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Current Biomechanical Rationale Concerning Composite Attachments in Aligner Orthodontics

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Introduction

The orthodontic technique that we now call "aligner orthodontics" has evolved considerably over the last 20 years. Improvements in behavior of aligner plastics, treatment planning software, and three-dimensional (3D) printing have served one basic but fundamental intention: to mitigate the biomechanical limitations inherent to aligner-based tooth movement. Another significant development designed to overcome the aforementioned biomechanical shortcomings of aligner systems has been the continuous improvement of biomechanically complementary composite attachments. Attachments were conceived to produce supplementary force vectors that, when applied to teeth by the aligner material, transform the resultant system, allowing complex tooth movements. The application of one of the initial geometric configurations was initially presented by the clinical team from Align Technology Inc., as basic 1 x 3 mm rectangular structures, bonded to the lower incisor buccal surface, in an attempt at controlling undesired tipping during space closure after incisor extraction (Fig. 2.1A).[1] As the incisors adjacent to the extraction space begin to incline mesially, the rigid, fixed structure of the attachment collides with aligner plastic, producing force couples that counteract the initial moment, reducing undesired tipping (see Fig. 2.1B).

Orthodontic tooth movement with conventional bracket techniques can deliver sophisticated force systems due to the manner in which the rigid ligature-archwire-bracket scheme "grasps" the malaligned tooth. This particular arrangement allows broad control of magnitude and direction of applied force vectors, and, consequentially, of tooth movement (Fig. 2.2).

It is important to keep in mind that attachments work, not as *active* agents that produce forces, but by passively "getting in the way" of plastic as it elastically deforms due to lack of coincidence between tooth position and aligner material ("mismatch"), establishing the force vector that subsequently affects the tooth (Fig. 2.3).

Biomaterials used for attachment fabrication must assure that requirements in adhesion, wear resistance, and esthetics are fulfilled. A recent study[2] suggests that contemporary microfilled resin composites provide sufficient wear resistance to deliver a stable attachment shape during treatment, assuring its functionality. Mantovani et al.[3] also concluded that the use of bulk-filled resins for attachment fabrication improved dimensional stability when compared to low-viscosity resins, which experience higher polymerization shrinkage. The use of translucent composites generally provides sufficient esthetic acceptance and stain resistance as long as an adequate bonding technique is executed, in which voids (bubbles) in attachment surface and excessive residue (flash) left on tooth surface[4] are avoided.

Several considerations come into play when determining the optimal attachment design for a specific clinical objective: geometry, location, and size.

Geometry (Active Surface Orientation)

At the time of aligner insertion, orthodontic forces will be produced in response to the particular complex pattern of mismatches between plastic and tooth structure. This pattern of mismatch–plastic deformation–orthodontic force is critical for attachment design during digital simulation to produce specific areas (active surfaces) that will contact aligner plastic with predetermined force magnitudes, producing the desired force vectors and consequent tooth movements. Not all the surface area of attachments will be in direct contact with the aligner. The active or functional surfaces can and should be determined with thoughtful biomechanical intentionality, in accordance with clinical objectives (Fig. 2.4A). While the magnitude of the force produced is determined by the amount of mismatch (along with the characteristics of aligner material), the direction of the force will depend on the orientation of the active surface. The principles of mechanics state that the direction of the normal component of the contact force (the vector that in this case acts upon the active surface of the attachment) will always be perpendicular to that surface (see Fig. 2.4B). Identifying the direction of these complementary force vectors is essential for treatment planning, especially when more than one force acts simultaneously. In these cases, the resultant forces must be properly recognized to deliver predictable tooth movements (see Fig. 2.4C).

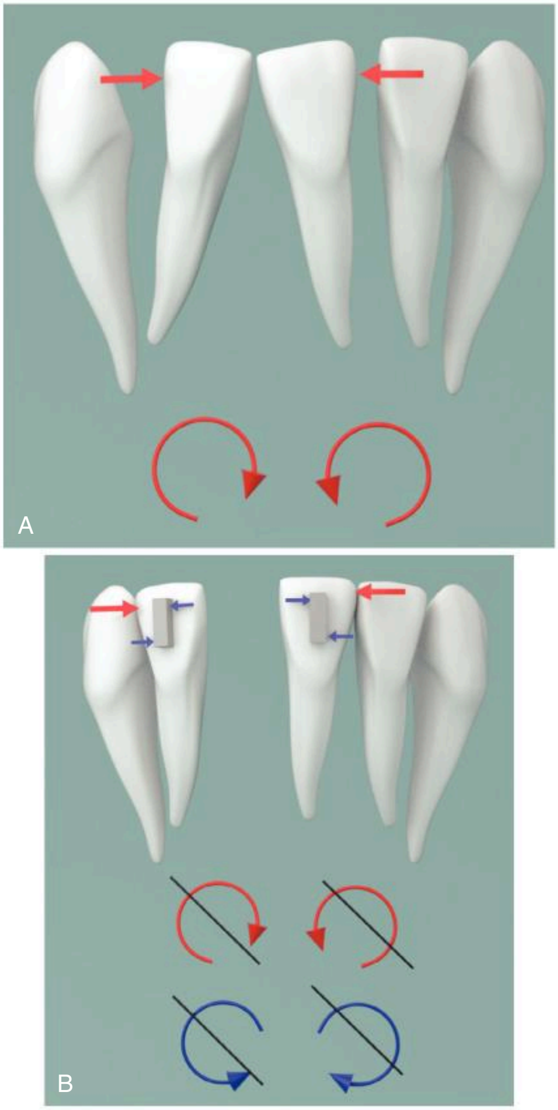

Fig. 2.1 (A) Mesial tipping moments *(red curved arrows)* produced by aligner forces *(red arrows)* occurring during space closure. Antitipping moments *(blue curved arrows)* produced by forces *(blue arrows)* acting at rectangular vertical attachments (B). Opposing moments are canceled out, promoting bodily movement.

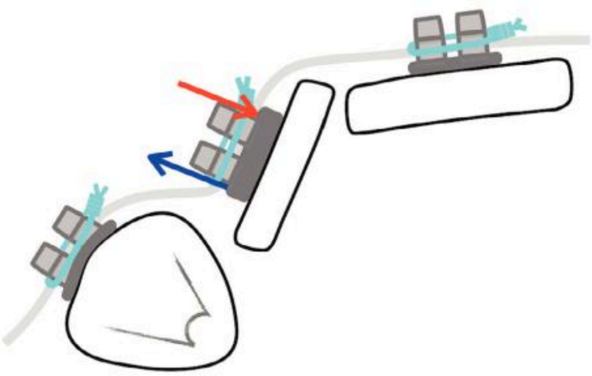

Fig. 2.2 The typical force couple generated during bracket-based alignment of rotated tooth with a fully engaged 0.014 NiTi archwire consists of two force vectors: one that pushes against the posterior wall of the slot *(red arrow)* and a second that pulls away from the same wall *(blue arrow)*.

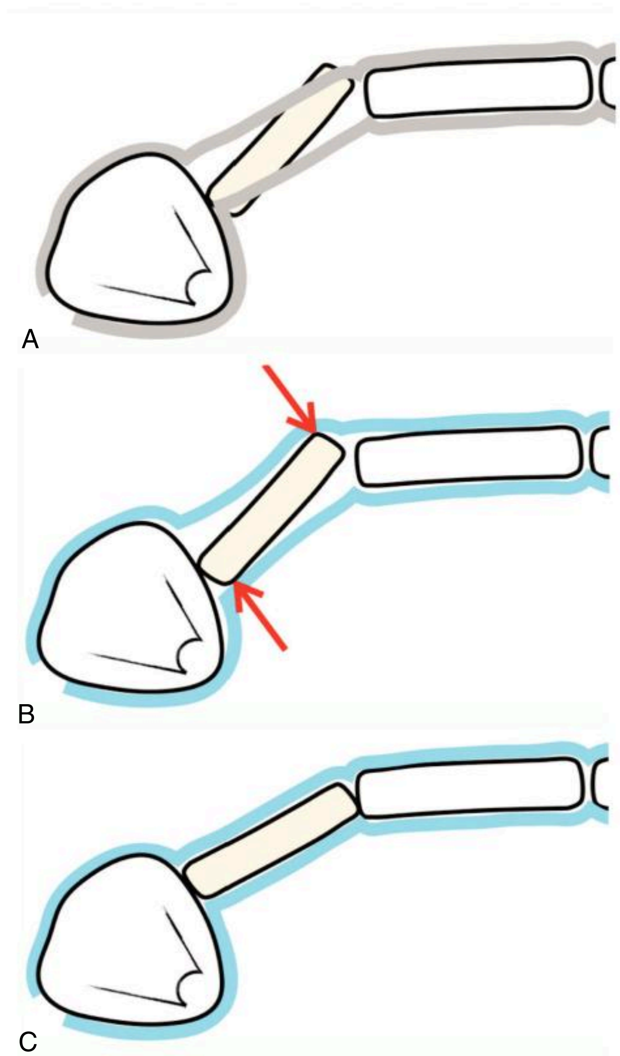

Fig. 2.3 (A) Aligner-tooth mismatch. (B) Elastic aligner deformation and activation of forces upon aligner insertion. (C) Tooth alignment after aligner sequence.

Location

Based on the premise that the magnitude of a moment is proportional to the perpendicular distance between the line of action and the center of resistance, to fully understand the effect of aligner-based orthodontic forces being applied in any particular moment, it is essential to establish this distance in the three planes of space. Once this correlation has been clearly established and quantified, there will be a much clearer picture of the effectiveness of expected rotational moments as well as the possibility of anticipating undesired occurrences such as buccolingual and mesiodistal tipping and intrusion. In a case in which mesiolingual rotation of the tooth is required, localization of attachment A will produce a strong mesial tipping moment and a weak mesiolingual rotational moment (Fig. 2.5A). In this specific clinical situation, a better alternative would be with attachment location B, in which modification in distance from line of action to center of resistance would reduce tipping

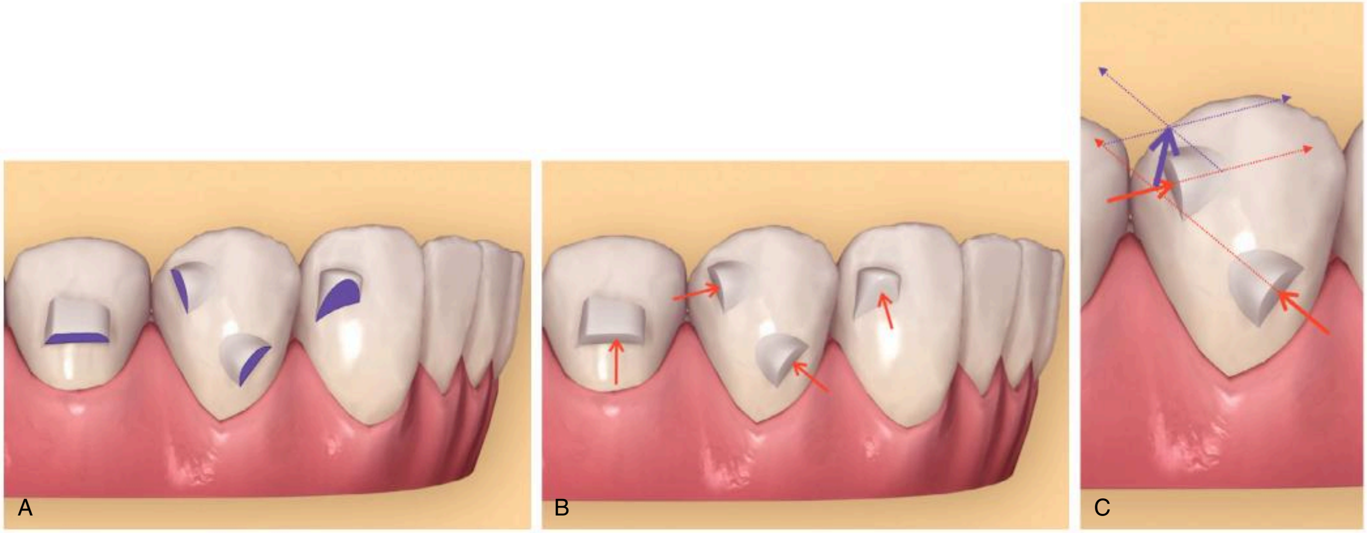

Fig. 2.4 (A) Active surfaces of attachments. (B) Direction of forces acting at active surfaces. (C) Resultant force affecting the first premolar will produce extrusion and clockwise, second-order rotation.

