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Review

Maxillary Deficiency: Treatments and Applications for Adolescents

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Abstract: Maxillary deficiency, a common transversal dentofacial deformity, affects aesthetics and function. Timely intervention during adolescence is crucial, as the growth potential of the maxilla provides an opportunity to optimize treatment outcomes. This review explores various approaches for adolescent maxillary expansion, including orthopedic and surgical methods. Orthopedic appliances effectively address transverse deficiencies without surgery and are particularly beneficial in managing conditions in children and early adolescents. In mid- to late-stage adolescents, bone-borne devices with mini-surgery offer better skeletal expansion outcomes. However, in cases of severe deficiencies, or where skeletal resistance limits non-surgical methods, surgical interventions become essential. Procedures like surgically assisted maxillary expansion and orthognathic surgery offer superior skeletal corrections. These techniques are particularly valuable for late adolescents with complex conditions. This review comprehensively summarizes the applications, outcomes, and limitations of these treatment options, highlighting the importance of selecting individualized, growth stage-appropriate interventions.

Keywords: maxillary deficiency; orthopedic techniques; orthognathic surgeries; adolescents

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1. Introduction

Maxillary deficiency, also known as maxillary hypoplasia, is a common dentofacial deformity affecting the bones of the upper jaw. These deficiencies can occur in the transverse, sagittal (anteroposterior), and vertical dimensions, typically presenting in all three facial planes rather than in isolation. The reduced size, impaired growth, and improper positioning of the maxilla result not only in aesthetic concerns but also in functional abnormalities, such as difficulties with breathing and mastication, which can have long-term and profound impacts on individual growth and development [1]. The etiology of maxillary deficiency is multifactorial, arising from congenital inheritance, traumatic events, and developmental factors such as unhealthy oral habits [2]. However, its onset and deterioration are closely associated with the growth peak of the maxilla, particularly during adolescence. Thus, timely medical intervention for adolescent maxillary deficiency is crucial for correcting dentofacial deformities and addressing associated functional concerns. Moreover, taking advantage of the growth potential of adolescents can optimize treatment outcomes. Considering that age classifications vary across different studies, and to improve the understanding of the adolescent dental stages and better grasp the indications for various treatment approaches, this present review categorizes adolescents into the following stages based on the age ranges found in the included literature: early adolescence (10–14 years), mid adolescence (14–16 years), and late adolescence (16–19 years). Additionally, for some studies, dental age is assessed through cone-beam computed tomography (CBCT) scans, which evaluate skeletal and mid-palatal suture maturation. This approach has further provided a refined dimension for categorizing patients, facilitating more precise treatment planning for adolescents [3–7].

Adolescent maxillary expansion represents a dynamic and transformative process due to the active bone growth occurring during this developmental stage. The growth potential of the maxilla during adolescence provides a crucial window of opportunity for treatment, allowing for a range of orthodontic and surgical interventions tailored to individual needs. Orthodontic techniques have been extensively employed for correcting transverse deficiencies, with each approach demonstrating distinct advantages depending on the patient's age, growth stage, and the degree of suture interdigitation [8]. As alternative to orthodontic techniques, surgical approaches have shown promising outcomes by enhancing skeletal modifications and optimizing maxillary protraction in patients with complex conditions such as cleft palate or craniosynostosis [9]. Moreover, some of the surgical approaches have emerged as a powerful option for late adolescents, offering superior skeletal effects and minimizing adverse periodontal outcomes.

For more severe or multi-dimensional deficiencies, surgical interventions such as orthognathic surgery are indispensable in addressing discrepancies simultaneously. This dynamic spectrum of treatment highlights the need for a comprehensive approach to selecting appropriate interventions.

To address maxillary expansion from a broader clinical perspective, the present literature review aims to comparatively summarize the existing treatment approaches. This enables clinicians to better navigate the complexities of adolescent maxillary deficiency and understand the available treatment options in various scenarios.

2. Orthopedic Approaches

Maxillary skeletal expansion using an orthopedic appliance is a relatively conservative procedure designed to correct transverse maxillary deficiencies in children and adolescents. The technique involves the application of mechanical forces with the intraoral appliance to widen the transverse dimension of the maxilla by separating the mid-palatal suture. This process is instrumental in addressing both skeletal and dental issues such as posterior crossbites and dental crowding that arise from insufficient maxillary width [3].

Maxillary expansion with an orthopedic appliance is a critical orthodontic intervention used to address a range of complex dental and craniofacial conditions. It is particularly effective in managing cleft lip and palate by correcting anterior bone deficits and resolving width insufficiencies, which prepares the maxilla for further reconstructive treatments [10]. In patients with skeletal Class III malocclusion, palatal expansion enhances the efficiency of the anterior protraction face mask, facilitating the forward movement of the maxilla and improving alignment [11]. Additionally, the alternately rapid maxillary expansion and constriction (Alt-RAMEC) protocol can be utilized to produce a more pronounced disarticulation of the maxilla than can be obtained using bone-borne maxillary expansion [12,13]. It also may assist in the correction of developing Class II malocclusion by aiding mandibular reposition, thus achieving the correction of the Class II relationship [14,15]. For individuals with Obstructive Sleep Apnea (OSA), it expands the nasal passages and pharynx, potentially reducing sleep apnea symptoms and enhancing respiratory function [16,17]. In addition, palatal expansion can improve the aesthetics of patients with a narrow smile arc by creating a broader, more appealing smile and providing a conservative solution for mild dental crowding by creating slight spaces within the arch, which improves dental aesthetics without the need for extractions [18,19].

Maxillary expansion protocols can be mainly categorized into two types based on various rates and forces: slow maxillary expansion (SME) and rapid maxillary expansion (RME), as shown in Table 1. Each type employs specialized appliances, tailored to the patient's specific needs and developmental stages [20]. The active components of orthopedic appliances for maxillary expansion are primarily comprised springs, jackscrews or both. Springs typically exert forces in the range of several hundred grams, facilitating slow expansion. Conversely, jackscrews offer versatile adjustment capabilities, allowing for protocols that can achieve slow, semi-rapid, or rapid expansion [21,22]. Selecting the appropriate technique based on the stage of mid-palatal suture maturation and corresponding dental age is essential to minimize the risk of failure, and effectively enhance facial aesthetics and function [3,6,7].

Table 1. Overview of available orthopedic options from reviewed studies.

