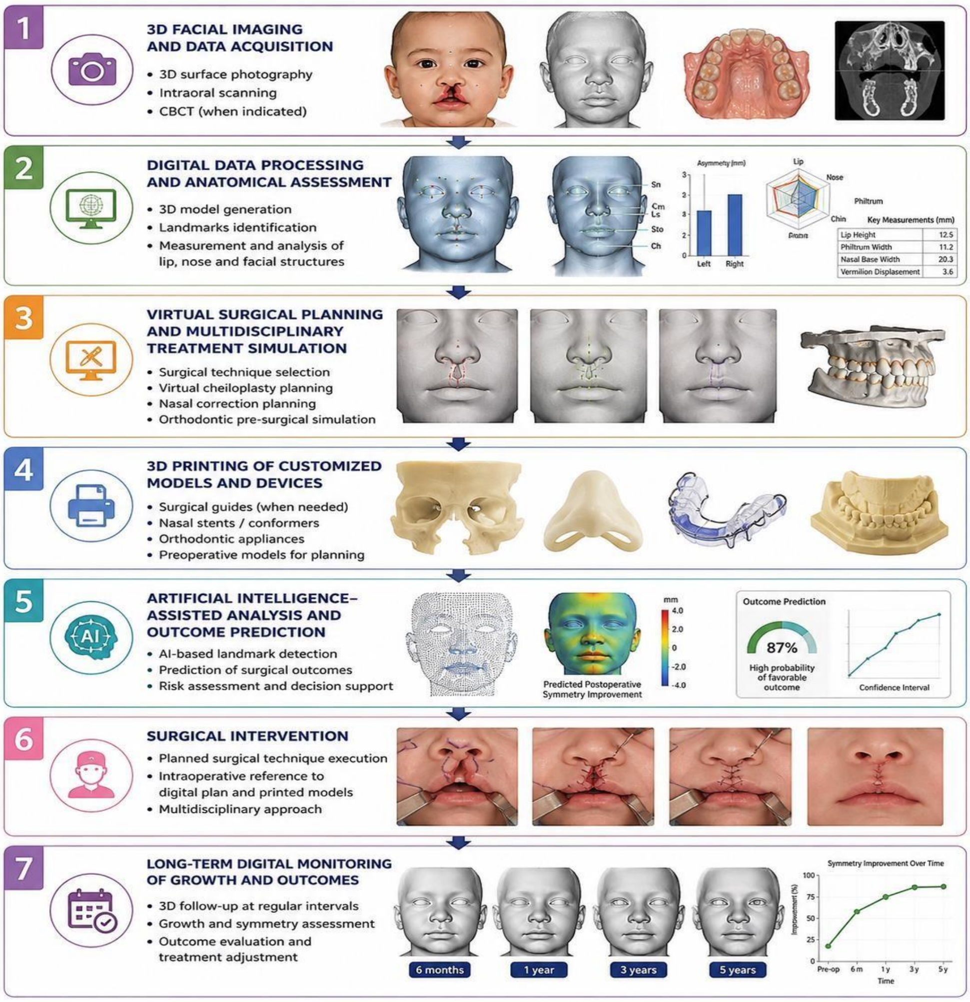

Figure 7. Digital Workflow in Contemporary Cleft Lip Management.

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Representative Clinical Illustrations of Cleft Lip and Residual Deformities

Representative Clinical Illustrations of Cleft Lip and Residual Deformities
Representative clinical photographs complement the evidence synthesized in the preceding sections by demonstrating how anatomical differences in cleft morphology, lip deficiency, nasal asymmetry, and residual soft-tissue distortion may influence clinical assessment and reconstructive decision-making. T. In such patients, careful assessment of lip height, vermilion continuity, Cupid's bow, orbicularis oris muscle alignment, nasal symmetry, and the relationship between the lip and alveolar segments is essential for individualized treatment planning. Their management requires comprehensive assessment and individualized planning, with secondary lip revision, orthodontic treatment, nasal correction, or other reconstructive procedures considered according to the specific anatomical and functional deficits. These illustrations reinforce the principle that cleft lip treatment should not be regarded as a single operative procedure but rather as a longitudinal process involving primary reconstruction, nasal and orthodontic management, functional rehabilitation, objective outcome assessment, and, when required, secondary correction. The clinical photographs also support the increasing importance of standardized three-dimensional assessment, which may provide quantitative information regarding facial symmetry, lip morphology, nasal position, and growth-related changes that cannot be adequately captured by conventional two-dimensional clinical photography alone.


. **Figure 8.** Preoperative clinical appearance of a child with cleft lip.
Figure 9. Postoperative clinical view two weeks after cleft lip repair.


