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Review

Clear Aligner Attachments: A Comprehensive Review

Artun Yangın, Hasan Camcı, Mehmet Soybelli

Afyonkarahisar Health Sciences University Faculty of Dentistry, Department of Orthodontics, Afyonkarahisar, Türkiye

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Main Points

- Attachments play a critical role in facilitating complex tooth movements, including rotation, extrusion and torque.
- Current evidence indicates that optimized attachments may offer some benefits, though their superiority over conventional designs is not consistently demonstrated.
- Careful selection of attachment design and position is essential to balance biomechanical efficiency with esthetic and patient-related considerations.
- Attachment selection and staged planning are of critical importance in managing complex or combined tooth movements.

ABSTRACT

Clear aligner therapy has gained significant popularity in orthodontics due to its aesthetic advantages and patient comfort. However, achieving complex and precise tooth movements with aligners often necessitates the use of auxiliary features such as attachments. This review explores the biomechanical role of attachments in clear aligner therapy and evaluates their effectiveness in facilitating various orthodontic tooth movements, including rotation, extrusion, intrusion, torque, distalization, and arch expansion. Attachments serve as critical components for enhancing force delivery, ensuring aligner retention, and improving the predictability of tooth movement. The morphology, quantity, and positioning of attachments have a direct impact on movement efficiency, patient comfort, and overall treatment success. The article highlights the importance of selecting appropriate attachment shapes (such as rectangular, ellipsoidal, or optimized designs) based on the intended movement. It emphasizes the relevance of strategic placement relative to the tooth's center of resistance. Furthermore, for cases requiring complex or combined movements, strategies such as phased treatment planning and the use of multiple or combined attachments are discussed. While optimized attachments have shown biomechanical advantages in some movements, clinical studies suggest that in many instances, their superiority over conventional attachments is not statistically significant, leaving the choice of design largely to clinician preference. This review underscores the necessity of individualized attachment planning to optimize biomechanics and improve treatment outcomes in aligner-based orthodontics.

Keywords: Attachments, clear aligner, invisalign, invisible orthodontics

INTRODUCTION

Orthodontic treatment has made significant progress over the past few decades, with clear aligner therapy emerging as a popular alternative to traditional fixed appliances. Initially introduced as a solution for mild orthodontic issues, clear aligners have evolved into a sophisticated treatment method capable of addressing complex malocclusions.[1,2] Their aesthetic appeal, comfort, and ease of use have contributed to their widespread acceptance among patients.[3]

Corresponding author: Artun Yangın, MD, **e-mail:** yangnartun@gmail.com
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In terms of aesthetics and comfort, clear aligners present a favorable alternative to traditional fixed orthodontic treatments. However, the literature also highlights concerns regarding the biomechanical limitations of clear aligners when compared to fixed treatments.[4] The biomechanical debate surrounding aligner therapy stems from differences in force transmission mechanisms and the need for additional mechanics to achieve certain tooth movements, such as mesialization or intrusion.[5] Unlike continuous force application in fixed appliances, aligners rely on intermittent forces that can diminish over time, making them less efficient in controlling specific types of movements. This challenge becomes more evident in root torque, bodily movement, and vertical control, all of which require more sophisticated biomechanics.[4]

A critical factor influencing the success of clear aligner treatment is the incorporation of auxiliary features, such as attachments, which are designed to enhance the biomechanical capabilities of the aligners. Attachments are small composite structures bonded to the teeth to improve appliance retention and facilitate specific movements, such as rotation, extrusion, or controlled tooth movements.[6] These adjuncts significantly increase the predictability of treatment outcomes by modifying the force application mechanism of the aligners.[7] Research has demonstrated that the placement, shape, size, and number of attachments can significantly influence the effectiveness of orthodontic treatment.[4] Each attachment's design must correspond precisely to the desired tooth movement, with considerations such as surface area contact, aligner deflection points, and resistance centers being critical to biomechanical success. Moreover, optimizing the attachment's orientation in relation to the aligner's insertion path can further improve force delivery.[5]

In this context, a deeper understanding of the forces and moments generated by different attachments, as well as their biomechanical principles, is essential for selecting the appropriate attachments and ultimately improving the effectiveness and efficiency of orthodontic treatment. Advances in digital orthodontics and artificial intelligence have enabled more precise customization of attachments to meet the specific biomechanical needs of each case. These technological innovations, in conjunction with ongoing research into material properties and force dynamics, continue to enhance the scope and efficacy of clear aligner therapy.[2,6] AI-powered treatment planning software can simulate and adjust force vectors based on patient-specific dental and periodontal conditions, offering a more personalized approach to attachment placement. This integration supports clinicians in developing evidence-based treatment plans that maximize efficiency and minimize complications.[8]

Clear aligners have yet to fully match the mechanical advantages offered by traditional bracket-based treatments. To mitigate the biomechanical limitations of aligners, particularly in complex cases, additional methods-such as attachments, buttons, power arms, precise cuts on the aligners, bite ramps, temporary anchorage devices, and intermaxillary elastics-are often employed. These auxiliaries, when applied strategically, can provide enhanced anchorage, better vertical and sagittal control, and facilitate movements that would otherwise be inefficient or unpredictable with aligners alone.[5]

This article aims to provide a comprehensive review of the biomechanical principles, design considerations, clinical applications, and potential limitations of attachments. By synthesizing the available evidence, the review seeks to emphasize the critical role of attachments in enhancing the effectiveness of clear aligner therapy.

