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Biomechanical Considerations in Clear Aligner Therapy: Force Delivery, Movement Control and Their Clinical Implications.

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ABSTRACT

Clear aligner therapy (CAT) has evolved as a viable orthodontic treatment approach as digital technology, biomaterials, and biomechanical principles have advanced over time. It was originally used for mild malocclusions, but improvements in aligner design, attachments and digital treatment planning have led to its use in more complex orthodontic situations. This review will present biomechanical principles that define force delivery and tooth movement control and their clinical implications in challenging patients treated with the use of clear aligners. The effects of aligner material properties, thickness, stress relaxation, staging protocols, and attachment design on the magnitude, direction, and predictability of force are discussed. The biomechanical properties of different tooth movements, such as tipping, bodily movement, rotation, intrusion, extrusion, torque and arch expansion are evaluated, highlighting limitations and opportunities for improving treatment outcomes.

Keywords: Clear aligner therapy (CAT), Orthodontic biomechanics, Force delivery

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INTRODUCTION

Clear aligners were previously used to correct minor anomalies in tooth position, but with the emergence of numerous technological tools and the rise of digital assistance, they have improved as potential solutions for treating complex malocclusions. Advances in computer-aided design and manufacturing (CAD/CAM) have contributed to the increased demand for plastic systems in dentistry. In 2005, Djeu et al. reported that first-generation Invisalign had minimal efficacy. The second-generation Invisalign included auxiliary components, including composite buttons and intermaxillary elastics, to improve orthodontic tooth movement. The third generation improved on this strategy by offering optimized attachments that are automatically fitted by the manufacturer's software, improving tooth movement control by responding to individual tooth shape [1]. For clear aligners to be effective, patients must wear them regularly and for at least 22 hours per day. Treatment may not be successful or take longer if aligners are not used as directed. These aligners were made of thermoplastic and were designed to gently reposition the teeth into the proper position [2].

In 1946, Kesling developed a concept of using several sets of thermoplastic tooth positioners, which led to the introduction of clear overlay orthodontic appliances. In 1997, Align Technology (Santa Clara, Calif.) developed the clear aligner therapy (CAT), making Kesling's concept an effective orthodontic treatment option [3]. The need for aesthetic appeal and comfort has driven the constant improvement and modification of clear aligners (CAs), though gradually and over time. CAs' superior vertical control performance has, in some situations, given treatment choices that better fulfill the requirements of both patients and orthodontists. Kwon et al. (2008) showed evidence of the force and energy transfer properties of transparent aligner materials. Simon et al. (2014) used a measuring and sensor system to determine the forces and moments associated with three types of tooth movements. Because of its noninvasive and accurate properties, an increasing number of researchers have recently preferred finite element analysis as a means of simulating tooth movement and evaluating stresses generated within periodontal tissues [4].

Clear aligners are usually made by scanning plaster casts for a virtual layout. The usual virtual layout shows moving crowns but neither roots nor jaws. In contrast, three-dimensional (3D) computerized models with roots facilitate evaluation of root positions in the jaws, assuring root parallelism and avoiding fenestration and dehiscence [6]. Fine element analysis permits the creation of many different simulations with tightly controlled variables and high reproducibility, resulting in an appropriate database for future clinical trials and avoiding unnecessary duplication (Romanyk et al., 2020; Liu et al., 2022) [7].

The disadvantages of ordinary thermoformed aligners include considerable geometric inaccuracies, dimensional instability, low strength, and lower wear resistance. These issues could be due to the materials chosen or the thermoforming process itself. Several studies demonstrate that thicker aligners generate greater force delivery. Directly 3D-printed aligners (DPAs) deliver more consistent and lower forces than thermoformed counterparts, bringing them closer to Proffit's optimal range. It is possible to attain higher dimensional accuracy and more optimal force ranges for tooth movement [8].

The 3D mechanical measurement platform with several sensors enables the analysis of force and moment variations on many teeth under different materials or force application schemes [9]. Vertical alterations ranged from 0.9 mm to 1.5 mm, while anteroposterior (AP) movement by maxillary molar distalization was highly predicted (88% accuracy) with at least 1.5 mm of translation [10]. Clinical solutions have evolved from optimizing individual to optimizing group teeth movement, while clinical indications have expanded from simple to complex cases, including surgical cases [11]. AI-powered orthodontic planning software can simulate and change force vectors depending on a patient's unique dental and periodontal characteristics, providing a more personalized approach to attachment placement. When used Strategically, these auxiliaries can give improved anchoring, greater vertical and sagittal control, and assist movements [12].

The literature has revealed proper explanations for the difficulty of root movements, which involve significant bone remodeling, and extrusive movements, which rely on pull forces [13]. In vivo studies have shown that simple movements, such as pure translations, frequently result in a combination of translation and unintentional crown torque, with insufficient root control[14]. Tweed suggested premolar extractions as a response to the adverse impacts of non-extraction treatments. Clear aligners were used to treat difficult malocclusions, including premolar extractions, as patient demand increased [15]. The introduction of rapid prototyping (RP) techniques enabled an industrial approach to both orthodontic treatment planning and polymeric aligner manufacture [16]. Hayashi proposed an entirely new method for studying the complex movement of teeth in three dimensions [17]. Radicular control movements often have a predictability of less than 50%. One of the most popular CAT-based maxillary molar distalization procedures is the stepwise distalization approach with Class II elastics. The CAT sequential distalization procedure, on the other hand, achieves only limited molar distalization. At the crown level, up to 2.25 mm distalization of the maxillary first molar (U6) mesial buccal cusp has been documented. However, the minimum reported amount of molar distalization was 0.25 ± 0.63 mm, just 6.8% of the projected amount of anteroposterior correction [18].