Patient Stage	Techniques	Appliances	Advantages	Disadvantage	Study
Children in primary and early mixed dentition (around ≤10 years of age)	Lingual arch	quadhelix	Gentle continuous force provides effective and safe skeletal changes, allowing up to 4 mm of expansion; it is also well -suited for molar derotation; cleft patients.	More buccal bone loss and fenestrations, limited to primarily dental changes when compared to the HYRAX expander.	[3,23,24]
	Fixed expander with the nickel–titanium spring	Leaf Expander	Delivers consistent force for precise control over expansion, achieving up to 6 mm of effective transverse widening.	Produces a smaller increase in posterior nasal and maxillary mid-alveolar widths in early adolescents compared to the HYRAX expander; requires monthly activation.	[8,25]
	Removable expander with the jackscrew	Removable expansion plate	More effective in increasing canine spacing compared to the quadhelix; allows patient-managed adjustments; easy to clean; suitable for patients with additional dental concerns.	Less effective at achieving skeletal changes, increasing inter-molar width, and shortening treatment duration compared to the quadhelix; patient handling may lead to inconsistent results.	[24,26–28]

Table 1. *Cont.*

Patient Stage	Techniques	Appliances	Advantages	Disadvantage	Study
Preadolescents in late mixed dentition and early adolescents (around 10–14 years of age)	Tooth-borne expander	HYRAX expander	Rapid sutural separation enables up to 10 mm of maxillary expansion, with approximately 80% of the initial expansion being skeletal.	Significant relapse observed, with about 50% retention of skeletal expansion; requires careful activation.	[16]
		Fan-type expander	Focuses expansion primarily on the anterior segment, exerting minimal effect in the molar region.	Limited effects on posterior dimensions.	[29,30]
		Expander with Differential Opening	Enhanced anterior expansion, creating a trapezoid-shaped opening for divergent expansion.	-	[31,32]
	Tooth-tissue-borne expander	Haas expander	Delivers improved force distribution, enhancing the orthopedic response and providing greater anchorage.	Less hygienic due to trapped food particles, more cumbersome than HYRAX.	[24,33–35]
Middle and late adolescents (around 14–19 years of age)	Bone-borne expander	Bone-borne maxillary skeletal expander	Generates nearly triple the expansion within the mid-palatal suture compared to HYRAX, with uplift of maxillary posterior teeth and substantial enhancement of the buccal alveolar bone support.	-	[36]
		C-expander	Delivers superior orthopedic outcomes with fewer dentoalveolar complications compared to the HYRAX appliance.	-	[37]

Table 1. *Cont.*

Patient Stage	Techniques	Appliances	Advantages	Disadvantage	Study
Middle and late adolescents (around 14–19 years of age)	Bone-borne expander	ATOZ expander	Delivers precise positioning with a thermoplastic guide to effectively influence sutural width compared to the C-expander; its compact size makes it suitable for narrower palates.	-	[38]
	Tooth-bone-borne expander	Tooth-bone-borne maxillary skeletal expander	Features precision-fit insertion slots that enable effective bicortical stabilization and apply lateral forces against critical resistance points.	Generates greater dental expansion and buccal alveolar bone height loss and thickness changes in late adolescent patients compared to the C-expander.	[39–41]
		Hybrid HYRAX	Suitable for patients lacking anterior teeth anchorage, maintains buccal bone thickness, and exhibits improved efficacy for maxillary protraction compared to conventional HYRAX.	Exhibits less increase in inter-premolar distances compared to the conventional HYRAX appliance.	[42–44]

2.1. Children in Primary and Early Mixed Dentition

SME is a widely used method for widening the maxillary dental arch and correcting posterior crossbite, particularly effective in children up to about age 10 during the primary and early mixed dentition stages [45], when the mid-palatal suture has not yet fused or only minimally fused [3]. While the dental expansion techniques with the SME protocol can induce some skeletal changes, its predominant effect is more pronounced dental changes and buccal bone loss. This occurs because these appliances primarily cause the teeth to tip buccally, resulting in less significant orthopedic impact on the maxillary base and a higher risk of buccal bone dehiscence [46]. Clear aligners have been proposed as a potential alternative to SME-based dental expansion techniques, but thus far there is no evidence indicating any skeletal effects [47,48]. However, in children or adolescents with cleft palate, the typical resistance provided by the mid-palatal suture is often significantly diminished or entirely absent [10]. To address this unique anatomical challenge, specialized appliances employing the SME protocol such as the Coffin spring, W-arch, or quadhelix can be utilized. These devices enable skeletal expansion in individuals with cleft conditions, widening the maxillary arch while minimizing tissue damage, in contrast to the expansion appliances with the RME approach [49,50].

SME can be effectively carried out using both removable and fixed appliances, each tailored to specific treatment needs. Removable appliances typically incorporate Adam clasps on the first permanent molars and ball-ended clasps on the deciduous molars, often supplemented with posterior acrylic capping [51]. Conversely, fixed appliances usually consist of bands that are securely bonded to the first permanent molars [49].

For treating maxillary constriction in young children with primary and early mixed dentitions, fixed expanders with the jackscrew, such as HYRAX, can be used to apply high forces for rapid expansion. However, the use of RME in young patients is associated with risks such as facial distortion [50]. Therefore, it is generally advised that the screw of fixed expanders should be activated very carefully and gradually. In fact, studies conducted a decade after treatment have shown that both rapid and slow palatal expansions with the fixed expander, despite being used for varying degrees of constriction, maintain stable results [52].

2.1.1. Lingual Arch and Leaf Expander

Over time, the design and functionality of the spring expanders have evolved significantly, progressing from the Coffin spring appliance to the W-Arch, and ultimately to the quadhelix appliance [23,53]. The Coffin spring, an omega-shaped heavy spring with ends embedded in acrylic, molds to the palatal contours to apply balanced forces on both tissue and teeth [54]. Originating from the Coffin appliance, the W-Arch is a fixed appliance constructed from W-shaped wire attached to molar bands. Activation of both appliances is achieved by using pliers to widen the spring's shape, expanding it 3–4 mm beyond its passive state before installation, thus allowing for maxillary expansion. The expansion rate is maintained at 2 mm per month until slight overcorrection of the crossbite is achieved. Compared to the removable appliance, the W-Arch can be adjusted to selectively expand either the anterior or posterior regions and derotate molars [53,55].