Figure 10. Preoperative view showing a unilateral cleft lip involving the vermilion and philtrum.
Figure 11. Three-week postoperative view demonstrating satisfactory healing, well-adapted lip margins, and improved symmetry of the upper lip and philtrum.


Figure 12. Preoperative view showing a unilateral cleft lip involving the vermilion and philtrum.
Figure 13. Three-week postoperative view demonstrating satisfactory healing, well-adapted lip margins, and improved symmetry of the upper lip and philtrum.


Figure 14. Preoperative view showing a complete bilateral cleft of the upper lip involving the philtrum and vermilion. **Figure 15**.One-week postoperative view demonstrating early healing, well-approximated lip margins, and improved symmetry of the lip.

Figure 16. a,b. Preoperative clinical appearance of an adult woman with cleft upper-lip and nasal asymmetry

Figure 17.a.b Postoperative clinical view two weeks after surgical repair of the cleft

DISCUSSION

Cleft lip remains one of the most extensively investigated congenital craniofacial anomalies, yet achieving consistently predictable long-term functional and aesthetic outcomes continues to represent a significant clinical challenge. Advances in embryology, molecular genetics, surgical reconstruction, orthodontic management, and digital technologies have profoundly changed the philosophy of cleft care. The current concept has evolved from simple closure of an anatomical defect toward individualized reconstruction aimed at restoring facial harmony, preserving normal growth potential, optimizing function, and improving psychosocial well-being. Contemporary cleft management therefore represents a complex continuum of care rather than a single surgical event. The findings synthesized in the present narrative review demonstrate that, despite considerable progress, substantial variation remains in clinical protocols among cleft centers worldwide. Differences exist regarding timing of primary cheiloplasty, selection of surgical technique, extent of primary nasal correction, application of presurgical orthopedic therapy, methods of postoperative evaluation, and indications for secondary revision procedures. This variability the multifactorial nature of cleft deformities and the absence of a universally accepted treatment algorithm. Previous multicenter investigations have similarly emphasized that outcomes are influenced not only by the selected operative technique but also by surgeon experience, institutional protocols, multidisciplinary coordination, and duration of follow-up.[25]

One of the most important developments in contemporary cleft surgery is the transition from procedure-based treatment toward anatomical and patient-specific reconstruction. Historically, successful cleft lip repair was primarily defined by closure of the cleft gap and acceptable early postoperative appearance. However, modern concepts emphasize restoration of normal facial anatomy through precise reconstruction of the orbicularis oris muscle, restoration of lip subunits, reconstruction of the philtral complex, preservation of Cupid’s bow morphology, and correction of associated nasal deformity.[15,16,36] This evolution reflects the broader transformation of craniofacial surgery from defect repair toward functional and aesthetic restoration based on detailed understanding of facial anatomy. The optimal surgical technique for unilateral cleft lip repair remains an ongoing subject of discussion. The comparison between rotation–advancement techniques, particularly the Millard approach, and anatomical subunit-based procedures such as Fisher repair illustrates the complexity of evaluating surgical superiority.[15,16] Although Fisher’s anatomical subunit repair has been associated with favorable scar placement, improved philtral definition, and more predictable vermilion reconstruction in some studies, comparative investigations have also demonstrated that both Fisher and modified Millard techniques may provide satisfactory functional and aesthetic outcomes when performed by experienced surgeons.[32] These observations suggest that future research should move beyond identifying a universally superior procedure and instead focus on determining which anatomical characteristics, surgical principles, and patient-related factors influence long-term outcomes.

The role of presurgical nasoalveolar molding (NAM) represents another important area of contemporary discussion. Available evidence indicates that NAM can improve preoperative anatomy by reducing alveolar segment displacement, decreasing soft tissue tension, and improving nasal symmetry before primary repair.[10–13] Long-term studies have demonstrated improved nasal morphology in selected patients treated with NAM; however, its influence on definitive facial growth and long-term aesthetic outcomes remains incompletely established.[12,14] Therefore, NAM should be regarded as an adjunctive component of multidisciplinary cleft management rather than a substitute for surgical reconstruction. Future prospective studies with standardized treatment protocols and long-term follow-up are required to better define patient groups most likely to benefit from NAM. Primary nasal reconstruction during cleft lip repair represents another important evolution in treatment philosophy. Historically, nasal deformity correction was frequently delayed because of concerns regarding potential effects on nasal growth. However, contemporary approaches increasingly support early anatomical repositioning of displaced nasal structures during primary cheiloplasty.[20–22,33] Current evidence suggests that primary nasal correction may improve nasal symmetry and reduce the severity of residual deformity requiring later rhinoplasty. Nevertheless, interpretation of available studies remains limited by heterogeneity in surgical techniques, inconsistent outcome measures, and differences in follow-up duration. The wider implementation of standardized three-dimensional assessment methods may provide more reliable evidence regarding the long-term effectiveness of early nasal interventions.[27,38]

A major advancement in contemporary cleft research is the incorporation of objective digital assessment technologies. Traditional evaluation methods based on clinical photography and subjective expert scoring remain valuable but are influenced by observer variability. Three-dimensional stereophotogrammetry and digital morphometric analysis provide quantitative evaluation of facial structures, allowing assessment of lip symmetry, nasal morphology, soft tissue changes, and growth-related alterations over time.[27,28,38] These technologies have improved both clinical research methodology and multidisciplinary communication by enabling more precise comparison of treatment outcomes. The integration of artificial intelligence represents one of the most promising future directions in cleft care.