FORCE DELIVERY IN CLEAR ALIGNERS:

Mechanism of force generation:

CA has the largest orthodontic force at first, which gradually reduces by 20%-30% on the second day and remains consistent for over two weeks[1].Orthodontic forces are caused by a complex pattern of mismatches between plastic and tooth structure. This pattern is crucial for attachment design during digital simulation to create specific areas with active surfaces. The aligner plastic will be contacted with predefined force magnitudes, resulting in appropriate force vectors and tooth movements. In 2020, an in vitro investigation compared the mechanical properties of CA before and after 2 weeks of wear. While the material maintained its elastic modulus and stress relaxation, its surface morphology revealed imperfections that could release allergenic elements[2].Aligner material and thickness are two of the most important elements influencing the biomechanics of transparent aligners, and hence the force magnitude supplied to the teeth. Aligner thickness is a significant influence of force delivery and stress relaxation rate.[11]

Aligner-based orthodontic treatment achieves tooth movement through a series of custom-made, sequential aligners, with each aligner producing small, controlled positional changes in the teeth. These incremental movements occur through two primary biomechanical mechanisms.[11]

1. The shape molding effect: The mechanism of aligner therapy is based on guiding tooth movement through the programmed geometry of a series of customized aligners. Each aligner incorporates a predetermined discrepancy, or activation, between its internal surface and the existing morphology of the dental crowns. This mismatch generates three-dimensional force systems that are transmitted across the tooth–aligner interface, creating areas of intimate contact and relief that facilitate controlled tooth movement. Complete orthodontic treatment is accomplished using a sequence of aligners with progressively modified geometries, enabling the gradual transition of teeth from their initial positions to the planned final alignment.
2. Auxiliary elements: Auxiliary elements, including attachments and power ridges, are incorporated into aligner therapy to improve the predictability and efficiency of specific tooth movements. These auxiliaries are strategically positioned either on the aligner or bonded directly to the tooth surface to optimize force application. By modifying the interaction between the aligner and the tooth, they facilitate precise force transmission and improve control over complex tooth movements, thereby enhancing the overall effectiveness of treatment.[11]

Effect of attachments on force delivery:

Attachments consist of three main components: an active surface, a passive surface, and a base. The aligner exerts pushing pressures on the active surface. The orientation of the surface dictates the direction of force vectors. Efficient vectors are typically perpendicular to the active surface. The attachment's passive surface, located on the buccal face, ensures stability and little interference when fitting the aligner. A limited volume passive surface can increase the danger of fractures, wear, and attachment separation, reducing durability. Attachments made of composite materials are prone to surface texture wear over time, making this especially crucial. Bevelled attachments have a higher angle of emergence, making it easier for teeth to glide into the aligner during the first few hours of use.

When filler content exceeds 72%, the attachment's bonding effectiveness does not improve significantly. Flowable composites or orthodontic bonding composites are the preferred materials for bonding attachments.

According to the study by Ahmad et al., the effects of attachment size are listed as follows:

1. The force and the moment increase with the thickness, length, and width of the attachment.
2. The attachment size has only a mild effect on moment/force.
3. The direction of force is better aligned with the desired movement direction when a larger attachment size is used.
4. The appropriate force magnitude can be obtained by selecting the right attachment size.

Attachments Based on Their Function:

Attachments are characterized as active or passive according to their function. Attachments can improve aligner retention (passive attachment) or promote tooth movement (active attachment).

Conventional and Optimized Attachments:

Another classification differentiates between optimized and ordinary attachments. The Invisalign system uses optimized attachments, which vary in shape based on tooth morphology and movement. Conventional attachments refer to those that are not particular to a tooth or movement.

Types of attachments that can be used for different types of movements:

Extrusion

Horizontal rectangular attachments, optimized extrusion attachments. When extruding incisors, focus on the active surface at the apex. Optimized designs may provide symmetrical force transfer during attachment placement.

Intrusion Horizontal rectangular attachments. Attachments can be utilized on adjacent teeth to improve plate stability during intrusion. For balanced force distribution, choose attachments with large and wide surfaces.

Expansion -Occlusally inclined attachments, cylindrical. Add occlusally slanted attachments to molars to prevent uncontrolled buccal tilting during arch extension. To ensure controlled movement of teeth, additional torque support may be essential.

Rotation -Vertical rectangular attachments, optimized rotation attachments. For rotation movements, attachments designed for lateral incisors can be utilized. Conical teeth, like canines, benefit from attachments with flat surfaces.

Distalization- Vertical rectangular attachments, guideline attachments. Attachments should be placed on both the buccal and palatal surfaces of upper molars during distalization. Double-sided attachments are recommended to avoid tipping during distalization.