Key Features and Clinical Implications of Attachments in Aligner Therapy

Attachments are composite additions that are temporarily bonded to the surfaces of teeth to enhance the interaction between the aligner and the tooth during clear orthodontic treatments.[8] The concept of attachments was originally introduced by Martz[9] in 1988, who described a removable device for positioning teeth and suggested using composite "buttons" as anchoring points for aligners to facilitate movement.

Attachments come in various shapes, sizes, and orientations, tailored to assist specific types of movements or to fit the natural contours of dental crowns. Initially, ellipsoidal and rectangular shapes were used,[10] with vertical and horizontal orientations as the primary options. These attachments can be placed on either the buccal or the palatal-lingual surfaces.

Attachments' Components

Attachments consist of three main components: an active surface, a passive surface, and a base. The active surface is the part that comes into contact with the aligner, enabling it to exert the necessary force vectors, for desired tooth movements. This means that the active surface receives the pushing forces from the aligner. The orientation of this surface determines the direction of the force vectors, with efficient vectors typically being directed perpendicularly to the active surface.

The passive surface is the part of the attachment that forms its buccal face, and provides stability and supports the fitting of the aligner with minimal interference. If the passive surface has a low volume, it can be detrimental as this increases the risk of fractures, wear, or detachment of the attachment, thereby compromising its durability. This is particularly important given that the composite materials used today for attachments are subject to gradual wear of their surface texture.

An additional concept related to attachment terminology is the bevel. A bevel refers to an angled cut at the edge or tip of an attachment, which changes its pointed end into a smooth, inclined surface. The idea of using a bevel emerged due to fitting challenges with rectangular attachments, which require the aligner to be fully seated over the attachment; as the angle of emergence at the junction between the tooth and the attachment forms a right angle. By incorporating a bevel, aligner adaptation becomes more seamless, as the aligner needs to fit over the corner of the beveled attachment.

The angle of emergence in a beveled attachment exceeds 90°, allowing the tooth to slide more easily into the aligner during the first few hours of wearing each new aligner. Conventional attachments, which have at least one beveled edge, are beneficial for both tooth movement and anchorage. Beveled attachments are designed to enhance biomechanical efficiency in aligner therapy by considering the direction of force and the center of resistance of the tooth. In cases where extrusion is required, gingivally inclined attachments are considered appropriate, while for rotated teeth, attachments inclined mesially or distally may be preferred. For both rotated and infra-positioned teeth, the attachment inclination can be designed to balance both axes (for example, inclined in the mesiogingival direction). Additionally, it has been reported that palatally positioned beveled attachments provide both an aesthetic advantage and more effective force transmission compared to labially positioned ones.[11]

Importance of Attachment Material

Attachments are critical components through which force is transmitted to the teeth, and for effective force transmission, both the attachment and the aligner must maintain contact under high stress. Therefore, it is crucial to minimize unwanted attachment debonding.

It has been observed that when more rigid and thicker attachment plates are used, the attachments are formed with higher accuracy; however, the risk of attachment breakage increases during plate removal after the attachments have been polymerized.[12] The effect of composite viscosity on attachment performance has been investigated, and it has been concluded that as the filler content of the composite increases, both shear strength and force transmission efficiency improve. However, when the filler content exceeds 72%, further increases do not result in a significant improvement in the bonding performance of the attachment.[13] As a result, flowable composites or orthodontic bonding composites are considered the most suitable materials for bonding attachments.[11]

Location of Attachments

The location of attachments is closely related to the optimal point of force application and the retention of the aligner. According to biomechanical principles, the farther the point of force application is from the center of resistance of the tooth, the greater the moment it generates. Attachments placed closer to the gingival margin produce less moment than those positioned near the occlusal surface. Studies have shown that in specific tooth movements such as extrusion, maximum retention can be achieved by placing the attachment closer to the gingival margin and using attachments without gingival inclination. In cases where maximum retention is not required, attachments facilitating appliance removal may be preferred.[14] Attachments should be placed at least 1.5 mm away from the gingival margin to prevent undesirable plastic deformation; this distance should also be maintained from other limiting surfaces.[15]

In rotational movements, attachments can be placed on the mesial and distal corners of the tooth to increase the rotational moment. For example, in a case requiring mesiopalatal rotation, the effectiveness of the movement can be enhanced depending on the position of the attachment. However, if not properly positioned, the applied force may cause tipping and lead to undesired tooth movement (Figure 1).[16]