The quadhelix is an advanced modification of the W-Arch, designed to enhance flexibility and deliver a gentle, continuous force. It features four helices in the anterior and posterior segments of the palatal arch. Constructed from either 0.9 to 1.0 mm stainless steel or 0.95 mm cobalt chromium wire, the quadhelix spans from bands around the first molars across the palate. It is activated to expand roughly the width of one molar tooth, generating a force of about 400 g, primarily causing dental expansion by up to 4 mm and potentially inducing skeletal changes in preadolescent children [23,24,56]. Fixed expansion devices like W-arch or quadhelix appliances require a cast of the maxillary arch and are fabricated in dental laboratories. These appliances are effective in young patients with early mixed dentition, approximately yielding one-third skeletal and two-thirds dental changes [57]. Some evidence suggests that fixed appliances not only surpass removable plate in success rate but also offer enhanced comfort for the patient and shortened treatment time [26,27].

The Leaf Expander (LE) features a double leaf nickel–titanium spring core and adjustable screw. Anchored on deciduous teeth and the first permanent molars, it delivers a consistent 450 g force, achieving up to 6mm of expansion. The device is preactivated by leaf spring for an initial 3–4.5 mm expansion. Monthly adjustments involve 10–15 quarter turns of the screw, each corresponding to 0.1 mm, to compress the spring further. Typically, active expansion requires five to six months, followed by three months of passive retention to stabilize the results [8,25]. In patients with early mixed dentition, the LE and RME produce comparable skeletal and dentoalveolar effects. No significant changes have been observed at the periodontal level. The LE only shows a significantly less increase in the posterior nasal and maxillary mid-alveolar width compared to the RME, but the differences are minimal [8,58–60]. In addition, the LE reduces the frequency of activations required by the orthodontist compared to the other fixed appliance for the SME, such as the W-Arch or quadhelix appliances. It is also well suited for patients with poor compliance, avoiding the issues of incorrect or insufficient activation of screws [61].

2.1.2. Removable Expansion Plate

The removable expansion plate incorporates screws set into the baseplate of an appliance, which are adjustable by the patient using a key. This mechanism efficiently applies balanced forces to both the tissues and teeth to facilitate arch expansion. Additional screws can be added to assist in shifting the buccal segments distally. Each quarter turn of the screw activates the device by approximately 0.2 mm, exerting around 2 pounds of pressure. Patients are advised to adjust the screw once or twice a week until the overcorrection of crossbite. After expansion, the posterior capping is removed, and the appliance is worn at night for three to six months as a retainer [24].

For children with early mixed dentition, the quadhelix appliance is superior to expansion plates in correcting posterior crossbite and increasing inter-molar distance, with a shorter treatment duration [24,56]. The advantages of a removable expansion plate compared to fixed appliances like the quadhelix extend beyond ease of cleaning. This device not only addresses palatal constriction but also simultaneously manages other dental issues. For instance, individual anterior crossbites or scattered anterior spacing can be addressed by embedding additional active elements such as a Z-spring or finger spring within the acrylic base [28]. If needed to reduce anterior occlusal interference, a posterior capping can also be integrated into the design [28].

2.2. Preadolescents in Late Mixed Dentition and Early Adolescents

As individuals age, the mid-palatal suture becomes increasingly interdigitated [3]. For preadolescents in the late mixed dentition phase and early adolescents, the RME is advised to split the mid-palatal suture before the peak of skeletal growth [62]. In contrast to the SME, the RME applies a larger force to the mid-palatal suture, effectively enlarging maxillary skeletal expansion and the dental arch perimeter. This process also reduces the buccal inclination of the maxillary first permanent molars and results in minor modifications to the buccal bone [63,64]. The prevalent designs of fixed expanders with the jackscrew for the RME include tooth-borne expanders or tooth-tissue-borne expanders with an acrylic plate [33,65,66].

RME treatment spans 2 to 4 weeks, during which patients adjust the appliance one to four times daily, achieving up to 1 mm of expansion per day, and expansions up to 10 mm are achievable [20,22,33,67]. A transient midline diastema often prompts overexpansion of the maxillary arch to manage relapse [68,69]. The appliance remains for at least three months post-expansion, though some relapse is typical [62].

Fixed expanders with the jackscrew can also achieve semi-rapid expansion by slowly separating the palatal suture at a rate of less than 2 mm per week [70]. This pace, which generates approximately 2 pounds of pressure, aligns closely with the maximum speed of bone formation in children with mixed dentition. While rapid expansion can produce a greater increase in inter-canine width and cause more tissue trauma compared to semi-rapid expansion, it ultimately yields similar skeletal and dental effects over a 10- to 12-week period and maintains these outcomes over a decade [71–73].

2.2.1. Tooth-Borne Expander

The HYRAX is a tooth-borne expander featuring a jackscrew within an all-wire frame. The expander has heavy-gauge wire extensions that conform to the palatal contours, either soldered to metal bands on teeth or embedded into acrylic on the buccal dentition (Figure 1a). It is capable of achieving a sutural separation rapidly by activating the jackscrew. Each activation of the screw produces approximately 0.2 mm of lateral expansion. These devices can exert up to 10 kg of force, with initially 80% of the expansion being skeletal, mainly in the anterior region. Over time, significant relapse occurs, retaining only about 50% of the skeletal expansion. Expansion with this appliance can effectively achieve up to 10 mm of maxillary expansion [16].

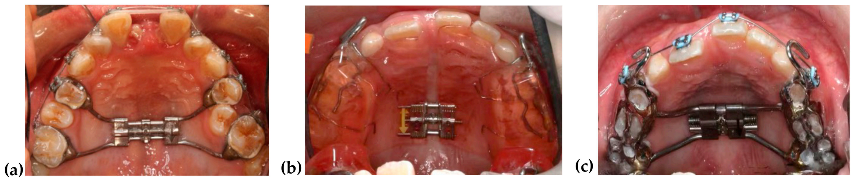

Figure 1. Designs of HYRAX and Hass Expanders. (**a**) The HYRAX expander with two premolar bands and two molar bands. It can be also applied following the surgical separation of the mid-palate suture; (**b**) the Hass expander with acrylic pad attached to the palate and acrylic cap bonding on the buccal dentition; (**c**) HYRAX expanders with metal cast splint bonding on the buccal dentition.

The bands of the HYRAX expander are affixed to the first premolars and first molars, or exclusively to the first molars with extension arms. Research indicates that compared to two-band devices, four-band devices enhance transverse expansion and arch perimeter, particularly in individuals over 12 years of age when the suture is more calcified, so banded first premolars are recommended when available [74]. Additionally, second primary teeth can be used as anchorage in two-band devices by substituting the first molars with bands, thereby mitigating premature stress on the first permanent molars and preventing their buccal tipping [60,75,76]. A retrospective multicenter radiographic study highlighted that the HYRAX expander anchored on deciduous molars achieved significant anterior and posterior skeletal expansions but minimized unwanted dental effects on maxillary permanent teeth compared to those using permanent molar anchorage [76]. A randomized clinical trial also demonstrated that the HYRAX expander anchored on deciduous molars produced more anterior expansion than the Leaf Expander [60].