Torque -Semi-ellipsoid attachments, horizontal attachments, power ridge. For torque motions of maxillary incisors, attachments close to the gingiva are recommended. Canine teeth benefit from palatally placed cylindrical attachments. Torque motions require extensive preparation as tooth movement sometimes lags behind.[5]

Attachment Type	Description / Shape	Recommended Activation	Over-Engineered Activation
Horizontal rectangular attachment	Horizontal rectangular attachment	0.25 mm displacement from the facial surface	2.0 mm displacement from the facial surface
Vertical rectangular attachment	Vertical rectangular attachment	0.20 mm displacement from the facial surface	2.0 mm displacement from the facial surface
Rectangular attachments placed on the lingual surface	Multiple rectangular attachments on the lingual surfaces	0.25 mm displacement from the lingual surface	4.0 mm displacement from the lingual surface
Optimized rotation attachment – maxillary canine	Optimized rotation attachment	Clear aligner provides planned tooth movement	Clear aligner provides increased facial movement
Optimized root control attachment – maxillary canine	Optimized root control attachment	Clear aligner provides planned tooth movement	Clear aligner provides increased facial movement
Incisally inclined attachment	Incisally inclined attachment	0.25 mm displacement from the facial surface	0.40 mm displacement from the facial surface
Occlusally inclined attachment	Occlusally inclined attachment	0.25 mm displacement from the facial surface	4.0 mm displacement from the facial surface
Optimized buccal attachment	Optimized buccal attachment	0.25 mm displacement from the facial surface	3.0 mm displacement from the facial surface
Optimized occlusal attachment	Optimized occlusal attachment	Clear aligner provides planned tooth movement based on preactivation	Clear aligner provides increased occlusal movement

Material properties influencing force magnitude and decay:

Aligners are known to do the following: (i) apply low force; (ii) work better with less activation; (iii) exhibit low flexibility; and (iv) undergo rapid force decay

The material composition of clear aligners plays a critical role in determining their mechanical behavior and clinical performance. Polyethylene terephthalate glycol (PET-G) is the most commonly used thermoplastic material in commercially available aligner systems. However, other materials, including polypropylene (PP), polycarbonate (PC), thermoplastic polyurethane (TPU), ethylene-vinyl acetate (EVA), and various proprietary polymer blends, are also employed by different manufacturers. Since its introduction in 2013, thermoplastic polyurethane has gained widespread acceptance because of its favorable mechanical properties, including enhanced elasticity, durability, and force delivery, making it a preferred material for aligner fabrication.

Clear aligners are manufactured in a range of thicknesses, typically between 0.50 mm and 1.50 mm. Variations in aligner thickness, together with the type of polymer used, influence stiffness, force magnitude, stress relaxation, and overall treatment efficiency. Consequently, both material composition and thickness are important determinants of the biomechanical performance of aligner systems.[19]

Clear aligners undergo stress relaxation and creep**,** causing gradual force decay that may reduce treatment efficiency and contribute to unwanted effects. Multilayer aligners show lower stress relaxation and better force stability than single-layer materials**,** providing more consistent orthodontic force delivery.[17]

From an esthetic perspective, clear aligners should maintain excellent transparency and color stability throughout the recommended wear period, which is generally 1–2 weeks per aligner. Preserving optical clarity during this interval is essential for ensuring patient satisfaction and maintaining the esthetic advantages that contribute to the popularity of aligner therapy.[19]

Shou-Min Chen et al(2023),found out that exposure to moisture and mechanical loading accelerates the degradation of thermoplastic aligner materials. Nevertheless, no significant increase in the residual orthodontic force was observed following simultaneous water immersion and mechanical loading. In polyethylene terephthalate glycol (PET-G), the amorphous regions of the polymer absorb water, which acts as a plasticizing agent and lowers the glass transition temperature (Tg). As the material approaches its Tg, its elastic modulus decreases, leading to reduced stiffness and less predictable force delivery during orthodontic treatment.[20]

Irreversible deformation of thermoplastic aligner materials alters the intermolecular interactions within the polymer matrix, resulting in permanent structural changes at the microscopic level. Prolonged application of orthodontic forces increases the likelihood of such permanent deformation, which may adversely affect the mechanical properties of the aligner. [20]

Effect of aligner thickness on force delivery

Studies have suggested that the optimal activation increment for clear aligners ranges between 0.20 and 0.50 mm to achieve efficient and biologically acceptable tooth movement. Furthermore, Hertan *et al.* reported that directly three-dimensional (3D)-printed aligners produce significantly lower orthodontic forces than conventional thermoformed aligners. Based on these findings, the present study selected an activation increment of 0.50 mm for directly printed aligners (DPAs), representing the upper limit of the recommended activation range for thermoformed aligners to ensure adequate force delivery.[11]

The biomechanical performance of directly three-dimensional (3D)-printed aligners can be optimized by modifying their thickness and surface geometry. Strategic increases in aligner thickness on the surface opposing the intended tooth movement, as well as around adjacent anchorage teeth, can improve the distribution of orthodontic forces and moments, magnitudes and more controlled force application compared with thinner aligners, thereby improving the efficiency and predictability of treatment.[11]