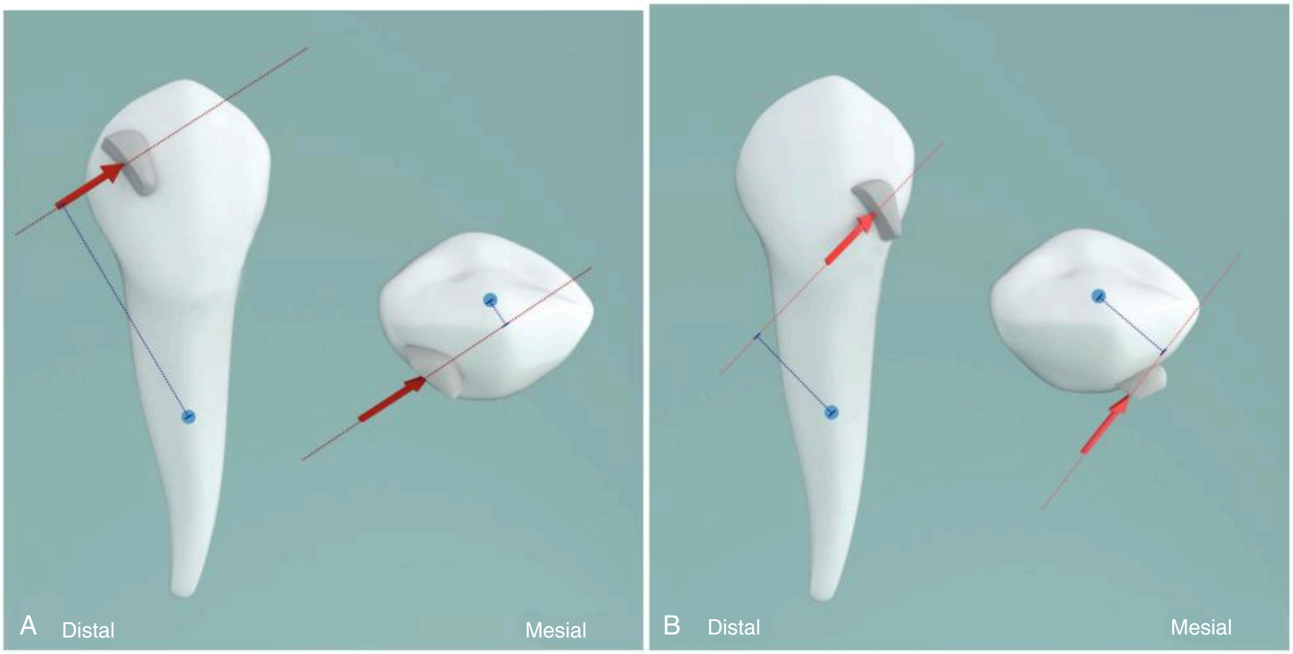

Fig. 2.5 (A) Due to the distance between the center of resistance *(blue dot)* and the line of action *(red dotted line),* large mesial tipping and negligible mesiolingual rotational moments should be expected. (B) A more mesial and apical attachment location will result in reduced mesial tipping and increased mesiolingual rotational moments, increasing clinical efficacy.

tendency as well as increase mesiolingual rotational capacity (see Fig. 2.5B).

Another example of the influence of attachment localization is observed during transverse arch expansion, when buccal tipping of posterior segments is detrimental to treatment objectives. A recent unpublished finite element analysis (FEA) study[5] of the mechanical effects of the bonding position of rectangular horizontal attachments found that the resultant tipping moment acting on the molars was greater when located on the lingual surface of the first upper molars versus the labial surface (Fig. 2.6).

Size

Attachment size is important because of its mechanical and esthetic implications. Small configurations are desirable because they are less noticeable; however, as size diminishes, so does the ability to produce predictable forces due to reduced active surface area. On the other hand, larger attachment designs are desirable because of their increased biomechanical capabilities, but they result in increased aligner retention (with subsequent patient discomfort) and negative esthetic perception, especially with high-profile configurations in anterior teeth.

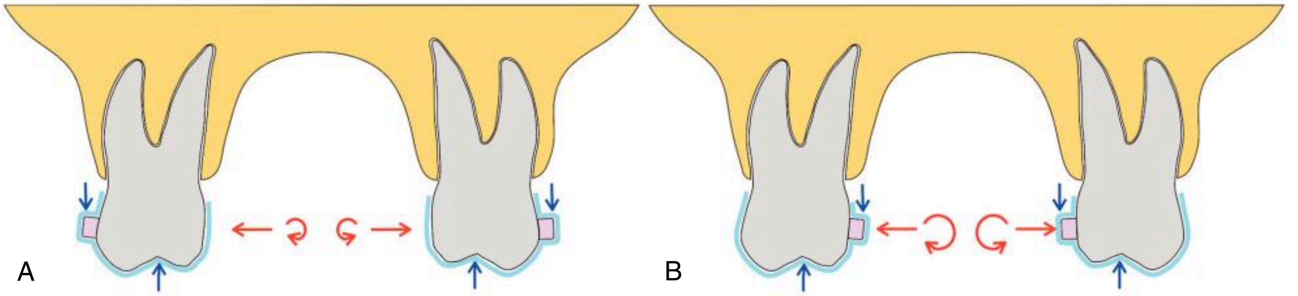

Fig. 2.6 During expansion, labial attachment location (A) produced smaller net buccal molar tipping moments than lingually bonded attachments (B).

Functions

PROVIDING ALIGNER RETENTION

For aligner-based orthodontic forces to affect teeth as conceived in digital simulation, the aligner must be stably seated after insertion and remain so for the duration of treatment. Occasionally, deficient adaptation of the aligner may occur, usually resulting from faulty fabrication, but may also occur due to the many reactive forces produced once properly fitted. For example, as a frequent response to intrusive forces acting on the posterior teeth, the aligner will tend to be dislodged in the anterior segment, and vice versa. The use of intermaxillary elastics, especially when they are engaged directly to the aligner, will also tend to vertically dislodge it in the direction of the elastic force. Bonding retentive attachments on teeth adjacent to those receptors of the elastic force is recommended to maintain proper aligner engagement (Fig. 2.7A). A study by Jones et al.[6] suggests that the optimal attachment configuration, when high aligner retention is imperative, is a nongingivally beveled (such as a horizontal rectangular or occlusally beveled) design, as close to the gingival margin as possible (see Fig. 2.7B). As a general rule of attachment design, occlusal beveling will facilitate aligner insertion due to the inclined plane configuration as well as increase force (and discomfort) required for aligner removal.

AVOIDING ALIGNER "SLIPPING"

Especially when rotating rounded teeth, the sum of a series of tangential forces is responsible for tooth movement (Fig. 2.8A), causing inconvenient displacement (slipping) of the aligner in relation to the tooth surface, reducing the system's efficacy and predictability, and resulting in lack of full expression of digitally planned rotation with the tooth lagging behind the corresponding aligner stage. Clinically, incomplete rotation and loss of tracking will be observed, manifesting as a space between tooth and plastic (see Fig. 2.8B). Appropriately designed attachments can help the aligner lock in to the tooth crown, greatly reducing this undesired slipping effect.

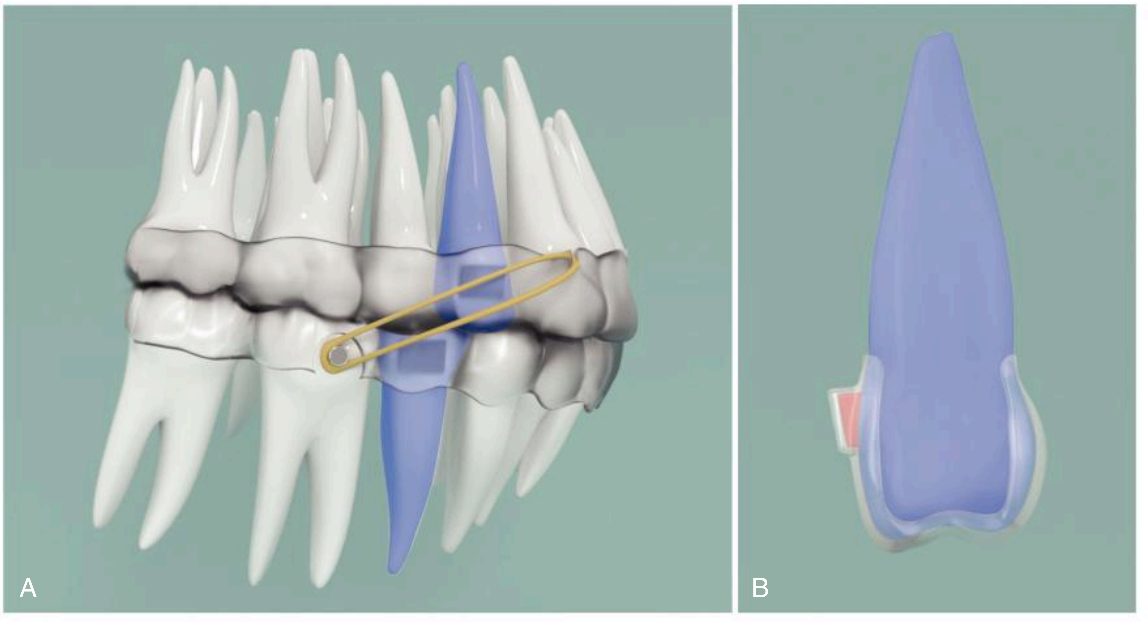

Fig. 2.7 (A) Attachments located on teeth adjacent to force application increase aligner retention when using intermaxillary elastics. (B) Attachment position close to the gingival margin and occlusally beveled geometry is ideal for aligner retention.