Current AI-based approaches have demonstrated potential for automated facial landmark detection, morphological classification, analysis of craniofacial abnormalities, and prediction of treatment outcomes.[30] The principal value of artificial intelligence is not replacement of surgical decision-making but enhancement of clinical analysis through objective data interpretation. Nevertheless, current applications remain at an early stage, and widespread clinical implementation requires validation through large multicenter datasets, external testing, standardized imaging protocols, and careful consideration of ethical and methodological limitations.

The present review contributes to the existing literature by integrating multiple aspects of contemporary cleft lip management within a unified clinical framework. Previous publications have frequently focused on specific components of treatment, including surgical techniques, NAM protocols, or digital technologies individually. In contrast, this review emphasizes the interconnected nature of modern cleft care by combining surgical reconstruction, orthodontic preparation, multidisciplinary rehabilitation, objective outcome assessment, and emerging digital innovations. This integrated perspective reflects the current transition toward personalized cleft management. Another important development in modern cleft care is the increasing recognition of patient-centered outcomes. Anatomical reconstruction alone does not fully define treatment success. Quality of life, psychosocial adaptation, satisfaction with facial appearance, and social confidence are increasingly considered essential outcome parameters.[26]

The incorporation of patient-reported outcome measures provides valuable information regarding the real-world impact of treatment and highlights the importance of evaluating outcomes from both clinician and patient perspectives. Despite significant advances, several limitations remain within the current evidence base. Many available studies are retrospective, include heterogeneous patient populations, and apply different surgical protocols and outcome assessment methods. Variability in surgical timing, operator experience, follow-up periods, and reporting standards limits direct comparison between studies

Furthermore, much of the available evidence originates from highly specialized cleft centers, which may reduce generalizability to different healthcare systems and resource settings. The evidence concerning NAM also requires careful interpretation. Although numerous studies have reported improvement in preoperative alveolar and nasal relationships, the magnitude of these benefits varies according to treatment protocol, appliance design, patient characteristics, and the timing of surgical repair. The 2024 systematic review and critical appraisal by Dunworth et al. emphasized the continuing limitations of the NAM evidence base.[14] More recent evidence comparing digital and conventional NAM fabrication may help clarify whether technological modifications can improve reproducibility and efficiency without compromising clinical effectiveness.[31]

The growing use of digital imaging offers an opportunity to address some of the methodological limitations of historical cleft research. Three-dimensional stereophotogrammetry can provide reproducible measurements of facial morphology without ionizing radiation and can be repeated longitudinally during growth.[27,28]

Such approaches may facilitate development of standardized outcome databases that allow more meaningful comparison between institutions and surgical techniques. Artificial intelligence may further enhance these developments by enabling automated extraction of quantitative facial parameters from large datasets. However, the clinical value of AI will depend on the quality and representativeness of the data used for model development. Differences in age, ethnicity, cleft phenotype, imaging equipment, surgical protocols, and follow-up duration may substantially influence algorithm performance. Consequently, future AI research should prioritize multicenter datasets, external validation, transparent reporting, and clinically meaningful endpoints rather than focusing exclusively on algorithmic accuracy. Future investigations should prioritize prospective multicenter studies using standardized outcome assessment protocols, including three-dimensional morphometric analysis, validated aesthetic scoring systems, and patient-reported outcome measures.[24,38–40] The combination of artificial intelligence, digital workflow integration, three-dimensional planning, and personalized treatment strategies may further transform cleft management by enabling predictive and individualized treatment approaches.

CONCLUSION

In conclusion, contemporary cleft lip management has evolved from traditional surgical closure toward a comprehensive model based on individualized reconstruction, multidisciplinary collaboration, objective assessment, and technological innovation. Current evidence supports the importance of anatomical precision, early optimization of deformities, long-term monitoring, and patient-centered evaluation. The future of cleft rehabilitation will likely depend on successful integration of surgical expertise with digital technologies and artificial intelligence, creating more predictable and personalized treatment pathways for children affected by this complex craniofacial condition.

DECLARATIONS

Ethical Approval

Not applicable.

Competing Interests

The authors declare no conflict of interest.

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