Optimal force levels

Compared with fixed orthodontic appliances, clear aligners demonstrated lower overall tooth movement accuracy; however, aligners with a 0.35-mm staging interval achieved the highest movement precision. Under high orthodontic forces, fixed appliances were associated with greater tissue damage, whereas aligners primarily resulted in minor discrepancies in tooth movement, indicating a more favourable safety profile.[9]

Root resorption was observed only under heavy force conditions, highlighting the importance of controlling force magnitude during treatment. These findings suggest that a 0.35-mm staging interval is both safe and effective and may serve as an alternative to the conventional 0.25-mm staging protocol. Nevertheless, because the oral environment is highly complex and influenced by multiple biological and mechanical factors, further clinical studies are required to validate these findings and optimize aligner treatment protocols[9]

Aligner retention and Gripping force

Gripping force refers to the force required to retain an object securely or prevent its displacement. In clear aligner therapy, retention is the ability of the aligner to remain firmly engaged on the teeth throughout wear. The magnitude of this retention is influenced by several factors, including tooth morphology, tooth position, the severity of malocclusion, aligner material properties, and the duration of aligner use.[5]

Previous studies have demonstrated that thicker aligner materials and extended aligner margins significantly increase retention. Similarly, increasing the number of attachments enhances aligner retention but also increases the force required for aligner removal. Consequently, excessive attachment use may reduce patient comfort and compliance by making aligners more difficult to insert and remove.[5]

Takara et al. reported that clear aligner retention depends on the location, morphology, and undercut area of attachments. Increasing the size of rectangular and semicircular attachments improved gripping force, while larger undercuts enhanced retention but also increased aligner deformation, emphasizing the need to balance retention with material distortion in attachment design.[5]

MOVEMENT CONTROL IN CLEAR ALIGNERS:

Tipping:

Conventional vertical attachment increases mesiodistal angulation and conventional horizontal attachments increase vestibulo-lingual inclination[7].Vertical rectangular attachments are recommended when large amounts of root movement are planned, and their presence improves the ability to translate the root apex. Future research should be directed at lower incisor extraction cases in which large amounts of root movement are required to achieve root parallelism and stable treatment outcomes[22].Mesio-distal translation of the incisal edge showed the highest predictability, with 0.7 mm achieved for every 1 mm of movement predicted[16].Simple tipping of anterior teeth can lead to pseudo correction of the overbite, known as the “drawbridge effect.” This impact does not involve a “true” intrusion of anterior teeth (a movement along the longitudinal axis of teeth) but rather just a relative movement of the incisor crown downward and backward.[19]

The limited ability of clear aligners to achieve effective root control is largely attributed to the inherent mechanical properties of the thermoplastic materials from which they are fabricated. Consequently, controlled tipping is the most predictable and readily accomplished tooth movement with aligner therapy. This biomechanical characteristic should be carefully considered during case selection and treatment planning. Malocclusions that can be corrected primarily through tipping movements—such as dental crowding, spacing, anterior open bite, deep bite, and transverse arch constriction—generally demonstrate greater treatment predictability and more favorable clinical outcomes with clear aligners than cases requiring substantial root movement or torque control[19].

Intrusion:

Clear aligners (CAs) are capable of achieving anterior intrusion without the use of attachments. However, intrusion with aligners alone may result in stress concentration in the cervical region of the incisors, irrespective of tooth inclination. This may lead to undesirable biomechanical effects, including lingual tipping, incisor extrusion, posterior mesial tipping, posterior intrusion, and the development of a buccal open-bite tendency.[1]

To improve biomechanical control, adjunctive mechanics such as intermaxillary elastics supported by temporary anchorage devices (TADs) or mini-screws are frequently employed to facilitate anterior intrusion while simultaneously providing palatal root torque. These auxiliaries help minimize incisor extrusion and lingual tipping. Nevertheless, conventional labial elastics may increase stress concentration at the incisor roots, whereas linguo-incisal elastic configurations have been shown to reduce the risk of root resorption and alveolar bone defects. In addition, the incorporation of optimally designed lingual attachments enhances rotational control during intrusion and minimizes unwanted tooth movements.[1]

In contrast, posterior intrusion has received comparatively less attention in the literature. Available evidence indicates that intrusion of the maxillary second molar using buccal or palatal attachments on the adjacent first molar is consistently associated with mesial tipping of the second molar as an unintended effect. Among the attachment configurations evaluated, the use of attachments on both the buccal and palatal surfaces produced the greatest intrusive effect, minimized buccolingual tipping, and promoted a more uniform stress distribution within the periodontal ligament, thereby offering superior biomechanical performance.[1]

Extrusion:

Anterior extrusion is commonly incorporated into clear aligner treatment to correct anterior open bites or to compensate for unwanted intrusive effects. This movement is typically facilitated by the use of buccally placed attachments on the target teeth to improve force application and movement predictability. In the studies included in this review, all extrusion protocols employed attachments, although their configurations—including shape, size, and position—varied considerably. Anterior extrusion also plays an important role during space closure following tooth extraction, particularly in controlling vertical tooth position. Furthermore, extrusion of mandibular incisors has been reported to be more efficient than that of maxillary incisors under comparable treatment conditions. Attachment design significantly influences the biomechanics of tooth extrusion by altering force distribution and movement efficiency. Laohachaiaroon et al. (2022) found that horizontal rectangular attachments generated the highest stress concentration, making them most effective for extrusion, while Kim et al. (2020) reported that oblique attachments produced the greatest contact pressure and the most controlled vertical tooth movement, highlighting the importance of attachment geometry in extrusion biomechanics.[1]