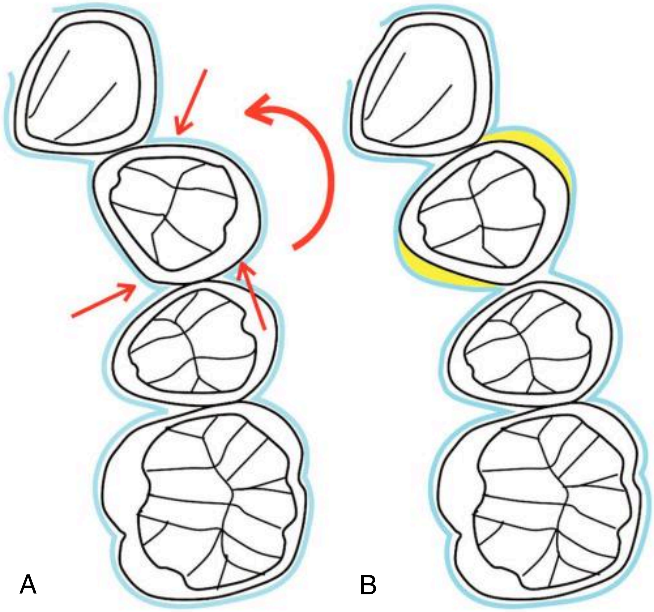

Fig. 2.8 (A) Multiple tangential forces *(red arrows)* acting during aligner-based, bicuspid rotation. (B) Due to slipping effect, incomplete expression of expected rotation with space between tooth and aligner *(in yellow)* will be observed.

DELIVERING PREDETERMINED FORCE VECTORS

The fundamental purpose of composite attachments in aligner orthodontics is to produce specific, complementary force vectors required for predictable tooth movement, which are not possible with the sole use of aligners thermoformed with existing materials (Fig. 2.9A).

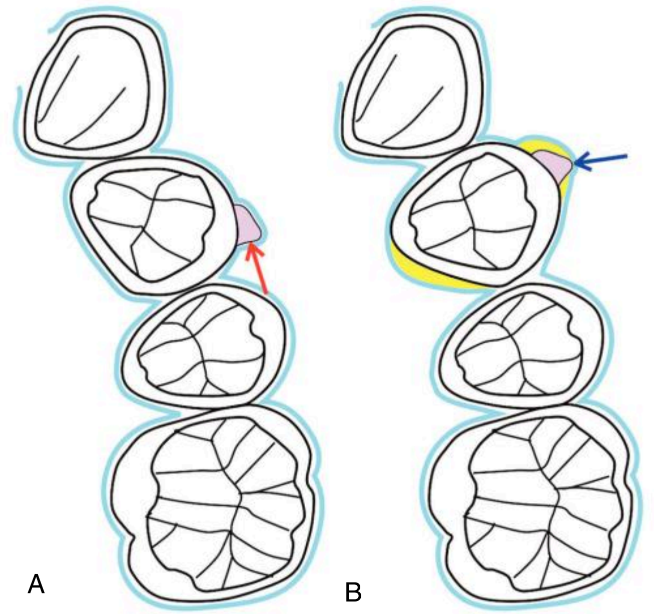

Fig. 2.9 (A) Properly designed attachments produce complementary force vectors required for predictable tooth movement. (B) Polymer stress relaxation and creep, along with incomplete rotation and unintended force *(blue arrow),* may occur during sequence of aligner-based, tooth rotation stages.

Unfortunately, to harness the full clinical potential of bonded attachments, current polymers have yet to resolve limitations associated with their viscoelastic and hygroscopic nature. Once inserted, the initial force produced by the aligner after it is elastically deformed is not constant and will decline with time. This time-dependent reduction of force under constant deformation is called stress relaxation.[7,8] Not infrequently, due to unwarranted localized stress (caused by excessive mismatch), lack of compliance, or shortcomings inherent to the polymer, the aligner is not able to accommodate the attachment. When forces exerted upon the aligner exceed its capability to adjust to the new position, unintended forces will appear, the tooth will lag behind, and control will be lost (see Fig. 2.9B). Fig. 2.9 illustrates how this phenomenon is responsible for the incomplete expression of the expected tooth movement, where only 35 of the 45 degrees of predicted rotation were achieved after completion of the entire sequence of stages. In this case, after the aligner is removed, plastic deformation of the aligner material is evident. This time-dependent plastic deformation under constant force is called creep and is attributed to reorganization of polymer chains.[9] It is important to underline that this permanent deformation, so detrimental to clinical performance of plastic aligners, is not caused by a violation of the materials' elastic limit but is due to a time-dependent, mechanochemical phenomenon of a different nature.

This inherent flaw of aligner plastics is the major cause behind the inconsistent force levels and plastic deformation that result in one of the most dreaded occurrences for orthodontists practicing aligner orthodontics, now commonly referred to as loss of tracking. Fig. 2.10 illustrates an example of the clinical manifestations of this complex reality in which mesiolingual rotation and extrusion of a first upper left bicuspid were incorporated in the digital treatment plan but did not fully occur. The lack of coincidence between the attachment and its corresponding recess in the aligner is unambiguous evidence of loss of tracking, a contingency that in many cases must be resolved by obtaining updated digital dental models from which a new treatment sequence must be designed.

Basic Attachment Configurations in Current Aligner Orthodontics

The evolution of attachments, derived from a better understanding of the effect of geometry, location, and size of the composite structure, has resulted in a diverse array of configurations with well-defined biomechanical objectives.

VERTICAL CONTROL

The tendency of conventional fixed orthodontics to increase vertical dimension, especially in open-bite patients with increased anterior facial height, has been studied.[10] Aligner-based treatment has proven to be an effective alternative for open-bite correction[11-13] with encouraging results.[13] Successful treatment often includes the sum of complementary clinical strategies such as the combined effect of counterclockwise mandibular rotation, posterior intrusion, and anterior extrusion.[14]

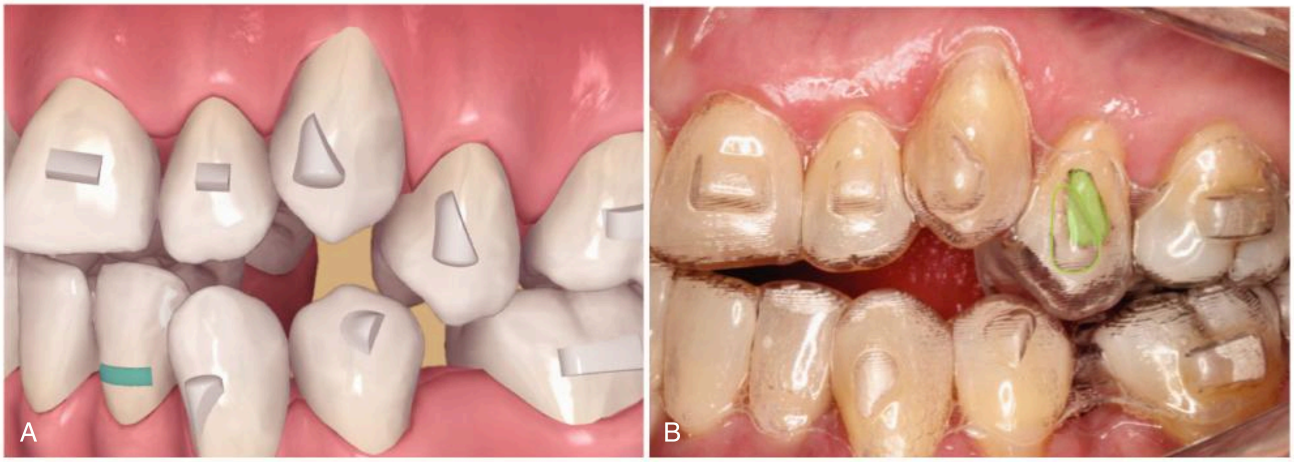

Fig. 2.10 (A) Image from ClinCheck treatment plan. (B) Loss of tracking with incomplete expression of rotation and extrusion of left upper bicuspid. Lack of coincidence between attachment *(green shaded area)* and its corresponding recess in the aligner *(green outline)* is observed.

ANTERIOR EXTRUSION

Correction of open bite based solely on anterior extrusion is to be viewed with caution because of possible negative effects such as root resorption, periodontal deterioration, instability, and unfavorable esthetics.[15,16] Along with these clinical restrictions, aligner extrusion poses mechanical limitations in anterior teeth in which buccal and lingual crown surfaces converge towards the incisal edge (Fig. 2.11A), facilitating aligner dislodgement and rendering this type of tooth movement virtually impossible (see Fig. 2.11B) without the use of supplementary composite attachments. A gingivally oriented, inclined plane configuration (Fig. 2.12) provides a force system that improves predictability of this type of movement. The importance of attachment design can be illustrated with a graphic simplification of a complex interaction of vectors. The resultant force acting on the

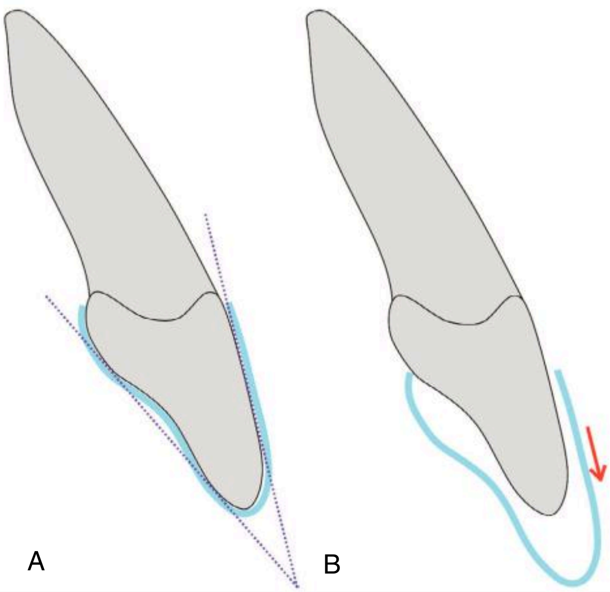

Fig. 2.11 (A) Converging buccal and lingual crown surfaces. (B) Undesired aligner dislodgment during extrusive movement.