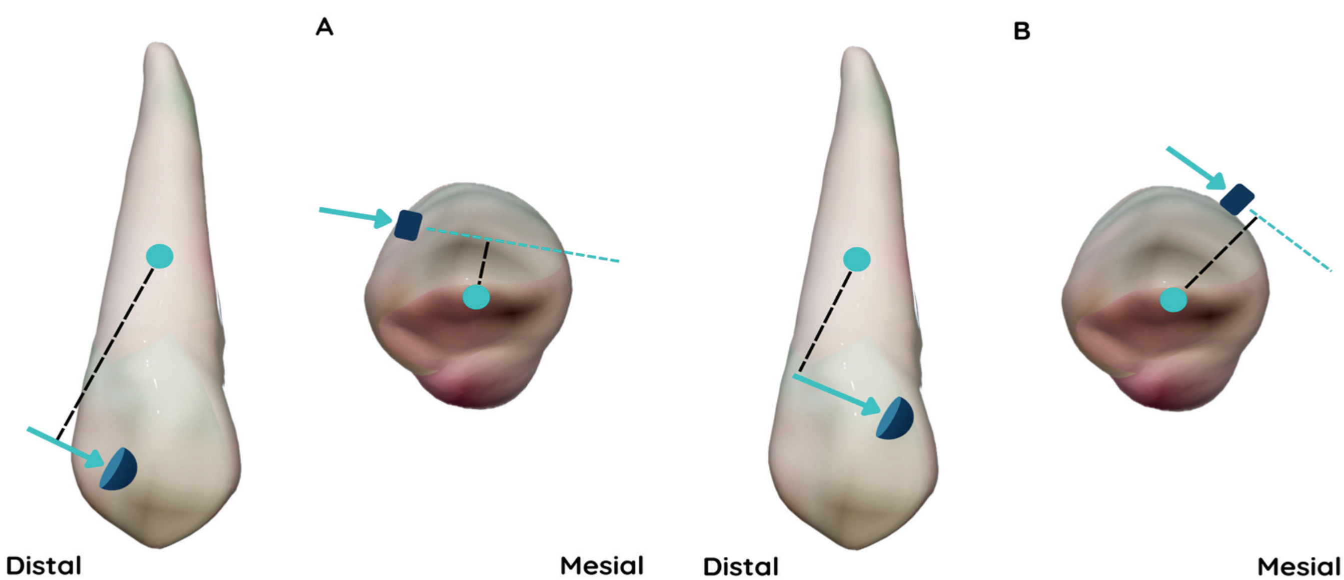


Figure 1. Schematic representation of the effect of attachment position on tooth movement. A) By placing the attachment in a more incisal and distal position, the distance between the direction of the force (blue arrow) and the center of resistance (blue dot) (black dashed line) increases in the labial view of the tooth, but remains negligible in the incisal view. As a result, more mesial tipping movement and less mesiopalatinal rotational movement have been observed. B) The attachment has been moved to a more gingival and mesial position, reducing the distance of the tipping force to the center of resistance (labial view). In the incisal view, the distance of the force responsible for rotating the tooth to the center of resistance has increased. Consequently, the moment responsible for tipping the tooth has been reduced, while the moment that rotates the tooth has been increased, thereby establishing a more efficient mechanism for derotation

A recent finite element analysis (FEA) study showed that placing horizontal rectangular attachments on the lingual surfaces of first molars, generates greater tipping moments than on the labial surfaces, especially during transverse arch expansion, highlighting the biomechanical importance of attachment positioning.[17]

Attachment Size

In achieving the desired tooth movements, the size of the attachments is as important as their location. As a general rule, more complex movements require larger attachments. However, it should be noted that larger attachments, especially in the anterior region, may pose aesthetic disadvantages. By optimizing the size of the attachments according to both aesthetic and functional needs, the treatment time can be reduced and the success rate increased.[18] The appropriate attachment sizes for different types of attachments are shown in Table 1.

According to the study by Ahmad et al.,[19] 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' Classification

Attachments used in the aligner system are generally classified in two ways: according to their function or their optimization status.

Attachments According to Their Function

Attachments are classified as active or passive based on their function. Attachments can be added to increase the retention of the aligner (passive attachment) or to facilitate tooth movement (active attachment). Detailed information on the use of attachments in each situation is provided under the heading "Attachments' Function."

Conventional and Optimized Attachments

Another classification distinguishes between optimized and conventional attachments. The concept of optimized attachments is specific to the Invisalign system, and the shape of the attachment varies according to the morphology of each tooth and the type of movement.[20] Conventional attachments refer to the remaining attachments, which are not tooth- or movement-specific.

Conventional and Optimized Attachment Comparison

Several previous studies have compared and evaluated the effectiveness of optimized and conventional attachments in different tooth movements. The optimized rotation attachment was the first design introduced by Invisalign. Karras et al.[10] retrospectively compared the effectiveness of optimized rotation attachments and conventional attachments in correcting rotations of canines and premolars. The results showed that optimized attachments achieved slightly higher success rates, and these differences were statistically significant.

In a retrospective study by Hassanaly et al.[21] examining 147 incisors, divided into two groups-vertical and optimized attachment-it was found that optimized attachments were more effective for the rotation of lateral incisors. However, vertical conventional attachments were more successful in correcting mesiodistal angulation. For torque movements, horizontal attachments were reported to perform best.[21]

In a retrospective study by Burashed and Sebai[22] which investigated deep bite treatment with Invisalign using two groups-optimized and conventional attachments-it was found that optimized attachments were not more successful than conventional attachments in correcting overbite. The study also discussed the difficulty of correcting deep bite, independent of the type of attachment used. Anterior open bite correction was examined by the same researchers using horizontal conventional and optimized extrusion attachments in two groups. Both groups successfully corrected the open bite, but the study showed that optimized attachments reduced the treatment duration.[23]

Karras et al.,[10] analyzed the effectiveness of conventional designs compared to optimized extrusion attachments for the extrusion of anterior teeth using the Invisalign system. The results showed that while the mean extrusion achieved with optimized attachments was slightly higher (0.14 mm or 4.3%), there was no clinically or statistically significant difference. Similarly, in their study investigating traditional designs that assist rotation, they did not specify the characteristics such as location, size, orientation, or inclination of the conventional attachments used for extrusion.

In a retrospective study, Stephens et al.[24] compared two groups using optimized rotation attachments (changed weekly and biweekly) with another group using conventional vertical rectangular attachments (changed biweekly) to correct mandibular canine derotation with Invisalign aligners. The results showed that the group with optimized attachments that were changed weekly achieved the highest success rate (81.5%), followed by the group with optimized attachments that were changed every 14 days (76.5%). The group using conventional attachments had the lowest rotation movement expression rate ((63.1%), but this group also managed more severe rotations.