Rotation:

To improve rotational predictability with clear aligners, the round-tripping approach has been proposed, where initial proclination creates interproximal clearance, followed by rotation during retraction. This reduces contact interference and improves aligner engagement but increases the number of aligners and treatment duration, often requiring refinement due to residual spaces. Mesiodistal compensatory movements, along with overexpansion, IPR, and sequential staging, further enhance rotational control. Advances in aligner materials, including shape-memory polymers (Graphy®), SmartTrack®, and SmartForce® technologies**,** improve adaptation, force delivery, and predictability of tooth movement.[4]

Translation/ Bodily Movement:

The biomechanics of clear aligner therapy are influenced by the relationship between the point of force application and the tooth's center of resistance. As the distance between these two points increases, the generated moment also increases proportionally, producing root rotation in the direction of the applied force. Owing to their limited ability to generate effective force couples, clear aligners alone are generally less effective in achieving precise mesiodistal root movement and second-order tooth control, particularly for correcting the angulation of anterior teeth.[1]

To overcome this limitation, specially designed attachments are incorporated into aligner therapy to generate additional force couples, thereby improving root control and facilitating more bodily tooth movement. Several studies have reported that the use of attachments enhances second-order control and increases the predictability of bodily movement. However, conflicting evidence exists, as Goto *et al.* observed that the incorporation of attachments did not significantly influence tensile forces or tipping moments. These inconsistent findings indicate that the biomechanical effectiveness of attachments may depend on factors such as attachment design, location, aligner material, and the specific tooth movement being performed.[1]

Torque:

Achieving effective maxillary incisor root torque remains one of the major biomechanical challenges in clear aligner therapy. The flexibility of thermoplastic aligner materials, combined with the anatomical morphology of tooth crowns, often results in uncontrolled crown tipping rather than the intended root movement. To improve torque expression, auxiliary features such as power ridges (PRs) and composite attachments have been incorporated into aligner systems. Finite element analyses, including the study by Sandhya et al**.**, demonstrated that aligners incorporating power ridges produced greater root movement than aligners without auxiliaries. Clinical investigations have reported comparable torque accuracy between aligners with and without power ridges, suggesting that the effectiveness of these auxiliaries in achieving predictable torque control may be influenced by additional clinical and biological factors.[23]

- The Invisalign appliance expressed 41.9% of the planned torque correction in maxillary central incisors among patients requiring a minimum of 10° of lingual root torque movement.
- Approximately 80% of maxillary central incisors demonstrated clinically significant underexpression of the prescribed torque movement, with an average discrepancy of ≥5° from the planned outcome.
- No statistically significant difference was observed between weekly and fortnightly aligner wear protocols (WP) regarding the accuracy of maxillary central incisor torque expression.
- The presence or absence of power ridges (PRs) incorporated in the aligner wear protocol did not significantly influence the accuracy of maxillary central incisor torque expression.23

CLINICAL IMPLICATIONS IN CHALLENGING CASES:

Non-Extraction

Kassas et al, reported that clear aligner therapy is effective in achieving leveling and alignment of the dental arches in patients with mild to moderate malocclusions, as well as in correcting buccolingual tooth inclinations. However, the authors noted that clear aligners are less effective in establishing ideal occlusal contacts. This limitation was attributed to the thickness of the aligners, which may interfere with the natural settling of the occlusion during treatment[25]

Interproximal reduction (IPR) is indicated in several clinical situations, including the correction of Bolton tooth-size discrepancies resulting from missing or malformed teeth, the management of gingival embrasure defects (black triangles) associated with periodontal tissue loss, and cases exhibiting unfavorable crown morphology, particularly when contact points are positioned close to the incisal edge.

In general, interproximal reduction (IPR) is performed primarily in the anterior segment when required to create space and facilitate tooth alignment. It is recommended that the amount of IPR be limited to a maximum of 0.25 mm per proximal surface of each tooth. Evidence suggests that IPR involving up to 50% of the enamel thickness does not significantly increase the risk of dental caries when performed appropriately.[9]

Extraction

Weihong et al, evaluated the effectiveness of the Invisalign system on mild to moderate cases treated with premolar extractions and compared the treatment results obtained with fixed appliances. Their results revealed that both systems can be used in the treatment of extraction cases, and that root angulation attained with clear aligners are adequate when proper attachments are to be used. However, it should be kept in mind that treating extraction cases requires experience and extensive knowledge of the system. Retrusion of mandibular central incisors is considered to be the most accurate single-tooth movement, whereas the rotation of mandibular canine is the least accurate movement.[25]

Two types of tooth extraction patterns are commonly used in clear alignment treatment: extraction of lower incisor and extraction of premolars (first or second).

Tooth extraction is a widely used space-gaining approach in orthodontic treatment and is primarily indicated when the discrepancy between the available arch space and the space required exceeds 8 mm**,** as seen in cases of severe dental crowding or pronounced maxillary and/or mandibular protrusion. In clear aligner therapy, the most commonly employed extraction protocols include mandibular incisor extraction and premolar extraction (either first or second premolars), depending on the patient's malocclusion and treatment objectives.