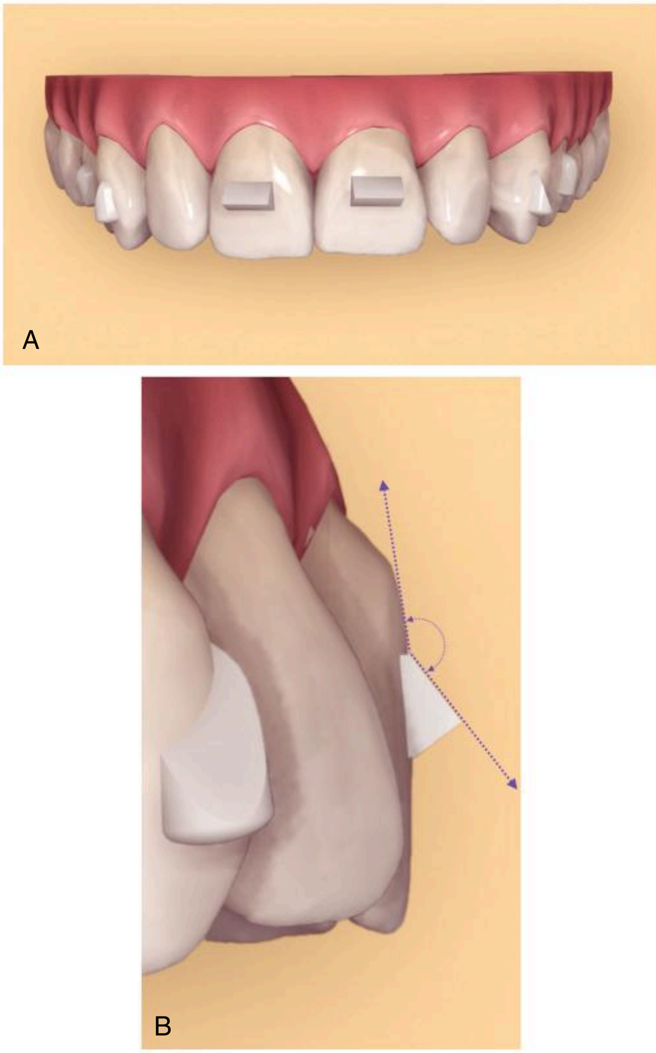

Fig. 2.12 (A) Optimized Extrusion Attachments (Align Technology, Santa Clara, CA) on central incisors. (B) Gingivallyoriented inclined plane with optimal active surface angulation.

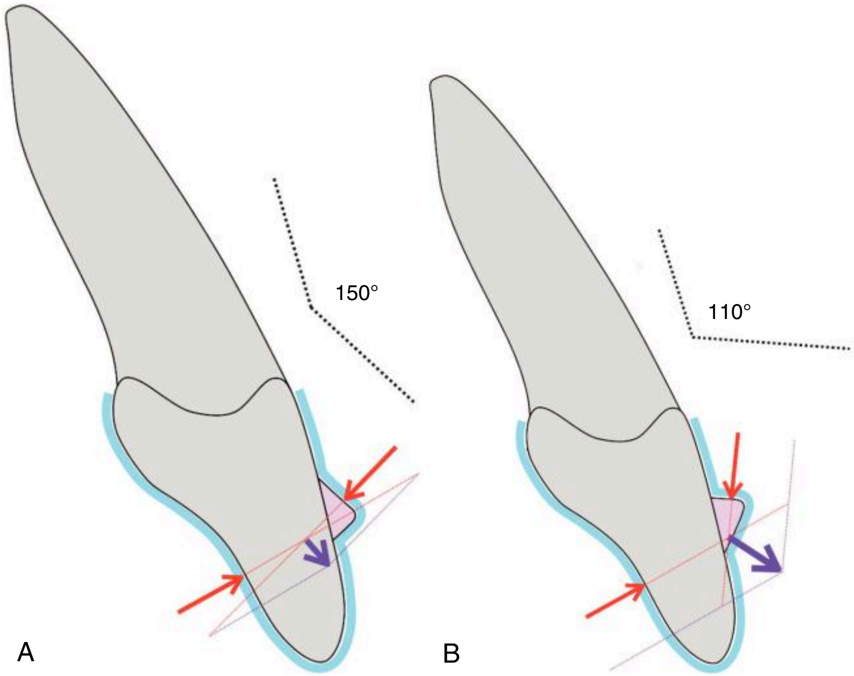

Fig. 2.13 (A) Forces transmitted by the aligner *(red arrows)* and resultant forces *(purple arrows)* acting on the tooth. (B) A reduction of the angle between active attachment surface and buccal tooth surface produces stronger resultant extrusive forces.

incisor is derived from the two red arrows that represent buccal and lingual forces present during aligner-based extrusion (Fig. 2.13A). Reducing the angle formed by the active surface of the attachment and the buccal surface of the tooth will result in a stronger resultant force (see Fig. 2.13B). Clinicians must be wary of excessive reduction of this angle, which along with excessive force may produce difficulty of aligner-attachment engagement with the ensuing localized plastic deformation.

POSTERIOR INTRUSION

Recent studies suggest that the presence of interocclusal plastic during aligner treatment[17,18] may produce a bite-block effect that potentiates bite closure and posterior intrusion capabilities. This improves treatment outlook, especially in cases in which anterior extrusion is not desirable and intrusion of posterior teeth, with the consequent mandibular rotation, are to be considered as part of the strategy for bite closure. As mentioned previously, intrusive forces acting in the posterior region will tend to dislodge the aligner in the occlusal direction. Even with light posterior intrusive forces, an opposite, reactive force should be expected in the anterior arch that will tend to vertically dislodge the aligner (Fig. 2.14). Gingivally positioned rectangular horizontal or occlusally attachments beveled towards the incisal edge should provide the necessary aligner stability for optimal treatment progress.

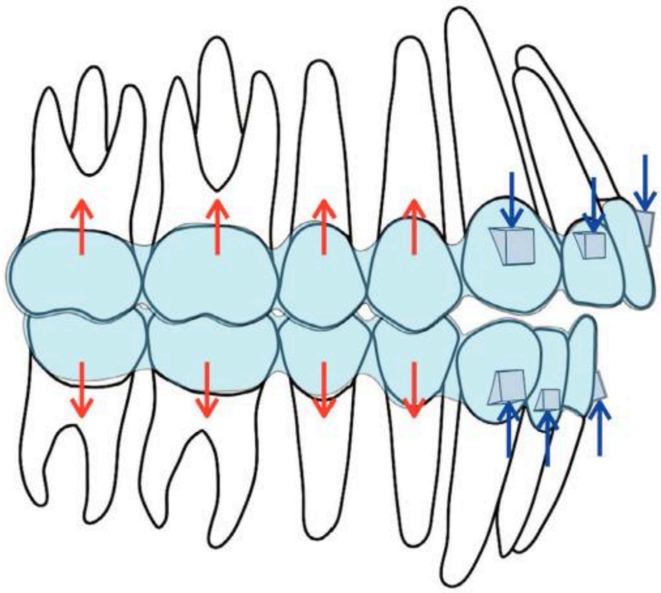

Fig. 2.14 Intrusion in the posterior segment *(red arrows)* produces reactive forces that will tend to dislodge the aligner anteriorly *(blue arrows)*. Adequate attachment selection on anterior teeth will counteract this undesired occurrence.

FIRST-ORDER CONTROL

Rotation

Rotation of teeth with rounded anatomies such as bicuspids and molars is another movement particularly difficult[19] to accomplish with plastic aligners without the help of specialized attachments, which improve biomechanical capabilities.

The limitations associated with rounded crown morphologies are due to some extent to three particular realities:

- As mentioned previously, in rounded crown configurations, the tangential nature of the forces produced during aligner-based tooth rotation, along with very low coefficient of friction between the two surfaces, facilitates a slipping effect between the aligner and tooth.

- The line of action of the normal force vectors resultant from tangential forces delivered during rotation of rounded crowns crosses at a short distance from the center of resistance, resulting in weaker rotational moments (Fig. 2.15A). These difficulties are overcome by means of specifically designed composite attachments, with properly oriented active surfaces, reconfiguring resultant force vectors with increased intervector distance (see Fig. 2.15B) and resulting in stronger, more effective rotational moments. Additionally, the attachment structure blocks the slipping effect between aligner and tooth surface, allowing a fuller expression of desired tooth movement.
- Another effect observed in laboratory experimentation[20] as well as in clinical practice is unintended intrusion during rotational tooth movement. In another study using finite element analysis,[21] researchers demonstrated that during aligner-based rotation of an upper canine without attachment, not only did the tooth lag behind the corresponding aligner stage almost by 30%, but it also displayed clinically significant intrusive forces that were found to be 3.71 times greater without than with attachments (Fig. 2.16). The same numeric model, from an incisal perspective, revealed distinct pressure areas on the mesial and distal slopes of the incisal ridge (Fig. 2.17), to which this undesirable effect can be attributed and corresponds to the normal components of the forces imparted by the aligner. Due to the orientation of

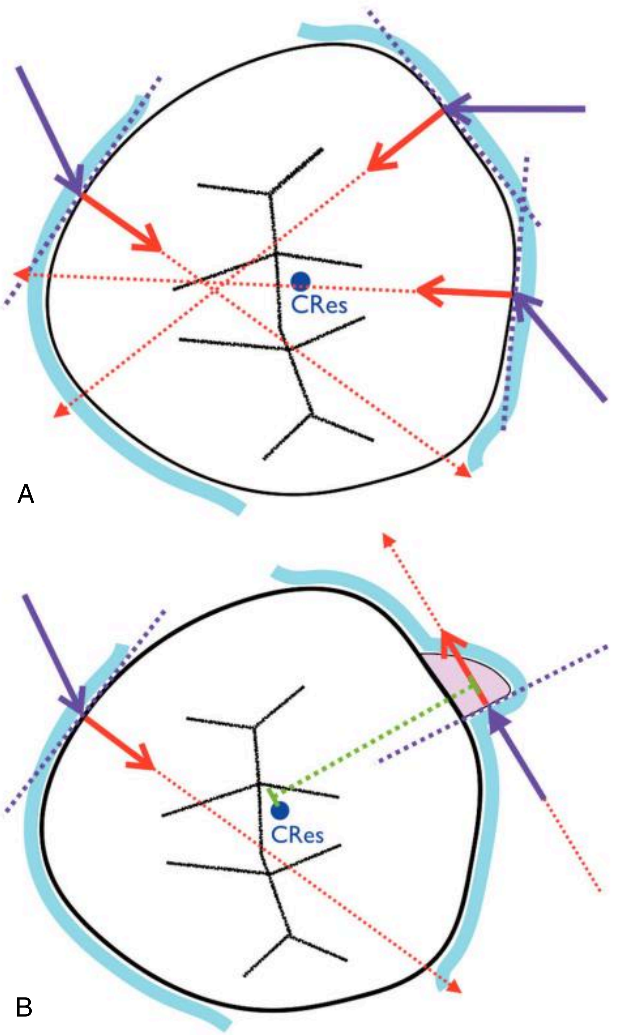

Fig. 2.15 (A) Rotational forces produced by the aligner *(purple arrows)* are transmitted to the tooth as normal force components *(red arrows)*, which are perpendicular to tooth surface tangents *(purple dotted lines)*. (B) Incorporation of bonded attachment increases the magnitude and efficacy of rotational moment by increasing the perpendicular distance *(green dotted line)* between the line of action *(red dotted line)* and the center of resistance *(CRes)*.