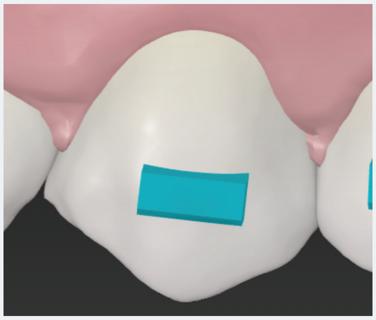
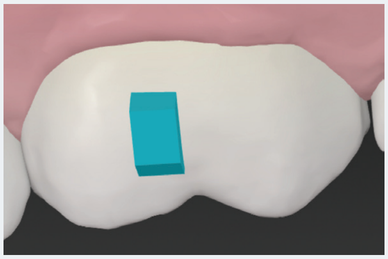
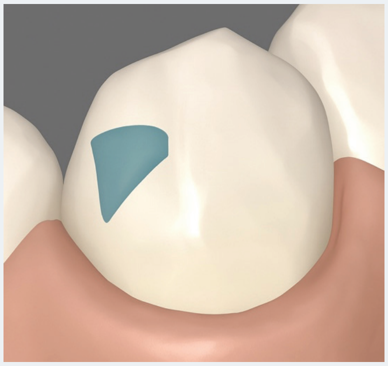
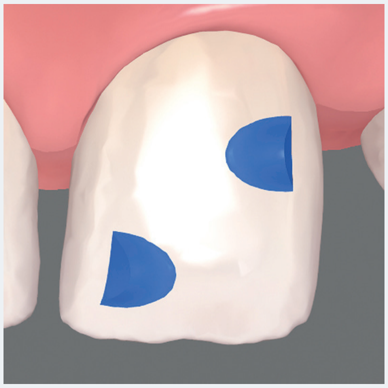
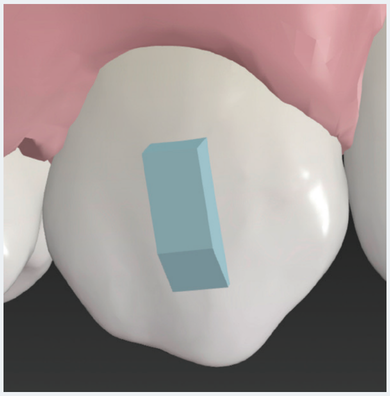
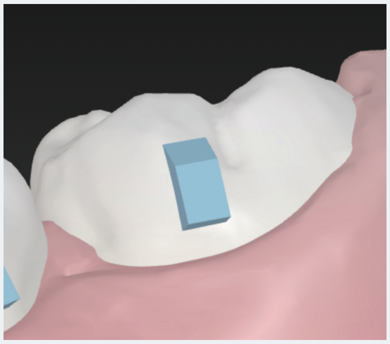
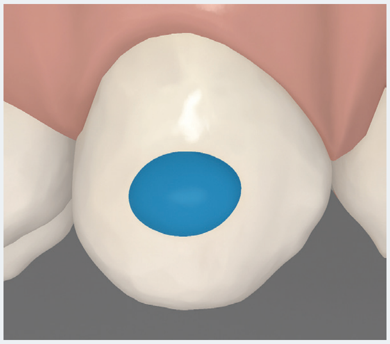
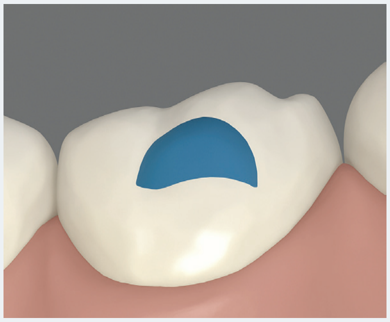
Table 1. Some commonly used attachments and their shapes			
Attachment's name	Attachment's design	Dimension	
		Mesiodistal	Occlusogingival
Horizontal rectangular attachments		2-5 mm (It depends on the clinical conditions)	2-5 mm (It depends on the clinical conditions)
Vertical rectangular attachments		2-5 mm (It depends on the clinical conditions)	2-5 mm (It depends on the clinical conditions)
Rectangular attachments placed on the lingual surface		2-5 mm (It depends on the clinical conditions)	2-5 mm (It depends on the clinical conditions)
Optimized rotation attachments (invisalign)		Clear aligner provider determined based on planned tooth movement	Clear aligner provider determined based on planned tooth movement
Optimized Root control attachments (invisalign)		Clear aligner provider determined based on planned tooth movement	Clear aligner provider determined based on planned tooth movement

Table 1. continued

Attachment's name	Attachment's design	Dimension	
		Mesiodistal	Occlusogingival
Incisally inclined attachments		2-5 mm (It depends on the clinical conditions)	2-5 mm (It depends on the clinical conditions)
Occlusally inclined attachments		2-5 mm (It depends on the clinical conditions)	2-5 mm (It depends on the clinical conditions)
Cylindrical/ellipsoid attachments		2-3,5 mm (It depends on the clinical conditions)	1-3 mm (It depends on the clinical conditions)
Optimized extrusion attachments (invisalign)		Clear aligner provider determined based on planned tooth movement	Clear aligner provider determined based on planned tooth movement

A FEA study by Goto et al.,[8] which examined the effects of optimized and conventional attachments on models with extraction spaces, used eight different optimized and three different conventional attachment models. No significant differences were found in the overall comparison of tensile force and tipping moment. However, it was revealed that larger conventional attachments generated 7% more tensile force and tipping moment compared to optimized attachments. However, this result did not result in a significant difference.[8]

When reviewing the existing clinical studies, no significant differences were observed in the effects of optimized and conventional attachments across nearly all types of movements. Therefore, it would be more accurate to conclude that using optimized attachments or alternative attachments depends on the doctor's preference.