In instances where first premolar anchorage is not available, bonded HYRAX expanders can be attached through acrylic or metal cast splint bonding on the buccal dentition (Figure 1b,c). The expanders with an acrylic cap cover the occlusal, facial, and lingual surfaces of the posterior teeth, raising the bite for patients with anterior occlusal interference [77]. The study found that there is no significant difference in molar tipping and extrusion between banded and bonded HYRAX expanders [78].

In contrast to conventional expanders, which employ a centrally positioned parallel-opening screw to dissociate the mid-palatal suture uniformly, the fan-type expander is engineered to focus expansion effects primarily in the anterior segment of the dental arch, exerting minimal influence on the molar region [29,30]. This appliance integrates a jackscrew within an acrylic-bonded expander framework. The hinge point of this screw is precisely located tangent to the distal surfaces of the upper first permanent molars, thereby selectively expanding the inter-canine region of the maxilla [29,30].

The Expander with Differential Opening (EDO) is specifically designed to facilitate differential expansion between the anterior and posterior region. Originally, the EDO was developed to achieve enhanced anterior expansion of the maxillary dental arch in patients with complete bilateral cleft lip and palate (BCLP) [79]. This appliance incorporates two parallel-opening screws located strategically within the palate—one positioned anteriorly and the other posteriorly. The differential activation of these anterior and posterior screws results in a trapezoid-shaped opening of the appliance, with a wider divergence toward the front [31].

Compared to the fan-type expander, the EDO produces greater transverse skeletal expansion, while the effects in the vertical and anteroposterior directions are similar [32].

Patients treated with the EDO show more significant dental changes in the molar region, whereas those treated with the fan-type expander exhibit greater changes in the canine region. However, changes in the arch length and perimeter are similar between these two expanders [80,81]. The EDO promotes more transverse changes in the anterior region of the maxilla compared to the Haas expander and facilitates greater transverse changes in the posterior region of the maxilla than the HARAX and Haas expanders [80,82].

2.2.2. Tooth-Tissue-Borne Expander

The Haas expander is a fixed tooth-tissue-borne appliance distinguished primarily by its acrylic pad, which rests against the lateral walls of the palatal vault. This configuration in the Haas-type expander enhances anchorage, promotes a greater orthopedic response, and improves force distribution during expansion [33]. In adolescents with permanent dentition, both the HYRAX and Haas expanders are similarly effective in increasing inter-molar width and correcting posterior crossbite through both tipping and bodily translation. The Haas expander produces more significant alterations in the axial inclination of teeth that support the appliance, with the first premolars experiencing the most pronounced changes [24,34,35]. However, compared to the HYRAX expander, the Haas expander is less hygienic due to food particles becoming trapped under the acrylic plate [83], while the HYRAX expander minimizes irritation to the palatal mucosa and simplifies cleaning [31].

2.3. Middle and Late Adolescents

In middle and late adolescents, the dense interdigitation of the maxillary suture complicates achieving skeletal expansion through RME alone [37]. As adolescents approach the end of their growth spurt, the interdigitation of the suture may become too advanced for mid-palatal suture expansion using tooth-borne expanders [3]. Traditional RME often results in limited skeletal effects, dentoalveolar tipping, root resorption, and adverse periodontal outcomes such as dehiscence, along with a lack of long-term stability in late adolescents [42,84,85]. To mitigate these issues, it is increasingly recommended that late adolescents undergo miniscrew-assisted RPE (MARPE) utilizing temporary skeletal anchorage devices [86]. Studies have demonstrated that bone screws in the palate ensure superior anchorage and significantly reduce tooth movement compared to traditional tooth-borne expanders [37,67]. This method involves an activation rate of one turn per day for late adolescents [87,88].

In comparison to surgically assisted rapid maxillary expansion (SARME), MARPE typically only requires the insertion of miniscrews, resulting in less trauma and pain for the patient. A study conducted on adult patients found MARPE offers greater transverse expansion at the midface and basal bone, providing a more uniform and parallel expansion in both coronal and axial views. However, MARPE results in less expansion of the alveolar process and smaller increases in inter-molar and inter-premolar distances. While MARPE avoids significant buccal inclination of the alveolar process and supporting teeth, this is a more pronounced effect in SARPE, which leads to a V-shaped opening in both a coronal and axial view [9].

2.3.1. Bone-Borne Maxillary Expander

The pure bone-borne expander does not utilize teeth for anchorage. Instead, only two or four miniscrews are directly inserted into the alveolar bone, located 6–8 mm palatal from the teeth's gingival margins, between the roots. For the maxillary skeletal expander (MSE) with four miniscrews, the front implants are symmetrically positioned in the spaces between the first and second premolars, while the implants at the back are set between the second premolars and the first molars. In an adolescent population, this bone-based technique with four miniscrews results in a nearly threefold increase in expansion at the mid-palatal suture compared to methods that anchor to the teeth [36]. Moreover, this approach significantly enhances the vertical alignment of the maxillary posterior teeth and markedly improves support for the outer alveolar bone [36,89]. However, for the bone-borne expander equipped with two miniscrews, which are positioned between the first and second premolars, there is no significant difference in mid-palatal suture separation compared to the HYRAX expander [87].

The C-expander is a tissue-bone-borne expander. It features four or six miniscrews implanted on both sides of the palatal slope, connected to expansion screws via an acrylic base. In late adolescent patients, C-expanders are demonstrated to have superior orthopedic outcomes and exhibit fewer dentoalveolar complications when compared to HYRAX expanders [37].

Recently, a new pure bone-borne maxillary expander known as the ATOZ expander has been introduced [38]. This expander utilizes a thermoplastic installation guide to help accurately position and install the device. One of the distinctive features of the ATOZ expander is its anteroposterior jackscrew design, which results in a narrower width, making it particularly suitable for patients with relatively narrower palates. Moreover, both the C-expander and the ATOZ expander influence the sutural width in the nasomaxillary zygomatic region. The C-expander reduces the width of the circumzygomatic suture, while the ATOZ expander increases the width of the frontozygomatic suture without affecting other surrounding sutures [90].