Mandibular Incisor Extraction

1. **Indications:**

   Mandibular incisor extraction is indicated in patients with a nearly normal facial profile, stable posterior occlusion, no requirement for maxillary extractions, and a mandibular space deficiency exceeding 6 mm**.** It is also considered in cases with Bolton tooth-size discrepancies resulting from missing or malformed maxillary teeth, or when a mandibular incisor has a poor prognosis because of periodontal disease or traumatic injury.

2. **Final Position Planning:**

   Following mandibular incisor extraction, the lower dental midline is absent. Consequently, the long axis of the remaining mandibular central incisor is generally used as the reference for the lower midline. Interproximal reduction (IPR) of the maxillary anterior teeth is often required to compensate for the Bolton discrepancy and to establish appropriate overjet and overbite relationships.

3. **Attachment Design:**

   Vertical rectangular or root-control attachments are recommended on the teeth adjacent to the extraction site to facilitate controlled reciprocal tooth movement, particularly root movement, thereby improving space closure.

4. **Staging Considerations:**

   Mandibular incisor extraction effectively alleviates anterior crowding and creates space for the intrusion of the lower anterior teeth, contributing to a high treatment success rate. Consequently, no special staging protocol is generally required during clear aligner therapy.

Extraction of the First Premolars

Extraction of all four first premolars is the most frequently used extraction protocol in orthodontics, following the principle of symmetry. However, this treatment approach is regarded as one of the more complex procedures in clear aligner therapy (CAT), requiring significant clinical expertise to achieve predictable outcomes.

1. **Indications**

   Extraction of the four first premolars is generally indicated when the discrepancy between the available arch space and the space required exceeds 8 mm**,** as commonly seen in patients with severe dental crowding, bimaxillary protrusion, or similar conditions.

2. **Considerations for Final Position Design**

   Orthodontic treatment involving premolar extractions is particularly challenging because it requires extensive three-dimensional tooth movement. Successful treatment depends on maintaining proper anterior torque while preventing unwanted mesial tipping of the posterior teeth. Consequently, overcorrection should be incorporated into the digital treatment plan to compensate for the limitations of aligner biomechanics.

- **Anterior teeth:** During retraction, the incisors should be planned with a slight labial inclination, maintaining an interincisal angle of approximately 120°**,** to minimize excessive lingual tipping. Adequate root-lingual torque should be incorporated throughout the retraction phase, particularly in patients with initially retroclined incisors or those requiring greater retraction distances, where higher positive torque values may be necessary.
- **Overjet and overbite:** The anterior teeth are often intentionally positioned with a shallow overjet and overbite or in an edge-to-edge relationship without occlusal contact. Because anterior retraction may produce a pendulum effect, especially in patients with a pre-existing deep bite, additional overcorrection of anterior intrusion is recommended.
- **Canines:** Canines should be planned with controlled mesial tipping, positioning their roots closer to the extraction sites to facilitate efficient space closure.
- **Posterior teeth:** Posterior teeth should be slightly distally tipped, with additional negative torque incorporated to minimize buccal crown inclination of the molars and preserve posterior anchorage during space closure.

iii)Attachment Design

Attachment selection should be tailored to maximize control during extraction treatment.

- **Incisors:** Power Ridges are recommended to improve anterior torque control and should be considered when more than 3° of root-lingual torque is prescribed.
- **Canines:** Optimized root-control attachments or conventional rectangular attachments are preferred to achieve effective bodily movement and root control.
- **Posterior teeth:** Horizontal rectangular attachments with enhanced retention are recommended to improve anchorage and facilitate controlled posterior tooth movement.

iv) Intermaxillary Elastics

To reinforce posterior anchorage during anterior retraction, Class II elastics may be incorporated by placing precision cuts on the maxillary canines and bonding buttons on the mandibular first molars. Alternatively, temporary anchorage devices (TADs) can be used to provide skeletal anchorage, assisting with anterior intrusion and bodily retraction while minimizing anchorage loss.

v) Staging Considerations

The staging sequence should be individualized according to the specific clinical presentation because extraction cases vary considerably in complexity. Nevertheless, a commonly recommended sequence includes:

1. Initial distalization of the canines accompanied by distal tipping of the posterior teeth to establish anchorage.
2. Once the canines have completed approximately one-third of their distal movement, simultaneous retraction of the six anterior teeth is initiated.
3. Mesial movement of the posterior teeth is performed only after anterior retraction has been completed.

This sequential approach helps minimize the risk of the bowing effect and improves control by avoiding simultaneous posterior mesialization and anterior retraction.

Extraction of the Second Premolars

i) Indications

- Extraction of the second premolars is considered in selected clinical situations where preserving the first premolars is advantageous. Although this approach may increase treatment complexity, it is indicated in the following circumstances:
- Extensive caries, structural defects, or compromised periodontal support affecting the second premolars.