Attachments Function

Attachments serve two primary functions: mobilization and retention.

Active Attachments

In cases where the appropriate tooth morphology is insufficient for tooth movement or when root movement cannot be achieved even if the appropriate morphology is present, active attachments are used. For example, if rotational movement is desired in conical premolar and canine teeth, or if extrusion movement is required in any tooth, the aligner would slip during the movement if the attachment is not added. This would prevent the planned movement from occurring. This phenomenon can be referred to as the "traffic cone effect." Traffic cones are designed to easily overlap and facilitate rotational movements due to their structure when placed on top of each other. If no attachment is used, the aligner will sit on the tooth like a cone, moving on its own, without applying force to the tooth during rotational or extrusive movements (Figure 2). This is where active attachments come into play. Tooth movements performed with aligners are as complex as those achieved in fixed orthodontic treatments. Below, we have summarized the relevant publications concerning these movements, with each movement presented under a separate heading. In addition, Table 2 provides a summary of which type of attachment is more suitable for each specific tooth movement.

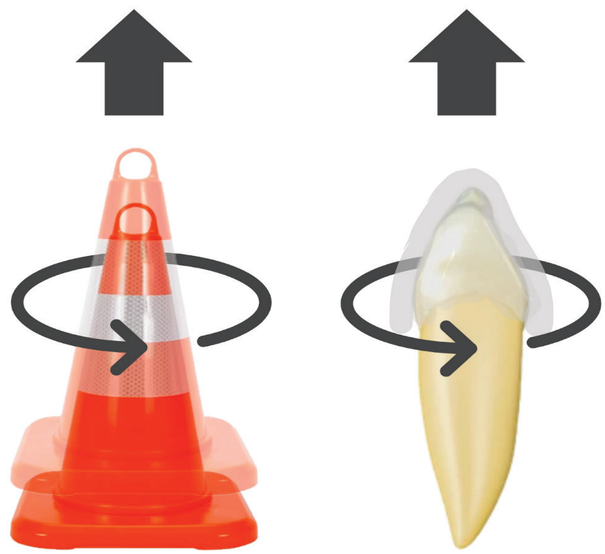


Figure 2. Traffic cone effect. When rotational and upward forces are applied to the upper cone of overlapping cones, the upper cone moves, while the lower cone remains stationary. Similarly, rotational and extrusive forces applied by the aligner to the canine tooth, as observed from the lateral side, cause the position of the aligner to shift, rather than the tooth itself

Table 2. Types of attachments that can be used for different types of movements

Type of movements	Attachments	Recommendations
Extrusion	Horizontal retrangular attachments optimized extrusion attachments	Focus should be on the apical part of the active surface during extrusion of incisors. Optimized designs may be preferred for symmetrical force transfer during attachment placement.
Intrusion	Horizontal rectangular attachments	Attachments can also be used on adjacent teeth to increase plate stability during intrusion. Large and wide surface attachments should be preferred to ensure balanced force distribution.
Expansion	Occlusally inclined attachments cylindrical attachments	Occlusally inclined attachments should be added to molars to prevent uncontrolled buccal tipping during arch expansion. Controlled movement of teeth should be provided with additional torque support when necessary.
Rotation	Vertical rectangular attachments optimized rotation attachments	In rotation movements, attachments optimized especially for lateral incisors can be used. Attachments providing flat surfaces should be preferred for conical teeth such as canines.
Distalization	Vertical rectangular attachments guideline attachments	Attachments should be placed on both buccal and palatal surfaces of upper molars during distalization. Double-sided attachments are recommended to prevent tipping during distalization.
Torque	Semi-ellipsoid attachments horizontal attachments power ridge	In torque movements of maxillary incisors, attachments placed close to the gingiva should be preferred. In canine teeth, cylindrical attachments placed palatally are more useful. In torque movements, it is necessary to plan the movement exaggeratedly, because in most cases, tooth movement lags behind the planning.

Rotational Movement

Rotational movements are among the most challenging movements for aligners to achieve. These movements are particularly difficult in teeth classified as "round" in the literature.[6] This is because for an aligner to apply an effective force, it requires a flat surface . When the tooth shape does not provide such a surface, attachments play a critical role. In incisors, the rectangular shape covered by the aligner provides a flat surface, allowing the aligner to apply force at the edges and rotate the tooth into the desired position.

Studies have shown that applying force in the correction of premolar rotation without attachments is minimally effective. Additionally, vertical rectangular attachments have been found to produce the most effective results.[25] Additionally, Fiorillo et al.[26] have confirmed that there is no significant difference between the use of optimized attachments and vertical rectangular attachments in rotation correction.

Extrusional Movement of Upper Incisors

Clear aligners, which accommodate teeth of varying shapes, move teeth sequentially to the desired position by applying thrust forces. However, some tooth movements, such as incisor extrusion, present challenges for clear aligners due to the lack of a sufficient thrust surface.