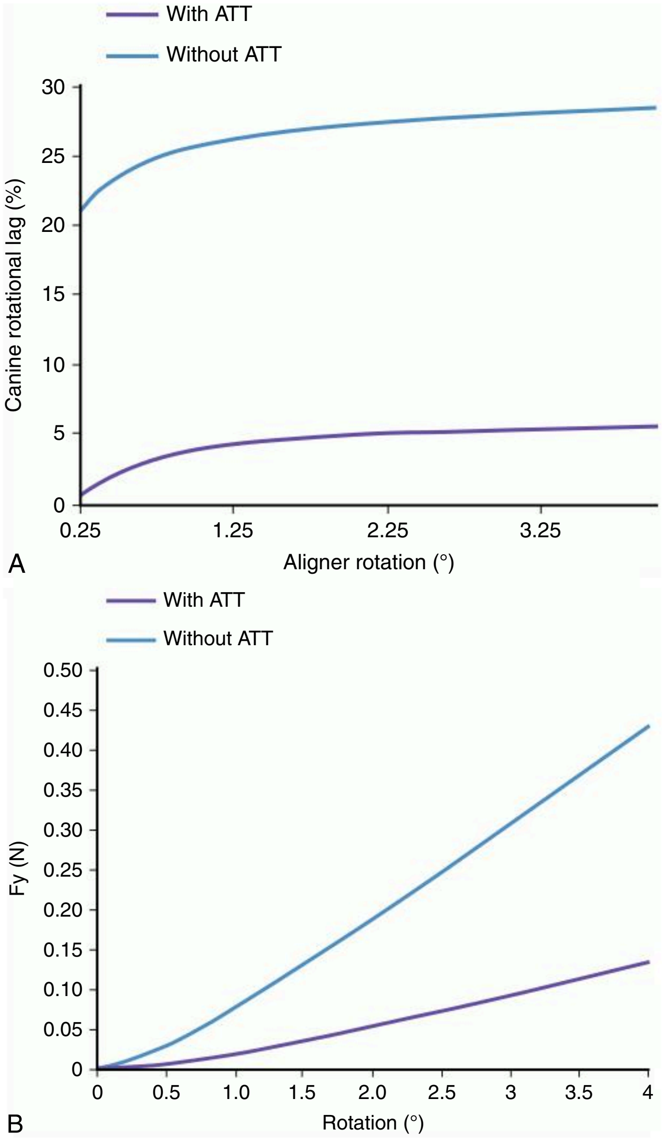

Fig. 2.16 (A) Without attachment, the tooth lagged behind the aligner almost by 30%. With attachment incorporation, this lag dropped to 5%. (B) Intrusive forces observed at the periodontal ligament without attachments was 0.078 N for every degree of rotation, while with attachments the load was reduced to 0.021 N for every degree. *ATT*, Attachment. (Adapted from Gómez JP, Peña FM, Valencia E, et al. Effect of composite attachment on initial force system generated during canine rotation with plastic aligners: a three dimensional finite elements analysis. *J Align Orthod*. 2018;2[1]:31-36.)

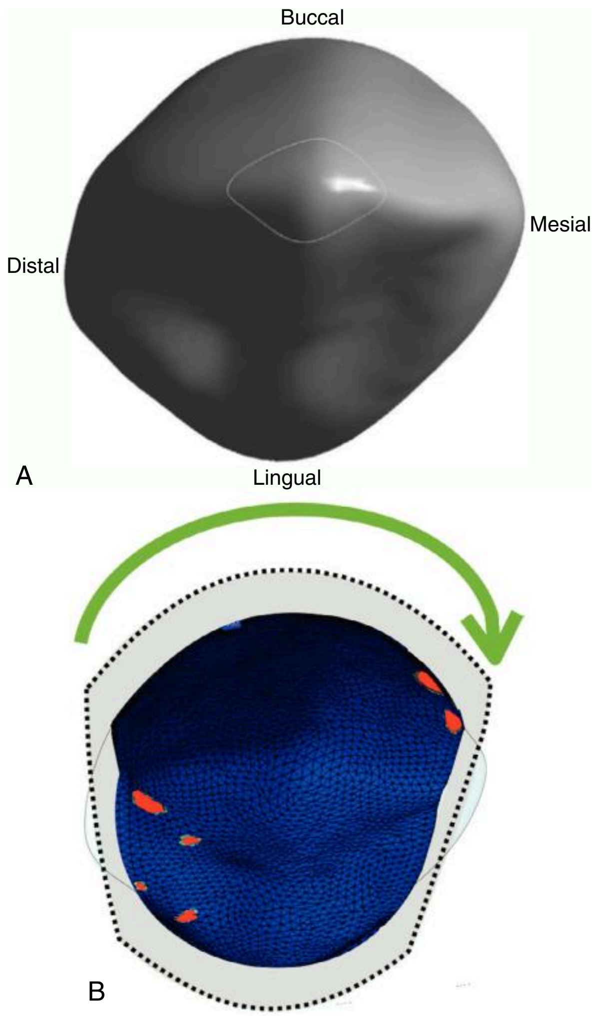

Fig. 2.17 (A) Digital image of occlusal view of right upper canine. Occlusal view of finite element method simulation of upper right canine during mesiolingual rotation. (B) Distinctly intrusive pressure areas *(red)* on mesiolabial and distolingual aspects of the tooth crown appear upon aligner insertion. The dotted line represents the aligner's profile. (Adapted from Gómez JP, Peña FM, Valencia E, et al. Effect of composite attachment on initial force system generated during canine rotation with plastic aligners: a three dimensional finite elements analysis. *J Align Orthod*. 2018;2[1]:31-36.)

the surface area, these forces are clearly intrusive. This undesirable intrusive effect can be reduced with appropriate attachment design, orienting the active surface at an angle in which the normal component of the force transmitted by the aligner will express an extrusive tendency (Fig. 2.18).

SECOND-ORDER CONTROL

Tipping movements are easily achieved with bracket-based biomechanics (Fig. 2.19A). On the other hand, aligners lack control of mesiodistal root position due to the system's inability to produce the required force couples, explaining why modification of anterior teeth angulation is so challenging. To improve second-order capabilities, aligner-based systems rely on specialized attachments that generate equivalent force couples (see Fig. 2.19B).

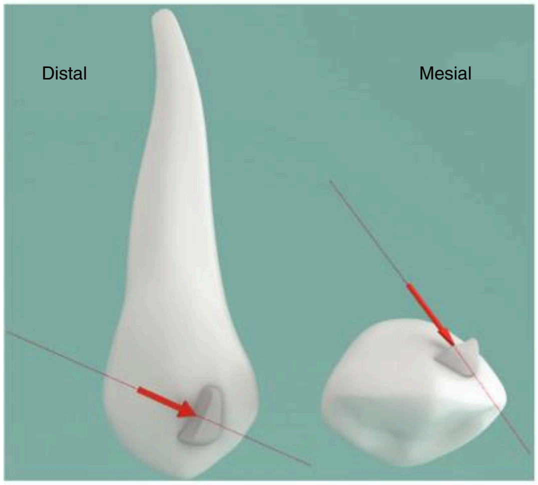

Fig. 2.18 Optimized Rotation Attachment (Align Technology, Santa Clara, CA) with active surface oriented to provide a compensatory extrusive force.

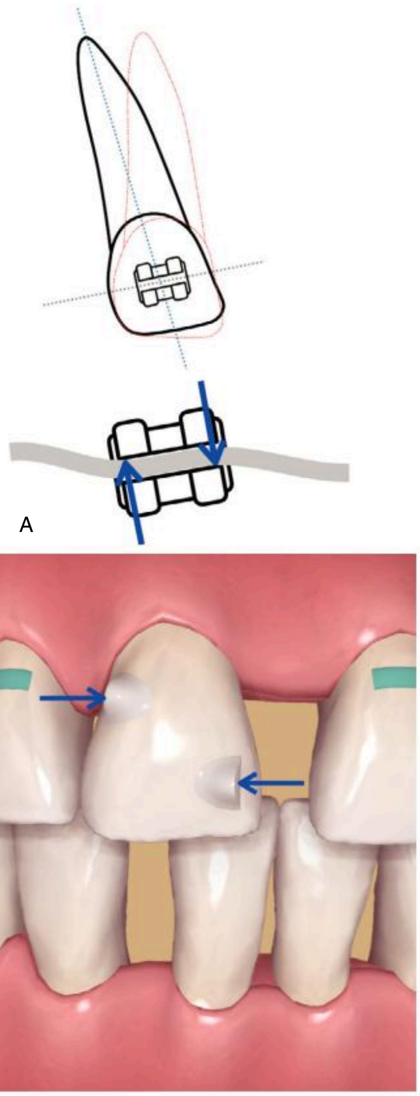

Fig. 2.19 (A) Force couple produced during bracket-based correction of excessive mesial tip. (B) Equivalent force couple produced at Optimized Root Control Attachments (Align Technology, Santa Clara, CA) during aligner-based tipping.

Anterior Teeth

Successful closure of extraction spaces with aligners is also particularly difficult without excessive tipping in the direction of tooth movement. Numeric models[22] describing tooth displacement (Fig. 2.20) and periodontal ligament (PDL) strain (Fig. 2.21) patterns during distal tooth movement have shown that Optimized Root Control Attachments (Align Technology, Santa Clara, CA), when bonded to upper cuspids, produce force systems capable of controlling undesired inclination during extraction space closure.

Posterior Teeth

In the posterior segment, tipping movements are not easily obtained with aligner-based mechanics without combining fixed auxiliaries (such as buccal tubes, power arms, etc.), and these tooth movements, although possible, require sophisticated treatment planning, clinical expertise, and patient cooperation. Additionally, as with most complex force systems, specialized attachments must be designed to enhance the biomechanical capabilities of the aligner. The goal of this configuration of composite attachments is to produce a force couple (and its corresponding moment) that will incline the tooth in the desired direction (Fig. 2.22A). Alternatively, the rectangular, horizontal attachment can be replaced with two shorter attachments, with variable distance separating them according to the clinician's plan (see Fig. 2.22B). It is important to remember that the magnitude of the moment will depend on the amount of activation (and corresponding mismatch) prescribed in the digital treatment plan. On the other hand, the magnitude of the individual force vectors acting at the

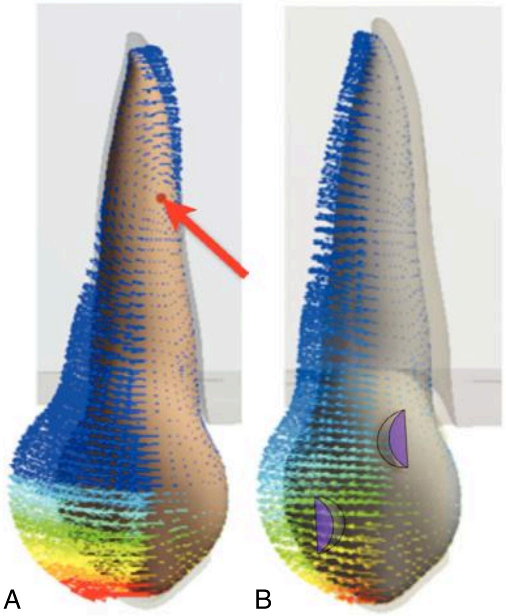

Fig. 2.20 Tooth displacement patterns during aligner-based distalization of upper right canine. (A) Without attachments, distinct uncontrolled distal tipping was observed, with center of rotation between apical and middle thirds of the root *(red arrow)*. (B) With attachments, the canine expressed distal bodily movement. (Adapted from Gomez JP, Peña FM, Mart√≠nez V, et al. Initial force systems during bodily tooth movement with plastic aligners and composite attachments: a three-dimensional finite element analysis. *Angle Orthod*. 2015;85[3]:454-460.)