- Impacted or ectopically positioned second premolars that cannot be aligned predictably.
- Cases planned with minimal anchorage**,** where mesial movement of the posterior teeth is desirable.

ii) Considerations for Final Position Design

Compared with first premolar extraction cases, second premolar extraction requires greater emphasis on posterior anchorage preparation. Since molars are more susceptible to unwanted mesial tipping—particularly when more than 3 mm of mesial molar movement is anticipated—they should be planned with increased distal crown inclination. In contrast, anterior teeth generally require less overcorrection because less anterior retraction is typically involved.

iii) **Intermaxillary Elastics**

Sagittal correction using bite jump mechanics commonly involves Class II or Class III intermaxillary elastics or functional orthodontic appliances capable of advancing the mandible and modifying jaw relationships.

iv) Bite Jump (Growth- or Surgery-Assisted)

A bite jump refers to the planned alteration in the three-dimensional position of the mandible or mandibular dentition achieved through intermaxillary elastics, growth modification, or orthognathic surgery. The timing and magnitude of the bite jump should be individualized according to each patient's skeletal and dental characteristics, while considering overall treatment feasibility. Except in orthognathic surgery, mandibular repositioning generally occurs progressively throughout treatment rather than instantaneously.

Indications

Bite jump mechanics are indicated in patients with:

- Mild skeletal or functional mandibular retrusion in growing adolescents.
- Functional Class III malocclusion, where the mandible can be guided into an edge-to-edge incisal relationship.
- Severe skeletal discrepancies requiring combined orthodontic and orthognathic surgical treatment.
- Mandibular displacement resulting from premature occlusal contacts.

v) Staging Considerations

A sequential staging protocol is recommended to improve movement predictability and anchorage control:

1. Sequential distal movement of the first premolars and canines, together with distal tipping of the first molars to establish anchorage.

2. Retraction or repositioning of the anterior teeth after adequate anchorage preparation has been achieved.
3. Sequential mesial movement of the molars to complete space closure.[9]

Root-control attachments and 15° virtual gable bends should be incorporated on the teeth adjacent to the extraction sites as well as on the first molars to minimize uncontrolled tipping during space closure. These biomechanical features facilitate bodily tooth movement, improve root parallelism, and ensure proper root alignment following extraction space closure.[2]

Open Bite

Anterior teeth need extrusion instead of intrusion; posterior teeth need intrusion instead of extrusion; and incisors have to be tipped back or retroclined for pseudo correction of the anterior open bite[9]

Clear aligner therapy has been shown to be an effective treatment modality for the correction of mild to moderate anterior open bite in adult non-extraction patients. The reported mean improvement in overbite was 3.3 ± 1.4 mm, with changes ranging from 0.7 mm to 7.1 mm, demonstrating the clinical effectiveness of aligners in achieving vertical bite closure.

Stepwise regression analysis showed that 0.4 mm of maxillary molar intrusion produced approximately 0.5 mm of overbite increase, contributing about 15% of the total bite closure in an average 3.3 mm open bite correction. A lower intrusion-to-overbite ratio compared with previous studies suggests that additional dentoalveolar movements contribute significantly to open bite correction with clear aligners.

In Class II patients, correction involved maxillary incisor retroclination, maxillary molar intrusion, and reduction of the mandibular plane angle, indicating effective vertical control despite Class II mechanics. In mild to moderate Class III open bite cases, bite closure was achieved mainly through mandibular incisor retroclination and extrusion, supported by programmed intrusion of maxillary molars and mandibular incisors to counteract elastic-related extrusion and improve vertical stability.26

DEEP BITE

In patients presenting with a deep overbite**,** anterior tooth retraction is frequently combined with simultaneous intrusion to achieve optimal vertical correction. Although clear aligners alone are capable of producing anterior intrusion, their use without auxiliaries may result in stress concentration around the cervical region of the incisors, irrespective of the initial inclination of the teeth. This unfavorable stress distribution may lead to undesirable effects such as lingual tipping and extrusion of the incisors, as well as mesial tipping and intrusion of the posterior teeth**,** thereby increasing the tendency for a posterior buccal open bite.

To improve the predictability of anterior intrusion, various auxiliaries, including attachments, temporary anchorage devices (TADs), and intermaxillary elastics, have been investigated. These adjuncts enhance intrusion and facilitate palatal root torque, thereby minimizing unwanted extrusion and lingual tipping of the incisors.

Lingual attachments have been reported to improve intrusion efficiency while minimizing unintended rotational movements during treatment. Their use enhances force control and contributes to more predictable vertical tooth movement[1]

Severe Crowding

Several treatment strategies are available to resolve arch-length discrepancy, including dental arch expansion, proclination of the incisors, and interproximal reduction (IPR). Among these approaches, the primary mechanism for creating space during clear aligner therapy is controlled crown tipping.

Tipping is considered one of the most predictable and easily achievable tooth movements because it requires less biomechanical precision than bodily movement. A single force applied to the crown generates a moment that causes the tooth to rotate around its center of resistance, resulting in crown tipping. Since the line of action of the force does not pass through the center of resistance, a rotational moment is produced, making tipping the natural biomechanical response.