A study by Savignano et al.[27] concluded that extrusion of the upper central incisor is not possible without the use of attachments. The study also found that the position of composite attachments had a stronger effect on tooth movement, while different composite attachment shapes in the same position produced equal extrusion forces.[27]

In contrast, a study by Costa et al.[28] utilized specially designed composite attachments, modified from conventional attachments, to extrude the upper central incisor. The study demonstrated that different attachment designs produced significantly varying directions and magnitudes of force.[28]

Laohachaiaroon et al.,[29] used the finite element method to study the initial displacement of a 0.15 mm extrusion of the upper central incisor with different attachment shapes. The attachment shapes examined included a horizontal rectangular attachment with an active surface thickness of 1 mm and no slope, a horizontal rectangular attachment inclined toward the gingiva with an active surface thickness of 0.25 mm, and a horizontal ellipsoidal attachment with an active surface thickness of 0.5 mm. In all models, the primary pressure area of the aligner was located on the cervical surface of the attachments, and the stress distribution in the periodontal ligament was similar. The highest extrusion was achieved with the horizontal rectangular attachment model without slope, followed by the ellipsoidal attachment. The horizontal rectangular attachment inclined toward the gingiva (simulating an optimized extrusion attachment) showed the lowest degree of extrusion due to its smaller active surface area compared to the other models. However, these differences were not clinically significant.

Rossini et al.[30] demonstrated that rectangular horizontal attachments located on the buccal or palatal surfaces of the upper incisors constitute the most effective force system for incisor extrusion. Based on this, it can be concluded that attachments with an active surface on the apical part of the upper incisor extrusion can facilitate movement when used with aligners.

Intrusional Movement of Molars

Plates facilitate the intrusion of teeth by covering the entire surface of the teeth and exhibiting "block effect" on the molars.[31] Transparent aligners have been reported to provide excellent clinical vertical control, particularly on the molar.[32] These aligners have been especially prominent in open bite cases, where posterior teeth intrusion is used as part of the treatment.[33]

A study evaluating different attachments and intrusion without attachments found that intrusion with attachments was significantly more effective.[34]

FEA study[33] examined the effect of attachment location on the intrusion of the second molar, specifically focusing the first molars. Horizontal rectangular attachments were placed either buccally, palatally, or both buccally and palatally on the upper first molar to simulate second molar intrusion. The results showed that the most effective second molar intrusion and the least tipping were achieved using horizontal rectangular attachments, placed both buccally and palatally. Additionally, this attachment configuration exhibited the most balanced stress distribution. In cases where no attachment was added, or a buccal attachment was used, buccal tipping was observed, whereas palatal tipping occurred when a palatal attachment was added.[33]

Bodily Movement

As with all orthodontic mechanics, the distance between the applied force and the center of resistance of the tooth directly affects the moment of force applied with aligners. As this distance increases, the resulting moment increases proportionally. As a result, the direction of the net moment causes the tooth root to rotate in the direction of the applied force. Transparent aligner systems are inadequate in mesiodistal root positioning because these systems do not generate the necessary force couples. This limitation explains the difficulty in changing the angulation (tilt) of the anterior teeth. Therefore, to enhance second-order control, transparent aligner systems rely on special attachments that can generate equivalent force couples.[16]

In the existing literature, there are studies confirming that the use of attachments leads to bodily movement.[16] However, Goto et al.[8] reported that attachments had no effect on the tensile forces and tipping moments.

Torque Movement

Achieving torque movement in teeth using aligners is one of the challenges. While buccolingual tipping movements can typically be achieved easily, root torque in the anterior region presents a significant challenge in transparent aligner-based treatments. The structure of aligners causes a decrease in rigidity in the gingival area, preventing the transmission of the gingival force necessary for torque control. In the absence of attachments, the center of rotation shifts toward the apex, resulting in tipping rather than root movement. Studies using different attachment models have shown that ellipsoidal attachments and power ridges facilitate torque movement and reduce crown tipping. No significant differences were found between these two auxiliary mechanics, and horizontal rectangular and cylindrical attachments showed similar torque values to models without attachments.[6]

The torque control and retraction of the anterior teeth are dependent on the establishment of proper posterior tooth anchorage. This anchorage can be enhanced by adding attachments to the teeth from the canine to the second molar.[35]

For torque movements, attachments are placed on the lingual (palate side) or buccal (cheek side) surfaces to ensure the proper transmission of force to the tooth root. In a FEA study by Karsli et al.[36] on palatally positioned lateral teeth, labial (front surface) attachments showed less tipping compared to palatal (roof of the mouth surface) attachments. The study also revealed that positioning the combined labial attachment closer to the incisal edge and using it in conjunction with the palatal attachment minimized tipping.[36]

In a study conducted using cone beam computed tomography, the success rate for torque planning of more than 5 degrees was found to be approximately 47%.[37] It should also be noted that in movements exceeding 10 degrees, a torque loss of approximately 50% may occur.[6]

In conclusion, attachments and power ridges may not be sufficient to achieve the desired result in teeth requiring torque movement, and the need for overcorrection or refinement should not be overlooked.

Distalization Movement

A systematic review evaluating the predictability of orthodontic movements with clear aligners found that molar distalization was the most predictable movement.[1,2] A retrospective clinical study showed that molar distalization had the highest effectiveness of approximately 87%, outperforming movements like incisor torque and premolar derotation.[6]

It is correct to say that there is no consensus on the role of attachments in distalization movements with clear aligners. In one case-control study and another retrospective cohort study, it was concluded that attachments play a significant role in enhancing the effectiveness of molar distalization.[38] In contrast, a systematic review, an FEA study, and a prospective study emphasized that the role of attachments in distalization movements with clear aligners is minimal.[39] Ravera et al.[40] showed that in the distalization movement of the first and second molars, with distances of 2.25 mm and 2.5 mm, respectively, no significant distal tipping was observed. They attributed this lack of tipping to vertical rectangular attachments.[38] Similarly, in the case report by Yurdakul and Karsli,[39] which applied sequential distalization at two different rates with the same types of attachments used in each group, the distal tipping movement yielded results similar to those found in previous studies.