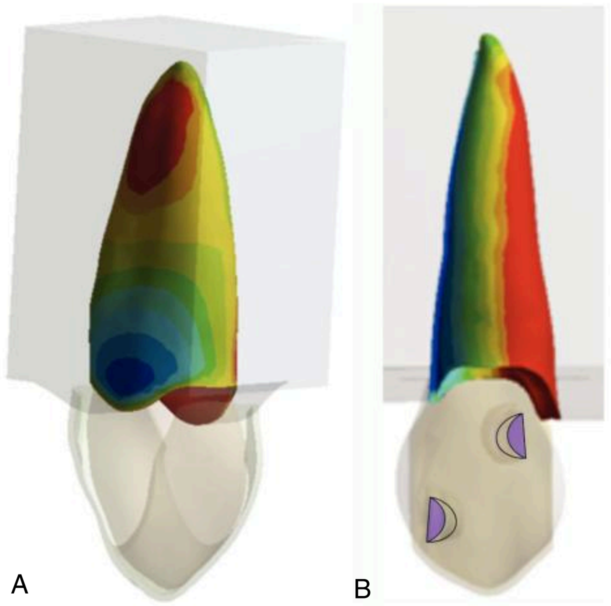

Fig. 2.21 Periodontal ligament strain patterns during aligner-based distalization of upper right canine. (A) Without attachments, distocervical pressure *(in blue)* and distoapical tension *(in red)* areas were observed, typical of uncontrolled distal tipping. (B) With attachments, uniform pressure along the distal root surface *(in blue)* and uniform tension *(in red)* along the medial surface, typical of distal bodily movement, were observed. (Adapted from Gomez JP, Peña FM, Martínez V, et al. Initial force systems during bodily tooth movement with plastic aligners and composite attachments: a three-dimensional finite element analysis. *Angle Orthod*. 2015;85[3]:454-460.)

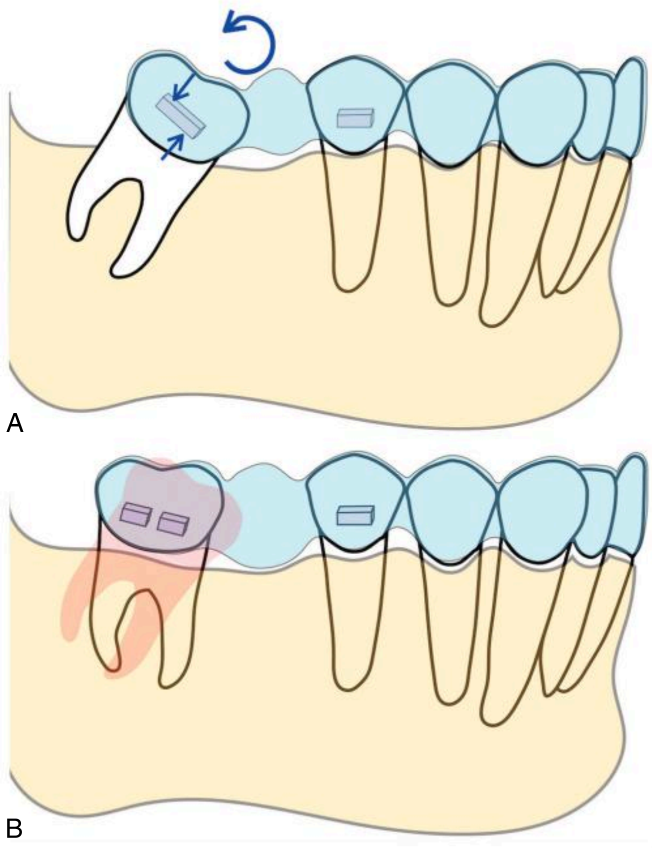

Fig. 2.22 (A) Uprighting moment produced at single rectangular horizontal attachment. (B) Alternative twin attachment configuration.

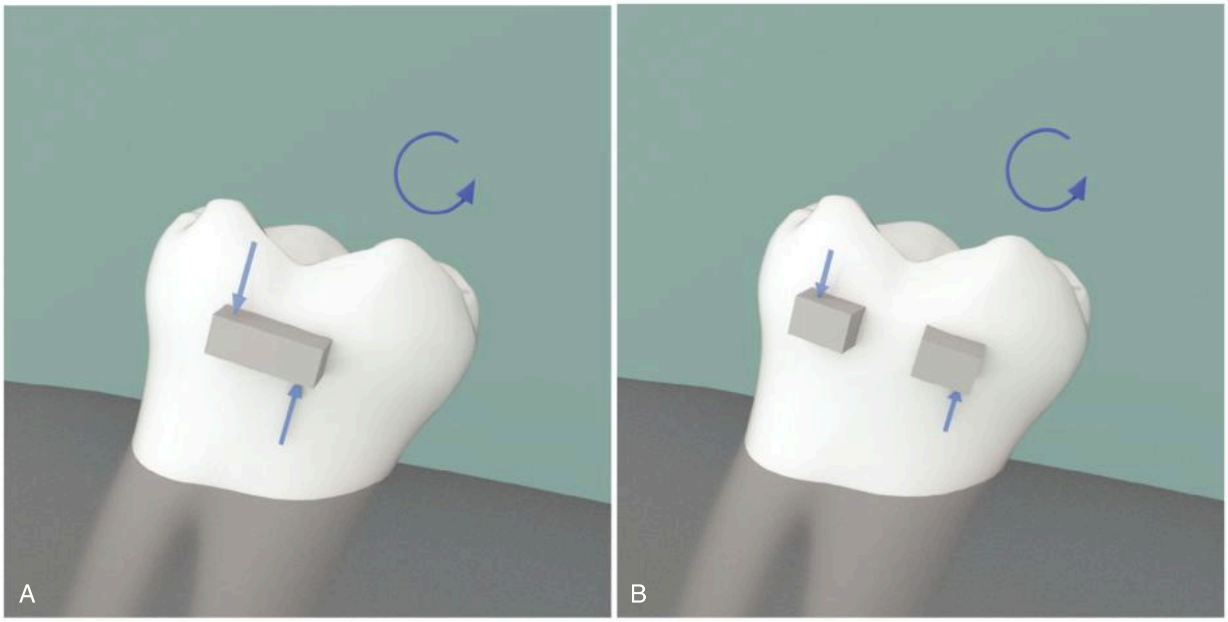

Fig. 2.23 Producing equivalent moments *(curved arrows)*, an increase in intervector distance proportionately reduces force magnitude *(blue arrows)* acting at attachment surface. Two degrees of distal tipping with a 4-mm rectangular attachment (A) will produce higher forces on the aligner than with a two-attachment configuration that significantly separates the force vectors (B) of the acting couple.

aligner-attachment contact will depend on the distance between these two vectors. As the distance between the vectors decreases, the forces produced at the active surfaces of the attachments to produce an equal uprighting moment will increase (Fig. 2.23). This is an extremely important detail, considering aligner polymers' high susceptibility to creep-related plastic deformation, which requires the use of the lowest forces possible.

Differential Moments

An effective strategy for controlling anchorage during extraction space closure is anterior and posterior moment to force ratio manipulation in favor of the segment that requires anchorage.[23] As shown in Fig. 2.24A, a reciprocal moment to force ratio between anterior (alpha) and posterior (beta) segments will result in group B space closure, in which both segments will meet at the middle of the extraction space resulting in class II malocclusion (see Fig. 2.24B). To obtain class I occlusion, posterior anchorage must be reinforced. Bonding rectangular horizontal attachments on the buccal surface of posterior teeth (Fig. 2.25A) will result in clockwise moments that will resist mesialization of posterior teeth, resulting in group A space closure and the desired class I occlusal outcome (see Fig. 2.25B).

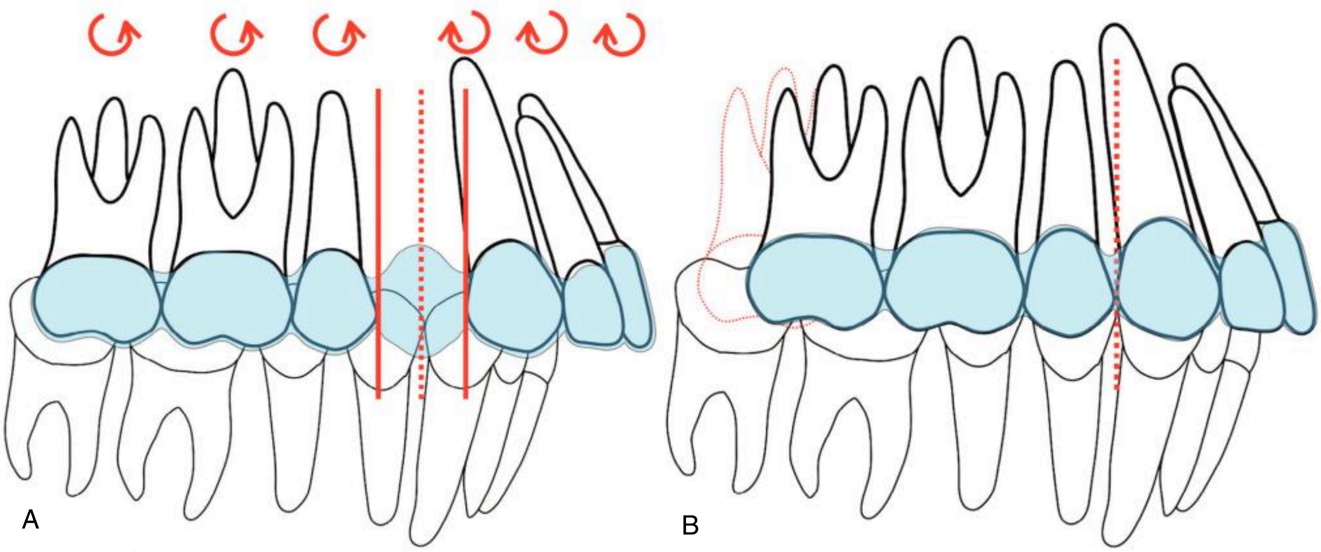

Fig. 2.24 Class II case in which reciprocal moments between anterior and posterior segments during extraction space closure (A) will result in 50% anchorage loss and class II occlusion (B).