2.3.2. Tooth-Bone-Borne Maxillary Expander

Since the first molars facilitate the positioning and insertion of miniscrews for the bone-borne MSE, a hybrid tooth and bone-borne device equipped with four miniscrews and anchored by two first molars has become increasingly popular [39,91]. The device features precision-fit insertion slots that secure the microimplants in a perpendicular orientation. The 11 mm length accounts for insertion slots, clearance between the appliance and the palatal surface, gingival thickness, and ensures at least 5 to 6 mm of bone engagement for effective bicortical stabilization [40]. The jackscrew size is chosen to fit closely within the palatal vault and is positioned to apply lateral forces against the pterygomaxillary buttress bone, a critical resistance point in maxillary expansion [39]. In late adolescent patients, although the MSE achieves skeletal expansion similar to that of the C-expander, it results in more buccal tipping of the anchorage teeth, and more significant loss in buccal alveolar bone height and changes in thickness. Additionally, it leads to a more frequent formation of dehiscences compared to the C-expander [41].

The hybrid HYRAX is anchored on the first molars and on two miniscrews in the anterior region of the palate. It is especially suitable for patients lacking anterior anchorage due to missing deciduous teeth or underdeveloped premolar roots [43]. Studies comparing hybrid and conventional HYRAX expanders in the mid adolescents found that both produced similar skeletal changes [44]. The conventional HYRAX increased inter-premolar distances but reduced buccal bone thickness in the premolar area, whereas the hybrid HYRAX maintained buccal bone thickness and more effectively widened the nasal cavity and maxillary width [42]. Both types showed similar dental effects and changes in arch size and shape [16]. Additionally, the hybrid HYRAX is recommended for anchorage in maxillary protraction with facemask therapy in growing patients [11].

3. Orthognathic Surgery Approaches

Non-surgically assisted maxillary expansion is always a safe and effective alternative for treating maxillary deficiency. In adolescents, the bone sutures, such as the mid-palatal suture (MPS), remain open or exhibit minimal interdigitation. Therefore, by taking advantage of growth potential, orthopedic expansion often achieves good prognosis, especially for maxillary transverse deficiency. However, in some premature adolescent patients or those with congenital diseases such as cleft palate or craniosynostosis, the skeletal effects of non-surgical expansion might be significantly restricted due to abnormal or absent MPS fusion, as well as the influence of adjacent structures to the maxilla, particularly the zygomatic buttress and pterygopalatine regions. For these patients, non-surgical maxillary expansion can produce undesirable effects including compromised occlusion, excessive root resorption, fenestration of the buccal cortex or palatal tissues, failure to separate the MPS, pain, and instability of the expansion. Therefore, as we summarized in Table 2, surgically assisted approaches are alternative treatment options, as they effectively eliminate resistance within the maxilla.

Table 2. Overview of available surgical options from reviewed studies.

Adolescent Patient Stage or Condition	Techniques	Modification	Indication	Advantages	Disadvantage	Study
Skeletally mature adolescents	Conventional SARME	-	Transverse maxillary deficiency ≥ 6.0 mm; age ≥ 18 years; no medical history of cleft and maxillary surgery	Straightforward and quick procedure; minimal impact on periodontal tissues and long-term dental health.	Temporary aesthetic concerns; limited bone expansion at the palatal level potential complications affecting the central incisors.	[92]
	Modified SARME	Cortical osteotomy	Bone-borne sutural expansion	Enhances efficiency by reducing resistance.	Lack of evidence-based research.	[93]
		Pterygomaxillary disjunction	Younger than 20 years with bone-borne devices	Greater respiratory function; nasal adjustment reduced resistance; ideal tipping of molars.	More invasive surgical procedures; associated with increased complications.	[94,95]
		Palatal preservation	Maxillary transverse discrepancies with skeletally mature	Reduces surgical invasiveness; potential for fewer complications.	Potential for less effectiveness; Resistance should be released at other sutures or buttress; lack of consensus and evidence.	[96–98]
		Segmental Le Fort I osteotomy	Anterior open bite with a dual-plane maxilla; moderate transversal maxillary hypoplasia; severe proclination of the maxillary anterior teeth	Provides effective maxillary expansion; reduces aesthetic compromise; minimizes disruption of the midline dental papilla; allows for asymmetric expansions in a conservative manner; improved dental alignment.	Risk of relapse; surgical complexity due to multiple osteotomies; larger transverse displacement in the paranasal area but less increase in nasal width.	[99–101]

Table 2. *Cont.*

Adolescent Patient Stage or Condition	Techniques	Modification	Indication	Advantages	Disadvantage	Study
Adolescents with congenital conditions or treatment challenges	Palatal segmental osteotomy	-	-	Enables advanced transverse maxillary expansion; facilitates correction of orthodontic arch discrepancies; provides better control over dentoalveolar segment movement.	Involves more complex surgical steps; risk of complications; requires precise execution to avoid unnecessary damage to the palate.	[102]
	Distraction osteogenesis	Extraoral distractors	Syndromal midface retrusion, age $\leq$ 17 years	Effective for large-scale movements and severe midface deficiencies; modifications to devices could be easily achieved.	Social inconvenience due to visible devices; potential for facial scarring; compromising long-term stability; extended treatment duration.	[103,104]
		Internal distractors	Syndromal midface retrusion, age $\leq$ 25 years	Compact and less visible design; better bone anchorage; simplified activation and removal procedures.	Limited to smaller or moderate movements compared to external devices; may require advanced surgical expertise for proper placement and activation.	[103,104]
		TSDO	Maxillary retrusion with midfacial dysplasia secondary to cleft lip and palate repair	Minimally invasive; utilizes growth potential to achieve more advanced expansion.	Patient without growth potential cannot benefit; social inconvenience and discomfort.	[105–107]
		Osteotomy-assisted distraction	Maxillary hypoplasia secondary to cleft lip and palate repair, with advancement $\geq$ 6 mm	Effective for severe maxillary deficiencies and syndromic conditions; achieves significant transverse expansion.	Invasiveness; challenges with stability; requires precise surgical technique to avoid complications.	[108–110]

3.1. Skeletally Mature Adolescents

To overcome the increased bone resistance that resulted from aberrant ossification or absent sutural patency, surgical techniques have been integrated with conventional orthodontic treatment for correcting maxillary deficiency.

Due to the ambiguous diagnosis of maxillary deficiency, the indication of orthognathic surgery for maxillary expansion remains as a lack of consensus among orthodontists and surgeons. The optimal balance between extensive surgically assisted techniques for adequate mobilization and conservative orthodontic procedures with minimal complications remains inconclusive. Nevertheless, orthognathic surgery in addition to orthodontics treatment is still widely employed nowadays [111], particularly for patients with limited remaining suture growth potential. In this part, we aim to examine the literature on orthognathic surgery techniques for skeletally mature adolescents, providing a detailed exploration of their practical application scenarios.