When evaluating all these studies, the following conclusion can be drawn: Although attachments may not directly affect the success of distalization movements with aligner systems, their use can be beneficial for predictable bodily movement and root control.

Passive Attachments

Passive attachments, which serve the retention function of attachments, are used to increase the retention of aligners. These attachments are especially useful in cases of microdontia, missing teeth, short crown lengths, and incompletely erupted teeth.[41] In some instances, even when teeth are of normal morphology and number, it may still be necessary to enhance the retention of the aligner. For example, patients with precise cuts made on their aligners and rubber bands used to engage these cuts may require additional retention. If a retaining attachment is not used in such cases, the aligner may be dislodged by the forces exerted by the rubber bands.

Increasing the retention of the aligner is also crucial for active movements. For instance, in intrusion cases, attachments are necessary on neighboring teeth. If intrusion is planned for the anterior teeth, the aligner will apply a force to push the anterior teeth apically. However, this force will cause the posterior region of the aligner to lift off the teeth. To prevent this, passive attachments added to the posterior part of the aligner will ensure that the plate remains stable, aiding the intrusion of the anterior teeth. As the number of attachments increases, the retention of the aligner is also enhanced.[42]

The shape and position of the attachments also play an important role in retention, in addition to the number of attachments. A study comparing horizontal rectangular attachments with occlusal and gingival inclination compared to a vertical rectangular attachment found that the vertical rectangular attachment provided the highest retention, followed by the horizontal rectangular attachment with occlusal inclination.[14] Attachments placed closer to the gingival area showed higher retention than those closer to the occlusal surface. The higher retention of the occlusal inclination attachment may be due to the design of providing a surface that is perpendicular to the extrusion movement. Consequently, the aligner with horizontal rectangular attachments with occlusal inclination is easier to attach and more difficult to remove. For similar reasons, the optimized extrusion attachment used by

Align Technology for anterior teeth features a gingival surface inclination. This design creates a less retentive area in the anterior gingival region, where the aligner is more rigid.[4]

However, it is important to note that too many attachments can be detrimental. Adding attachments to every tooth to increase retention can lead to undesirable effects if the planned movements do not occur. In such cases, the system may experience deformations, and the aligner may lose its effectiveness.[42]

Effect of Attachments on Aligner Retention and Gripping Force

Gripping force refers to the force applied to hold an object steady or prevent it from being displaced. In the case of clear aligners, although they are firmly attached to the teeth, their retention can be influenced by various factors, including tooth morphology and position, degree of malocclusion, aligner material, and the duration of appliance use.

To better control orthodontic tooth movement during aligner treatment, the placement of attachments has been recommended to strengthen the retention force of aligners. Various types of attachments have been developed to improve retention within these systems.

Studies have shown that thicker aligner materials increase retention, and longer aligner edges enhance it.[16] Increasing the number of attachments can make aligners more difficult to remove, reducing user comfort and potentially decreasing the amount of time patients wear their aligners.

In a study on gripping force by Takara et al.,[4] the force required for the removal of an aligner varied depending on the placement location and morphology of the attachments. It was demonstrated that increasing the thickness of the rectangular attachment placed on the lateral incisor and increasing the size of the semicircular attachment placed on the first premolar contributed to an increase in retention force on the labial side of the aligner. The study also found that the undercut area of the attachments played a significant role in enhancing the retention of the aligners. However, as the undercut area increased, the aligners also experienced more deflection in this region.[4]

Effect of Attachments on Expansion Movements

Since buccolingual tilting is one of the movements that are easier to achieve with clear aligners, clear aligners are commonly used in patients requiring mild to moderate tooth-alveolar expansion.[4]

When clear plates are used to expand the arches in individuals who have completed their growth period, correction involves buccal tipping of the posterior teeth, causing the palatal cusps to move in the occlusal direction. To minimize this tipping and provide more controlled movement of the teeth, torque compensation has been suggested by adding buccal root torque.[43,44]

The application of horizontal rectangular attachments to the posterior teeth has been suggested as one way to improve arch expansion with clear aligners.[20] Yao et al.[43] studied different attachment designs during expansion with clear aligners, including round, cubic, and cylindrical shapes with compensatory torque. The study found that torque transmission was nonlinear, with the cylindrical design being the most effective type among the attachments tested. However, this design is not commonly used in clinical practice.

Zhang et al.[44] used FEA to study the effects of additional torque and concluded that it was effective in controlling tipping, but it reduced the efficiency of maxillary arch expansion. In a study by Karsli et al.,[45] FEA was used to examine the effect of different attachments on tipping movement. The study found that expansion with clear aligners caused buccal and mesial tipping of maxillary molars, with the amount of buccal tipping increasing from the first to the second molars. The addition of occlusally inclined attachments and buccal torque compensation resulted in a significant reduction in the rate of uncontrolled buccal tipping.

Role of Attachments on Extraction Cases

Extraction cases treated with clear aligners are one of the challenges that aligners need to overcome. To close the extraction space, different anchorage methods and attachment designs have been proposed to achieve bodily movement of the anterior teeth without tipping and to ensure torque control. The common belief in this regard is that vertical or horizontal attachments placed on the canine, premolars, or molars are beneficial for anchorage retention and tooth movement.[46]

In extraction cases, the goal of the G6 protocol developed by Invisalign is to achieve torque control, bodily movement, and anterior vertical control. For this purpose, optimized attachments are preferred. To prevent anchorage loss in the posterior teeth, optimized anchorage attachments are used on these teeth, while optimized root control attachments are used to manage the angulation of the canines.[47] This is shown in Figure 3.