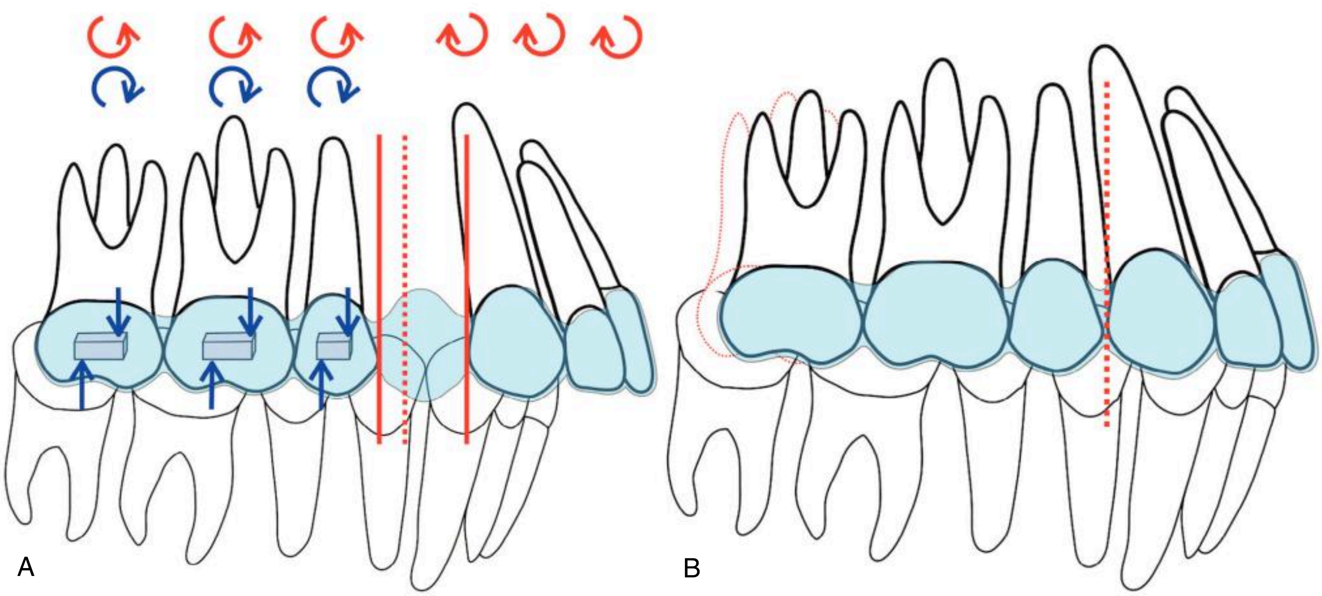

Fig. 2.25 Clockwise moments *(blue curved arrows)* produced by attachments bonded to posterior teeth (A) will counteract posterior anchorage loss, reducing it to 25%, resulting in class I occlusion (B).

THIRD-ORDER CONTROL

Anterior Torque

Torque modification of anterior teeth with conventional brackets is easily achieved by means of preactivation of the rectangular archwire, producing a complex, high-force couple when fully engaged in the rectangular slot (Fig. 2.26A). Accomplishing the same type of movement with plastic aligners demands an equivalent couple, derived from horizontal, parallel, and opposing forces applied on buccal and lingual surfaces (see Fig. 2.26B). Because of the relatively ample distance between the couple vectors, force magnitudes required for third-order control are significantly lower than those required in equivalent bracket-based force systems.

Posterior Torque

Correction of transverse deficiencies by expansion of the dental arch continues to be a challenging clinical objective with current aligner-based techniques.[24] This has led to a widespread tendency of clinicians to overcorrect expansive movements in 3D treatment planning.[25] The main reasons for lack of efficacy and predictability in the transverse plane are excess buccal tipping and insufficient force levels.

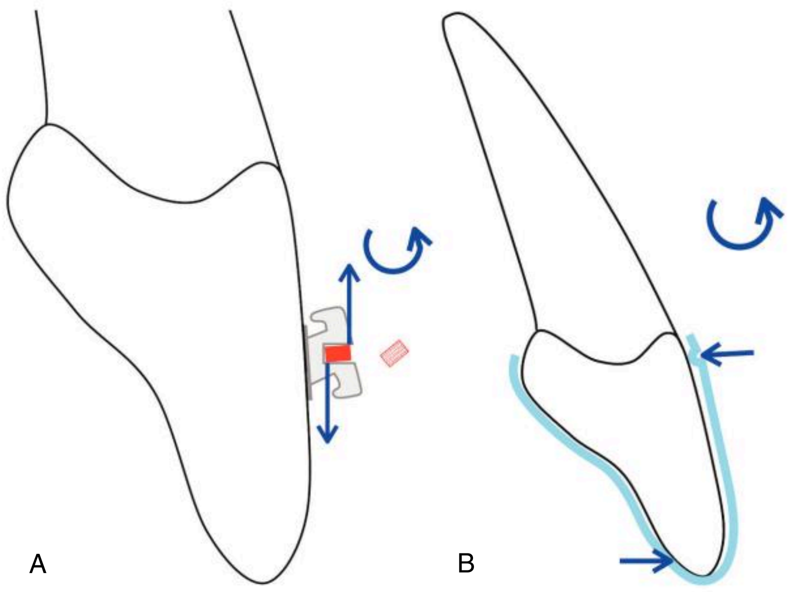

Fig. 2.26 (A) By preactivating *(*red shaded*)* and subsequently inserting *(red)* the archwire, a force couple *(blue arrows)* and its corresponding counterclockwise moment *(blue curved arrow)* will be produced. (B) The same positive torque can be achieved with aligners by producing an equivalent couple, with lower forces and increased intervector distance.

Excess Buccal Tipping

Because forces act at a distance from the molar's center of resistance (Fig. 2.27A), buccal tipping must always be expected when expansive forces are applied, especially when aligner-based forces are used.[26] With negligible friction (and consequent pervasive sliding effect) between plastic and tooth crown, and relatively low stiffness as uncontrolled tipping occurs during expansion, the aligner will tend to flare, losing control as dissociation between tooth and plastic occurs (see Fig. 2.27B).

The use of attachments (horizontal rectangular or occlusally beveled) bonded to the buccal surface of posterior teeth helps improve third-order control by counteracting the undesired tipping moment as a result of a couple with opposite forces acting at the occlusal surface and at the gingival aspect of the attachment (Fig. 2.28).

Insufficient Force Levels

Due to their horseshoe-shaped geometry, orthodontic aligners deliver expansive forces in a particular manner in which an anteroposterior decreasing force gradient will be observed (Fig. 2.29). Because of this distinct mode of force transmission, researchers have found that efficacy (planned vs. final increase in arch width) of upper arch expansion dropped from 70% at first premolars to 29% at the second molar.[24,25] Increasing force levels during arch expansion by using thicker or lower elastic modulus polymers for aligner fabrication would improve this shortcoming, but not without the inconvenient increase in force levels of all other tooth movements programmed during the expansive stages. An alternative solution is the use of intermaxillary elastics, especially in cases with reduced anterior facial height, in which buccolingual tipping and

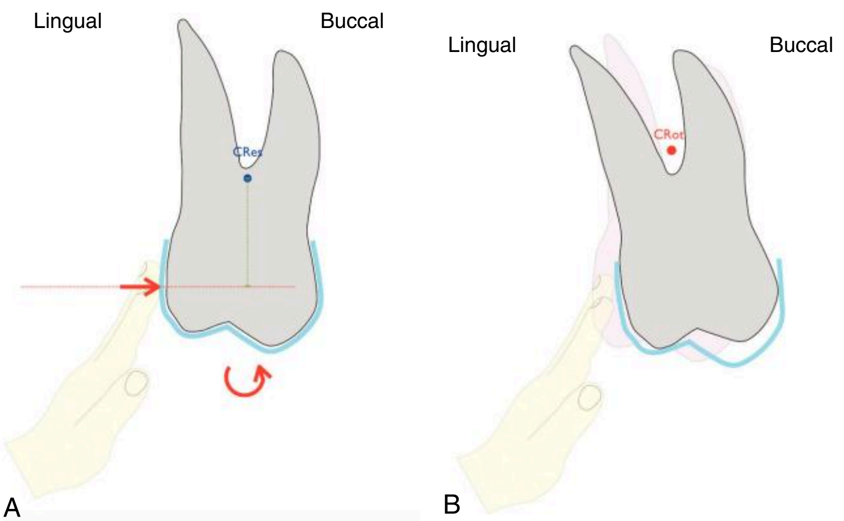

Fig. 2.27 (A) Aligner-based expansive force *(red arrow)* applied at a distance from the center of resistance *(CRes)* will produce counterclockwise moment *(red curved arrow)*. (B) Without preventive measures, buccal tipping with center of rotation *(CRot)* above the furcation will occur, followed by aligner deformation and loss of control.

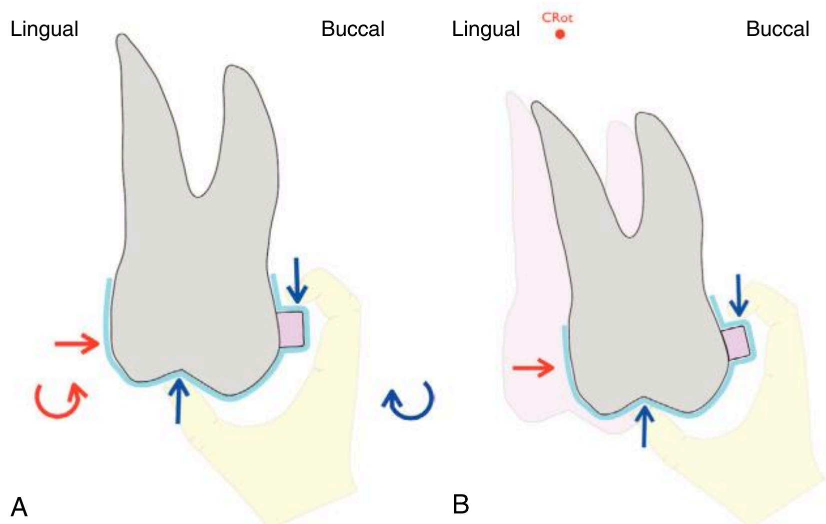

Fig. 2.28 (A) Opposing forces *(blue arrows)* acting at the occlusal surface and gingival aspect of a rectangular horizontal buccal attachment will provide a clockwise moment *(blue curved arrow)* that reduces buccal tipping, with apical migration of the center of rotation *(CRot)* (B).