3.1.1. Conventional Surgically Assisted Rapid Maxillary Expansion (SARME)

Originally designed to correct maxillary transverse deficiency, the conventional SARME, first introduced in 1938 by Brown et al., involves the segmental splitting of the maxilla or palatal bone [112]. It has since been renovated to improve efficiency and outcomes by reducing resistance to lateral expansion in the midface (Figure 2).

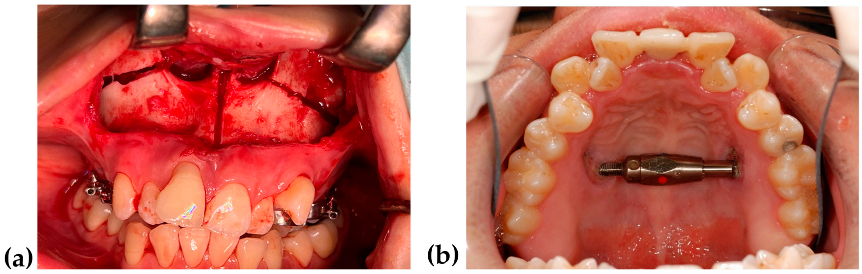

Figure 2. Bone-borne SARME. (**a**) Surgical image showing palatal segmental splitting with Le Fort I osteotomy; (**b**) intraoral image of the bone-borne expander.

By splitting the maxilla into two halves at the midline between the central incisors, the conventional SARME has proven to be a reliable method for skeletally mature, non-growing adolescents, providing transverse expansion of the dental arch, adequate space for tongue positioning, and future dental arch harmonization [113].

Conventional SARME is a straightforward and easy-to-follow procedure that requires minimal time; thus, it is a well-established and reliable surgical technique. While conventional SARME effectively addresses occlusal concerns, it compromises actual bone expansion at the palatal level. Moreover, patients often experience temporary aesthetic issues, such as midline diastema [92]. Retrospective studies have shown that the conventional two-segment SARME has minimal impact on periodontal tissues, with no significant changes in attachment levels or gingival recession observed under clinical and CBCT assessments. However, a reduction in the buccal cortex of the alveolar bone has been noted. Potential complications following the two-segment SARME include effects on the central incisors, such as tooth mobility, root resorption, discoloration, and even necrosis, due to the osteotomy being performed between the central incisors [92].

Collectively, SARME is typically chosen when the maxillary transverse discrepancy is too severe for MARPE to handle, especially in patients with significant skeletal hypoplasia or those in need of orthognathic surgery. It is also recommended for adult patients or older adolescents, as the mid-palatal suture becomes less responsive to expansion in these age groups. One of its main benefits is its ability to provide more stable and robust long-term results compared to less invasive methods like MARPE, especially in severe cases. SARME is also suitable for various age groups, particularly older patients whose mid-palatal suture has completed its growth. In addition, it can be used as an adjunctive treatment in orthognathic surgery, addressing both dental and skeletal issues simultaneously. Another advantage is its effects on facial soft tissues, as it can improve facial aesthetics by correcting skeletal discrepancies. However, SARPE requires longer treatment time, greater trauma, and a longer recovery period, making it more suitable for cases that cannot be adequately addressed by less invasive methods.

3.1.2. Modified SARME

While conventional SARME has proven effective in achieving stable maxillary transverse expansion, the development of modified SARME techniques has aimed to address specific clinical challenges. These include accommodating unique medical histories, achieving greater or more precise expansion, and meeting higher aesthetic standards. Modified SARME offers tailored approaches that decrease complication risk, enhance treatment efficiency, and expand its applicability to diverse patient needs.

The primary principle of these modified incision techniques remains consistent: to release the resistance areas in the midface that impede lateral expansion. These resistance areas are classified into four categories: anterior support (piriform aperture pillars), lateral support (zygomatic buttresses), posterior support (pterygoid junctions), and median support (mid-palatal suture) [114].

- Cortical osteotomy:

Kole et al. proposed the use of selective dentoalveolar osteotomies to section the cortical bone and reduce resistance to orthodontic movement [115]. Similarly, Converse and Horowitz et al. recommended both labial and palatal cortical osteotomies for expansion [93]. There is reason to believe that cortical osteotomy could enhance the efficiency of SARME. However, sufficient clinical research—whether through retrospective studies or randomized controlled trials—is currently lacking to provide solid evidence-based support.

- Pterygomaxillary disjunction:

Although some scholars suggest avoiding attempts to separate the maxilla from the pterygoid plates to prevent entering the pterygomaxillary junction, believing that such separation requires significant force and is prone to fractures, later studies have recognized the pterygomaxillary junction as a key resistance area [116]. In cases where pterygomaxillary disjunction was performed, the SAMRE resulted in more uniform maxillary expansion. In contrast, the SAMRE without pterygomaxillary disjunction demonstrated greater anterior maxillary expansion, confirming a V-shaped suture opening pattern, with less posterior expansion compared to the SAMRE with pterygomaxillary disjunction group [94,117]. The maxillary expansion without pterygomaxillary disjunction showed differential expansion between the anterior and posterior regions, up to 3 mm, with the anterior region expanding more than the posterior region [113]. However, some studies have suggested that pterygomaxillary disjunction might be more effective in patients over 20 years of age, but no analysis of its additional benefits for younger patients has been provided [95]. In terms of anterior-posterior analysis, maxillary expansion was greater in the alveolar bone than in the palatal region. Although significant increases in the middle and lower facial heights were observed in the SAMRE with pterygomaxillary disjunction group at the end of the activation phase, these changes were reversed and returned to baseline during the stabilization phase. Regarding the direction of bone movement, the SAMRE with pterygomaxillary disjunction group showed outward segmental tipping from anterior to posterior, whereas the SAMRE without pterygomaxillary disjunction group exhibited inward tipping [113]. For pterygomaxillary disjunction, the tipping of the teeth primarily occurred in the SAMRE without pterygomaxillary disjunction group. The SAMRE with pterygomaxillary disjunction group showed lower buccal tipping of the molars, both immediately after device removal and after a 6-month follow-up. The SAMRE without pterygomaxillary disjunction group demonstrated greater molar tipping, resulting in a larger molar expansion compared to the SAMRE with pterygomaxillary disjunction group, particularly in the dental-supported device group [113]. As for pterygomaxillary disjunction, studies found that maxillary expansion improved nasal width and respiratory function. After both the post-expansion and 6-month follow-up periods, the SAMRE with pterygomaxillary disjunction group demonstrated significantly greater nasopharyngeal volume and minimum cross-sectional area of the pharynx [118]. Pterygomaxillary disjunction also led to a significant widening of the nasal wing base, a change that persisted up to 36 months post-surgery. However, considering that the SAMRE with pterygomaxillary disjunction involves more invasive surgical procedures, complications such as bleeding, facial nerve paralysis, and maxillary sinus infections are more commonly associated with this approach.