Attachment Hierarchy in Combined Movements

In clinical practice, it is rare to apply a single type of movement to a tooth. Typically, a combination of movements is required, such as torque, rotation, and angulation correction. Therefore, what type of attachments should be used in such cases?

Three different options arise when dealing with multiple movements. One approach is to prioritize the movement that is most dominant. For example, if both torque and angulation movements are involved, but torque is the more dominant movement (and is also more challenging to achieve), a horizontal attachment may be preferred. However, in this approach, the secondary movement may not be achieved as accurately.

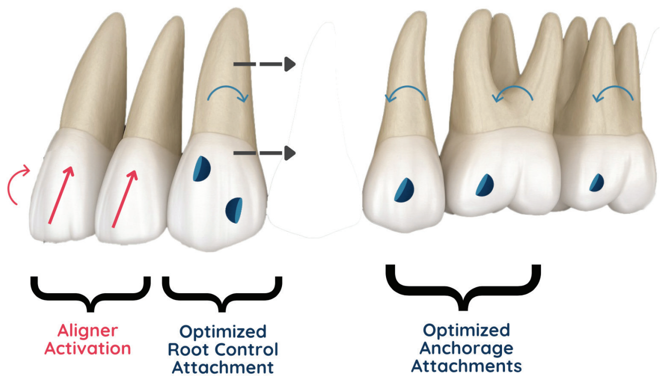


Figure 3. In the invisalign G6 protocol, the attachment procedure for extraction cases is as follows: To facilitate the parallel movement of the canine tooth in the extraction space, an optimized root control attachment (optimize retraction attachment) is used. This attachment allows for the correction of the canine tooth's angulation, represented by the blue arrow. To prevent anchorage loss in the posterior teeth, optimized anchorage attachments are employed. The effect of these attachments is also depicted by the blue arrow. Additionally, the central incisors are aimed to be retracted in a controlled manner through plaque activation

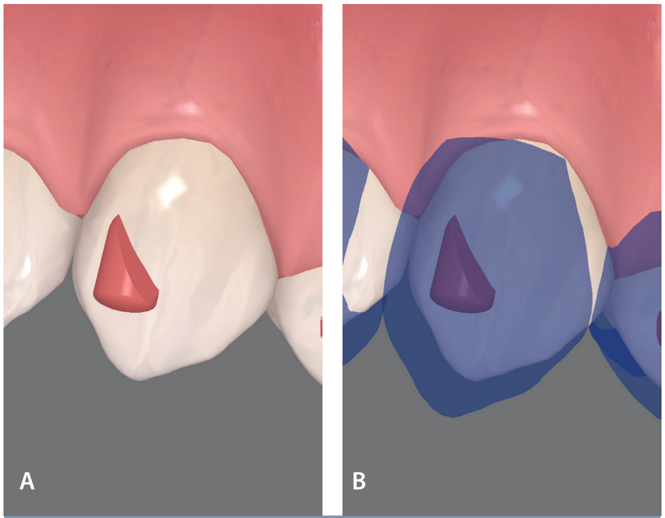


Figure 4. A) Optimized rotation attachment added to the upper left canine tooth in the Invisalign system. B) Final tooth position is simulated in blue. Rotational and extrusive movements were planned for the relevant tooth. In order to facilitate both rotation and extrusion, the active surface of the attachment was designed to face both the gingival and distal directions, rather than in a single direction. Note that the attachment position was moved to the mesial position due to the greater extrusion movement required in the mesial direction and the need for mesiopalatial rotation of the tooth.

A second approach involves changing the attachment geometry. The goal is to increase the surface area of the attachment to enhance force transmission.[48] This may involve using combined attachments, such as a horizontal attachment for torque and a vertical attachment for angulation. By combining attachments into a larger, angled attachment, the surface area is increased, improving the accuracy of the movements.

The third approach, seen in systems like Invisalign, involves using optimized attachments designed specifically for each tooth. These attachments are designed to apply combined movements in a single design. For example, Figure 4 shows an optimized rotation attachment applied to a canine tooth. The active surface of the attachment faces two different directions (gingival and distal), and the attachment is relatively large. This configuration allows for both rotational and extrusive movements to be performed effectively.

Attachments with more surface area provide more movement accuracy.[11,49,50] However, this situation may lead to an increase in the retention of the aligner and therefore to patients having more difficulty in putting on and taking off the aligners.[49] In addition, the use of larger attachments may cause a negative perception of the aesthetic. According to an eye screening study, people's attention is focused more on the oral area when using larger attachments.[50] This reduces the "unnoticeable" property of the aligners.

A third way of executing combined movements is to stage the movements and apply a different attachment type at each stage. This method gives more accurate results than the use of combined attachments.[48] Castroflorio et al.[49] stated that movement accuracy can be increased with three-dimensional planning and staging.

CONCLUSION

Attachments are crucial components of clear aligner treatments, directly influencing their effectiveness. Proper attachment selection and placement are essential for achieving predictable and accurate results. As treatment protocols continue to evolve, further research into attachment design and usage will improve the clinical efficacy and comfort of clear aligner systems. The information provided here offers valuable guidance for clinicians and researchers, helping to optimize treatment plans and contributing to the future development of these systems. The success of clear aligner treatments relies on the correct selection of attachments, thoughtful attachment design, and well-planned movement phases to the biomechanical challenges associated with them.

Footnotes

Author Contributions: Concept - A.Y., H.C.; Design - A.Y., H.C.; Data Collection and/or Processing - A.Y., M.S.; Analysis and/or Interpretation - M.S.; Literature Search - A.Y., M.S.; Writing - H.C.

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