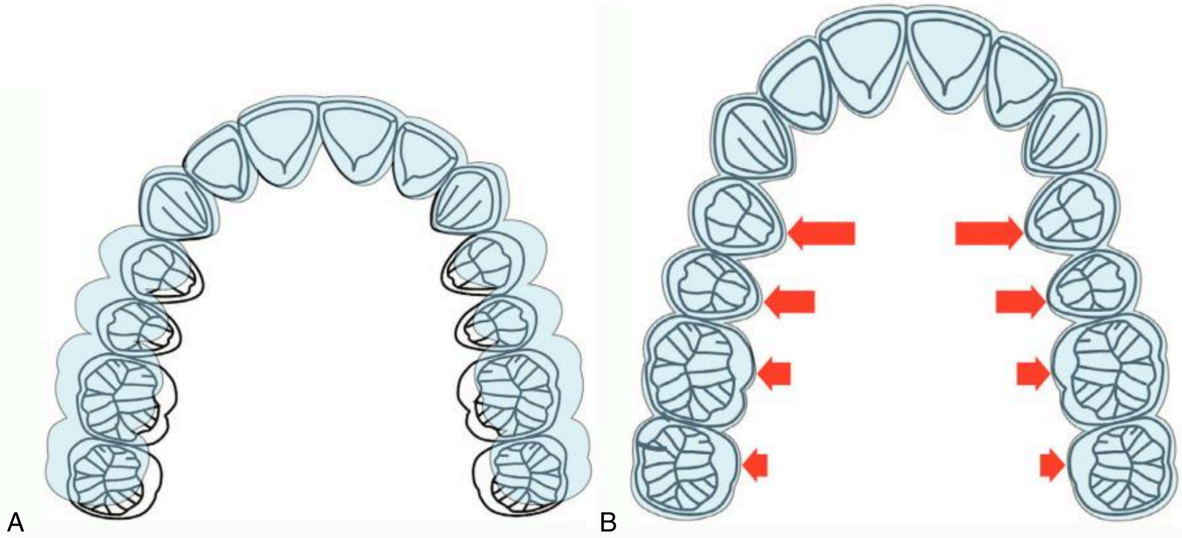

Fig. 2.29 (A) Programmed expansive mismatch between aligner and dental arch. (B) Once inserted, the resultant expansive forces will have a distally decreasing magnitude gradient.

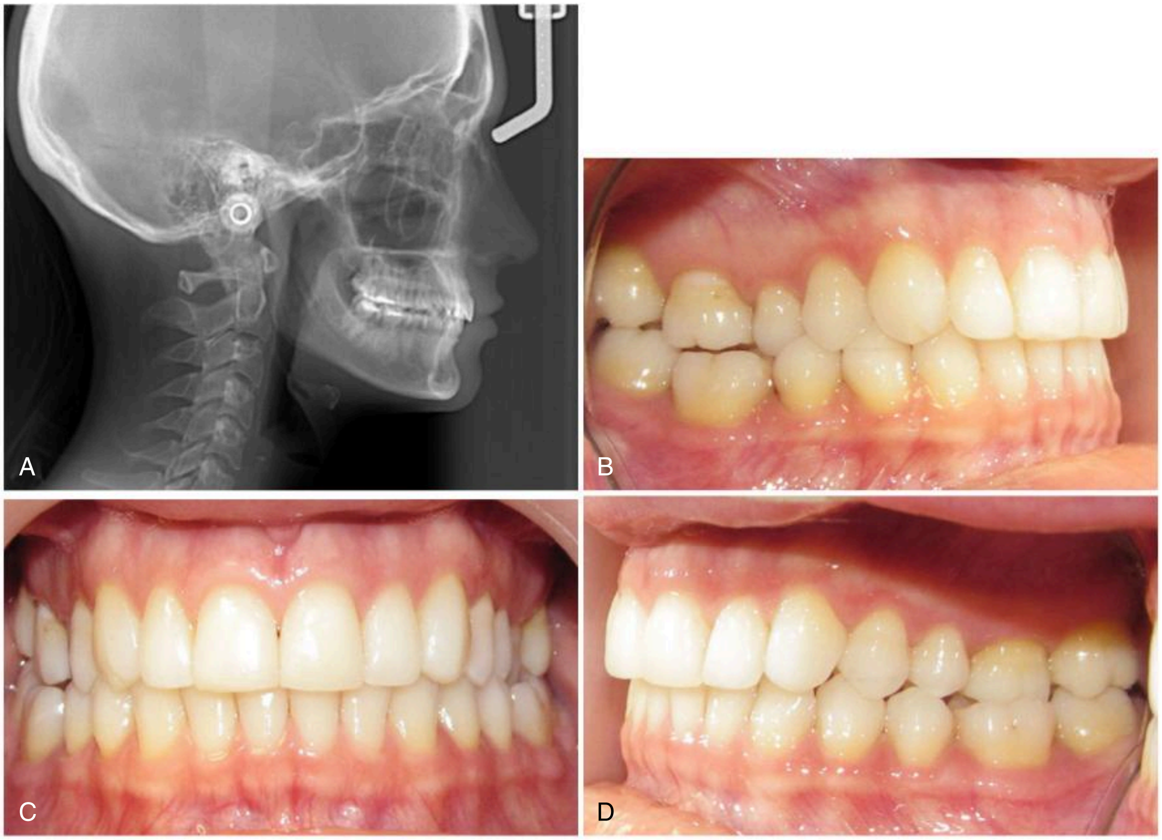

Fig. 2.30 Low angle patient (A), with bilateral posterior crossbite (B, D) and midline discrepancy (C).

extrusion of posterior segments are acceptable (Fig. 2.30). Elastic forces originated from buttons bonded to palatal upper and buccal lower aspects of molars (Fig. 2.31) will produce a force vector with vertical and horizontal components of clinically relevant magnitudes that must be considered during treatment planning. In the example in Fig. 2.32, a 100-gmf vector produced by a crossed intermaxillary elastic will be transmitted to the system as 90 gmf of horizontal and 40 gmf of vertical force. As mentioned previously, horizontal rectangular attachments are effective in mitigating undesired tipping by counteracting excessive rotational moments (Fig. 2.33). By controlling vertical and transverse force levels, as well as desired and undesired tipping moments, predictable aligner-based treatment of different types of transverse discrepancies is possible (Fig. 2.34).

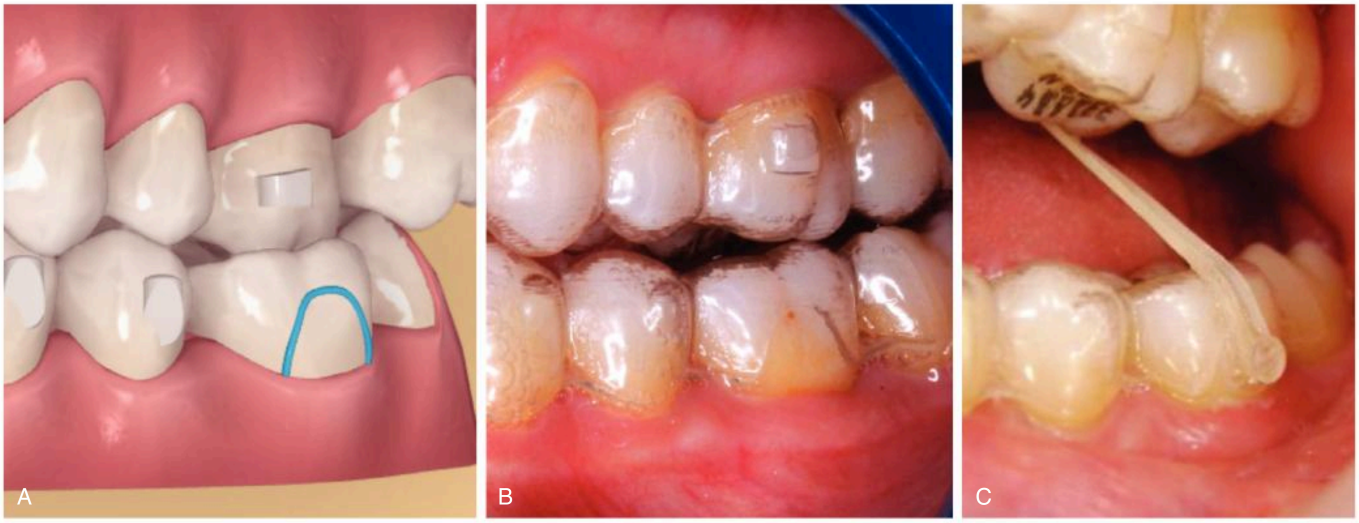

Fig. 2.31 (A) Initial ClinCheck stage. (B) Aligners inserted, prior to bonding of upper palatal and lower buccal buttons. (C) Crossbite elastic.

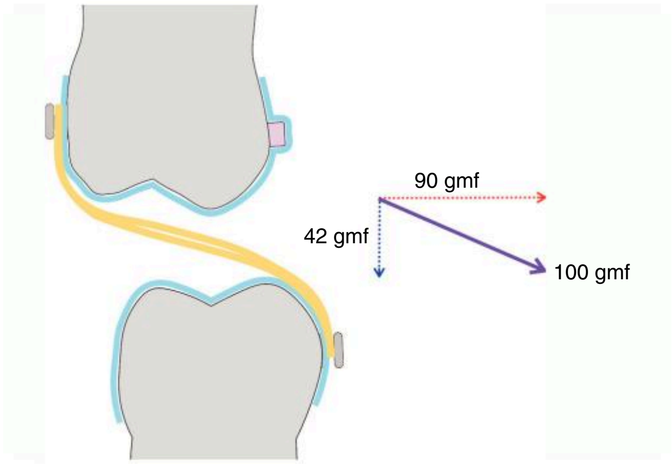

Fig. 2.32 A 100-gmf intermaxillary elastic force will produce a 90-gmf effective transverse force, expanding the upper arch and compressing the lower arch. Additionally, 42 gmf of extrusive force will equally influence upper and lower arches.

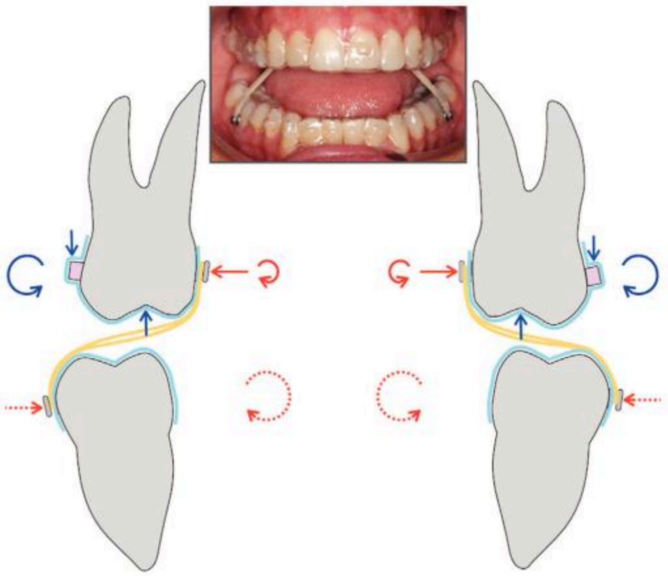

Fig. 2.33 In the upper arch, the moments provided by upper buccal attachments *(blue curved arrows)* will counteract moments *(red curved arrows)* produced by elastic expansive forces *(red arrows)*, reducing undesired upper tipping. In the lower arch, unopposed lingual elastic forces *(dotted red arrows)* will result in expected lingual tipping *(dotted red curved arrows)*.