In two recent Finite Element Analysis studies, when the pterygomaxillary plates were separated, less stress was observed on the bone and teeth. The separation of the pterygomaxillary junction in the SARME procedure helps reduce stress in the facial skeleton during maxillary expansion [119,120]. Therefore, whether applying pterygomaxillary disjunction during SARME remains a complex consideration, involving factors such as surgical strategy, expansion outcomes, and associated complications. This will be an important basis for decision making by researchers and clinicians.

- Palatal preservation:

In conventional SARME, the palatal split is a critical step for relieving resistance to maxillary expansion, as initial reports identified the mid-palatal suture as the greatest resistance to expansion [4]. However, with further understanding, it has become evident that other craniofacial sutures also serve as significant limitations to maxillary expansion. Consequently, some studies have suggested omitting the palatal split in SARME procedures. Lehman et al. argued that removing resistance at the zygomatic buttress alone is sufficient to facilitate expansion [96]. This conservative technique has been supported by other researchers as well. For instance, Schimming et al., in a retrospective study, found that performing osteotomies only at the lateral and anterior walls of the maxilla yielded satisfactory results for most patients in their study [97]. Similarly, Pogrel et al. recommended a mid-palatal cut combined with transection of the lateral support [98]. In contrast, some researchers advocate replacing the single midline split of the maxilla with two paramedian palatal osteotomies extending from the posterior nasal spine to a point just posterior to the incisive canal.

- Segmental Le Fort I osteotomy:

Betts and Ziccardi et al. recommended a comprehensive bilateral maxillary osteotomy extending from the pyriform aperture to the pterygomaxillary fissure, accompanied by a mid-palatal split from the anterior to the posterior nasal spines [121]. This approach involves sectioning all articulations and areas of resistance, including anterior, lateral, posterior, and median supports of the maxillary arch. Combining a Le Fort I osteotomy with a sagittal osteotomy of the mid-palatal suture proved to be the most effective surgical method for maxillary expansion. Landes et al. introduced a three-segment osteotomy involving bilateral transalveolar osteotomies between the lateral incisors and canines [99]. Compared to the conventional two-segment SARME, the three-segment technique offers several advantages: (1) Reduced aesthetic compromise, as the expansion space is divided into interproximal spaces between the lateral incisors and canines rather than forming a prominent midline diastema; (2) Less disruption of the midline dental papilla, particularly for adolescent patients; (3) Preservation of the nasopalatine bundle; (4) The possibility of performing asymmetric expansions in a conservative manner. However, a systematic review found no statistically significant difference between two-segment and three-segment techniques regarding maxillary expansion symmetry [113,122,123]. But the three-segment

SARME demonstrated greater transverse expansion, as well as increased dental tipping, as the central incisors and canines exhibited greater inward angulation, and the lateral incisors angled outward more prominently. The position of the postoperative diastema in three-segment SARME is between the lateral incisors and canines, which had a better psychological impact on patients because of better aesthetic outcomes. When it comes to upper airway, Prado et al. reported that the three-segment technique resulted in less increase in nasal width, but larger transverse displacement in the paranasal area [100]. Skeletal stability was similar between the techniques, with no significant relapse observed after six months of follow-up. However, Da Costa et al. reported a unilateral posterior crossbite relapse in 6.2% of patients who underwent the three-piece technique and 4.8% of those who underwent the two-segment technique one year postoperatively [101].

3.2. Adolescents with Congenital Conditions or Treatment Challenges

Transverse discrepancies are a common feature of malocclusion and are frequently associated with congenital facial anomalies, including cleft lip and palate [124]. Correction of maxillary deficiency individuals with congenital conditions or severe challenges involves critical clinical considerations, particularly with respect to functional improvements. These include enhancing tongue space and achieving proper arch coordination, which are essential for long-term oral and systemic health.

For adolescents with severe transverse discrepancies and complex medical conditions that cannot be effectively managed through previously mentioned SARME techniques, segmental maxillary surgery with simultaneous posterior segment expansion offers a viable alternative. This approach allows for precise correction of transverse deficiencies, accommodating the unique anatomical and functional needs of this patient population.

3.2.1. Palatal Segmental Osteotomy

Palatal osteotomy is typically incorporated into the Le Fort I maxillary osteotomy. While not initially intended to address transverse maxillary deficiencies, this approach allows the maxilla to be segmented from its down-fractured position to facilitate expansion or manage orthodontic arch discrepancies. To achieve more advanced transverse maxillary expansion, a midline osteotomy of the palate can be performed. As an improvement over the conventional single midline palatal osteotomy, a 'U-shaped' palatal osteotomy can be conducted in the central palate and mobilized using an osteotome [102]. The midline or para-midline interdental osteotomy sites are then connected to the palatal osteotomy, and fine osteotomes are employed to finalize the interdental osteotomies, allowing for the mobilization of the dentoalveolar segments.

3.2.2. Distraction Osteogenesis

With conventional surgical methods, there are limitations of the extent of possible movement, and reliance on the comprehensive conditions of patients. Apart from bony status, soft tissues, particularly in cases involving clefts or scar tissue from multiple surgeries, can present further challenges. Therefore, distraction osteogenesis offers an alternative surgical approach, providing optimized outcomes with improved stability and simplified procedures [125]. Although the primary goal of distraction osteogenesis is to address sagittal deficiencies, clinical cases have demonstrated incidental transverse expansion during the process.

- Extraoral vs. internal maxillary distractors:

Two primary approaches to distraction osteogenesis in the craniofacial region have been described: extraoral and internal maxillary distractors [103,126]. Extraoral distractors typically involve a semicircular metal frame affixed to the skull using multiple screws.

A vertical bar connects this frame to facial plates via wires and coils, generating the anteroposterior forces required to advance the midface. Various modifications have been introduced by manufacturers to enhance skull stability, vector control, attachment methods, and connectors. However, these devices come with significant drawbacks, including social inconvenience, facial scarring, and, critically, the premature removal of distractors before completing the distraction consolidation phase. This latter issue, especially in cases requiring large movements and extended treatment durations (up to a year), compromises long-term stability.