Clear aligners primarily achieve this movement through the shape-molding effect, whereby the programmed geometry of the aligner delivers forces to the tooth surface.[1]

Bimaxillary Protrusion with Gummy Smile

In Invisalign, extraction cases using mini-screw anchorage, compensatory biomechanical strategies similar to those used for gummy smile correction can be incorporated into the treatment setup. The use of four TADs helps prevent undesirable bowing effects during space closure and reduces the need for additional aligners. IZC screws produce distal and intrusive force components through canine precision cuts, creating a clockwise moment around the estimated center of resistance (CR) of the maxillary arch, while anterior inter-radicular screws provide intrusive forces that generate a counterclockwise moment to improve vertical control. Palatal precision cuts inclined mesially can be used as effective elastic attachment sites for bilateral incisal OrthoBoneScrews®, enhancing anchorage and enabling more predictable three-dimensional control of maxillary tooth movement, particularly during extraction treatment and gummy smile correction[27]

Class III Malocclusion with Expansion

The slow expansion rate of 1 mm per month proved clinically manageable and periodontally favorable, consistent with prior studies that showed this activation schedule reduces tissue trauma and relapse amount compared to rapid activation protocol4–7, 9, 20. Especially in adult patients, where sutural resistance is greater and periodontal remodeling is slower, slow expansion may offer a biologically advantageous alternative to conventional rapid palatal expansion (RPE)[24]

Elastic Traction Method For Maxillary Dentition Distalization

Clear aligners are increasingly being used in the management of Class II malocclusions**,** particularly for maxillary molar distalization**,** which has emerged as an effective non-extraction treatment strategy in patients presenting with mild crowding**.**

Two clinical traction modalities—precision laser-cut clear aligner (CA) hooks and bonded composite traction buttons—have been biomechanically evaluated to assess their effectiveness in redistributing orthodontic stresses during force application. Comparative analyses indicate that these traction mechanisms influence force transmission and stress distribution differently, providing valuable insights into their biomechanical performance and their ability to facilitate controlled and efficient tooth movement.

Biomechanical analysis has demonstrated that bonded composite traction buttons provide significantly greater force transmission efficiency than laser-cut aligner hooks**,** achieving approximately 98.1% force retention compared with 84.8% for laser-cut hooks. In the hook configuration, traction forces are primarily concentrated on the canines, resulting in greater force dissipation within the aligner. In contrast, traction through bonded composite buttons minimizes force loss and improves force transmission, thereby enhancing anchorage preservation of both the anterior and posterior teeth and contributing to more predictable orthodontic outcomes.

In addition to their biomechanical advantages, bonded composite buttons offer several clinical benefits. They can be bonded to the canines and mandibular molars without requiring cutouts in the aligner, thereby preserving aligner integrity and attachment design. Elastic engagement through buttons is also simpler for patients, improving ease of use and compliance. Furthermore, because the buttons are incorporated during the aligner manufacturing process, clinical chairside time is reduced, increasing overall treatment efficiency.[10]

Impacted Canines

The combination of clear aligners and TADs appears to be an effective approach based on current evidence. In cases of impacted canines, the integration of aligners with TADs and sectional wires provides a viable alternative to conventional disimpaction methods. This approach allows controlled biomechanical management of forced eruption using one or two mini-screws, minimizing the need for additional patient cooperation while improving treatment predictability.[28]

ARCH EXPANSION

Buccolingual tooth movement is among the most predictable movements achieved with clear aligners, making them particularly suitable for patients requiring mild to moderate dentoalveolar expansion**.** During expansion in non-growing patients, clear aligners primarily produce buccal crown tipping of the posterior teeth rather than true bodily movement, resulting in occlusal displacement of the palatal cusps. To improve movement control and minimize uncontrolled tipping, buccal root torque compensation has been recommended during treatment planning.

Several biomechanical strategies have been proposed to enhance posterior expansion. One commonly advocated approach is the placement of horizontal rectangular attachments on the posterior teeth to improve aligner retention and force transmission. Yao et al. evaluated various attachment designs, including round, cubic, and cylindrical configurations combined with compensatory torque. Their finite element analysis demonstrated that torque transmission was nonlinear, with cylindrical attachments providing the greatest torque control. However, despite their biomechanical advantages, cylindrical attachments are not routinely used in clinical practice.

Similarly, Zhang et al. used finite element analysis to investigate the effect of additional buccal root torque during maxillary expansion. Their findings showed that while torque compensation effectively reduced uncontrolled buccal tipping, it also decreased the efficiency of transverse expansion. Karsli et al. further assessed the influence of different attachment designs on expansion mechanics and reported that clear aligners produced both buccal and improving posterior tooth control during expansion.[5]

Embossment of the cylindrical structure could result in a higher movement efficiency than that with cuboid and ball structures. Torque compensation could enhance torque control. The torque per millimeter of the first premolar decreased by 0.26° /mm for approximately every 1° increase in compensation.[12]

Clear Aligners In Periodontal Cases

Excellent control of incisor torque with clear aligners helps stabilize anterior tooth roots within the central region of the alveolar bone, reducing abnormal occlusal forces and contributing to periodontal health maintenance. The findings indicate that orthodontic treatment with clear aligners does not cause irreversible periodontal damage. Furthermore, clear aligner therapy may provide significant benefits in patients with periodontal conditions by facilitating orthodontic and prosthodontic rehabilitation, particularly in individuals with well-controlled chronic periodontitis.[28]

CONCLUSION:

Clear aligner therapy requires precise biomechanical planning to optimize force application and movement control. Advances in aligner materials, attachments, and digital treatment protocols have improved predictability in challenging cases, enabling effective management of complex orthodontic movements while minimizing treatment limitations.

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