In contrast, internal maxillary distractors consist of a compact design with a barrel mechanism activated between anterior and posterior plates for bone fixation. Continuous innovations in design aim to improve bone anchorage, simplify activation and removal, and enhance vector control.

- Trans-suture distraction osteogenesis:

Distraction osteogenesis can also be classified into two types based on whether osteotomy is performed. Trans-suture distraction osteogenesis (TSDO), which the growth potential of cranial sutures is taken advantage of without an osteotomy, is a minimally invasive, non-osteotomy traction technique designed to effectively address midfacial dysplasia [105]. By utilizing a rigid external distraction system equipped with a nickel–titanium-shape memory alloy spring and bone-borne traction hooks anchored to the lateral nasal wall, this approach allows for significant advancement of the midfacial skeleton along with concurrent maxillary expansion (Figure 3).

- Osteotomy-assisted distraction:

(a) (b)

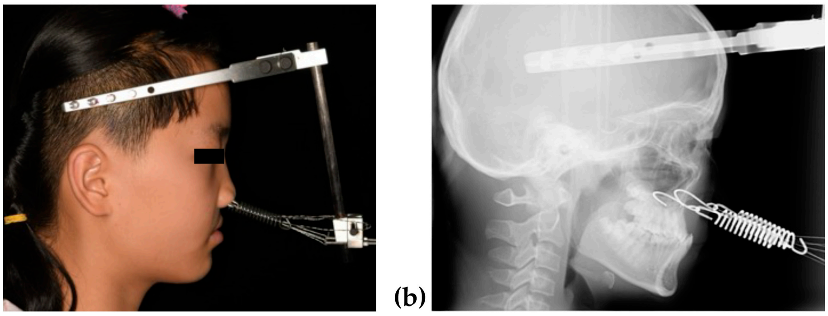

Figure 3. Rigid external distraction system of TSDO. (**a**) Patient wearing a rigid external distraction system featuring a nickel–titanium-shape memory alloy spring and bone-borne traction hooks; (**b**) cephalometric radiographic image displaying the traction hooks anchored to the lateral nasal wall of the maxillary sinus.

Osteotomy-assisted distraction, where bone is surgically separated, is common for achieving maxillary advancement in adolescent patients with severe maxillary deficiencies, sleep apnea, prior failures in maxillary advancement, anatomical limitations for traditional surgery, or syndromic deficiencies [108]. According to a systematic review evaluating 129 cases of maxillary distraction osteogenesis, approximately 55.7% of patients aged 5–13 underwent incomplete Le Fort I osteotomy [109]. In contrast, for other age groups, maxillary distraction osteogenesis with complete Le Fort I osteotomy remains the predominant approach.

Regarding the transverse effects of maxillary distraction osteogenesis, reports indicate that even with incomplete Le Fort I osteotomy, where the anterior (piriform aperture), lateral (zygomatic buttress), and median (mid-palatal suture) bony supports of the maxilla are osteotomized, transverse maxillary expansion can be achieved. Another study involving 276 cases found that 10 cases specifically focused on transverse maxillary expansion, with the majority achieving 5–9 mm of expansion [110]. While all patients included in this study had cleft lip and palate, it was noted that distraction in the transverse dimension resulted in significant maxillary expansion without creating an oro-nasal fistula.

This outcome contrasts with conventional orthognathic approaches for cleft deformities, where large transverse expansions are generally discouraged due to high relapse rates caused by palatal scar tension. Nonetheless, small-scale transverse expansions are technically feasible during conventional osteotomy procedures. Thus, it can be concluded that while the primary maxillary distraction osteogenesis may not be transversely directed, the transverse effects should not be overlooked. Instead, they should be acknowledged and effectively utilized to optimize treatment outcomes.

4. Comprehensive Clinical Consideration

Based on the summary shown in Table 1, for children in primary and early mixed dentition, the appliances with the SME protocol, such as the quadhelix and removable expansion plate, provide gentle force, enabling effective expansion, but these appliances primarily induce dental rather than skeletal changes. For preadolescents in late mixed dentition and early adolescents, tooth-borne and tooth-tissue-borne expanders, including the HYRAX and Haas expanders, achieve greater skeletal expansion through sutural separation. Despite their efficacy, concerns such as significant relapse remain when using the RME protocol. For middle to late adolescents, bone-borne expanders and tooth-bone-borne expanders like the MSE, C-expander, ATOZ expander, and Hybrid HYRAX generate superior skeletal expansion with fewer dentoalveolar effects.

As summarized in Table 2, regarding skeletally mature adolescents, conventional SARME is a straightforward and efficient procedure with minimal long-term impact on periodontal tissues, though it presents temporary aesthetic concerns and limited palatal bone expansion. Modifications such as cortical osteotomy, pterygomaxillary disjunction, and palatal preservation aim to enhance efficiency, respiratory function, and surgical invasiveness, but they are associated with increased complications, resistance concerns, and a lack of strong evidence. Segmental Le Fort I osteotomy is particularly beneficial for asymmetric expansions and dental alignment while minimizing midline disruption, though it carries risks of relapse and surgical complexity. For adolescents with congenital conditions or complex treatment needs, palatal segmental osteotomy provides precise control over dentoalveolar segment movement but demands advanced surgical execution. Distraction osteogenesis, using extraoral or internal distractors, enables substantial skeletal movement for severe deficiencies, with internal distractors offering better aesthetics and anchorage. However, external distractors pose social and scarring concerns, and both approaches require extended treatment durations. Osteotomy-assisted distraction and TSDO are viable for significant transverse expansion in severe maxillary deficiencies, but their stability, invasiveness, and effectiveness in non-growing patients remain key challenges.

5. Conclusions

Adolescent maxillary expansion serves as a cornerstone in managing craniofacial and dental conditions, affecting aesthetics and function, and requires timely and targeted intervention during the critical growth period to maximize treatment outcomes.

Briefly, orthodontic techniques effectively address common transverse deficiencies, while surgical approaches are indispensable for complex or multidimensional cases, offering superior skeletal corrections and minimizing adverse effects.

6. Outlook

Further advancements in treatment approaches should focus on enhancing the predictability and efficiency of these techniques. In particular, research on the correlation between palatal suture maturation and other clinical indicators can guide the selection of appropriate orthopedic approaches. Additionally, further research is warranted to refine protocols that integrate both orthopedic and surgical approaches, ensuring comprehensive management of complex craniofacial anomalies.

It is also hoped that high-quality research in related fields will be further advanced through efforts in the future, together with peers, providing stronger evidence-based support. Ultimately, these efforts will lay the foundation for systematic reviews and contribute to the development of clinical guidelines in this field.

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