Original Article

Influence of attachment position and torque overcorrection on arch expansion in clear aligner treatment: a three-dimensional finite element analysis

Ziwei Tang[a]; Hu Long[b]; Lu Liu[c]; Wenli Lai[d]; Fan Jian[e]

ABSTRACT

Objectives: To investigate the influence of attachment position and torque overcorrection on stress distribution and tooth displacement trends during arch expansion in clear aligner therapy (CAT).

Materials and Methods: Dental and skeletal models were obtained from an adult volunteer with angle Class I and mild crowding. Attachments were designed on the buccal, lingual, and buccolingual surfaces of the first molar. Different overcorrection torques were designed on the first molar. The displacement and stress of the whole arch were analyzed using a three-dimensional finite element analysis model.

Results: Crown buccal tipping was observed during arch expansion, while the lingual attachment showed more buccal crown and lingual root movement. Based on the trend of displacement, 1.5° of buccal root torque overcorrection without attachments could lead to bodily movement, 1.8° with a lingual attachment, 0.5° with a buccal attachment, and 0.9° with a buccolingual attachment.

Conclusions: Arch expansion is primarily achieved by teeth tipping despite attachments placed on the buccal or lingual side of teeth in CAT. Appropriate overcorrection of buccal root torque could contribute to the achievement of bodily movement. (*Angle Orthod*. 2025;00:000–000.)

KEY WORDS: Finite element; Clear aligner; Expansion; Overcorrection

INTRODUCTION

As orthodontic technology continues to advance and patient demands for esthetics rise, clear aligner therapy (CAT) is gaining increasing attention from patients and dental practitioners. Some researchers have found that CAT can achieve buccal expansion, increasing the length and width of the dental arch and, thus, resolving mild to moderate crowding.[1,2] In addition, the virtual setup of the arch shape after expansion can be better achieved via CAT design software,[3] allowing more harmonized arch shape coordination. CAT can be used to achieve arch width expansion of 2–3 mm per quadrant to reduce the risk of relapse and gingival recession. Authors of a previous study found that the efficiency of first molar expansion was 68.31%.[4] However, authors of many studies have found that, in most cases, arch expansion is caused by buccal tooth crown tipping.[5,6] To overcome these limitations, resin material, referred to as *attachments*, is often added to tooth crowns during CAT to increase tooth movement efficiency.[7,8] The presence of an attachment helps to counteract unexpected tipping changes during tooth movement, as it creates a reverse or countermoment.[9]

Orthodontic tooth movement is a complex mechanical system. To better understand the stress distribution

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Accepted: February 8, 2025. Submitted: June 14, 2024.
Published Online: March 20, 2025

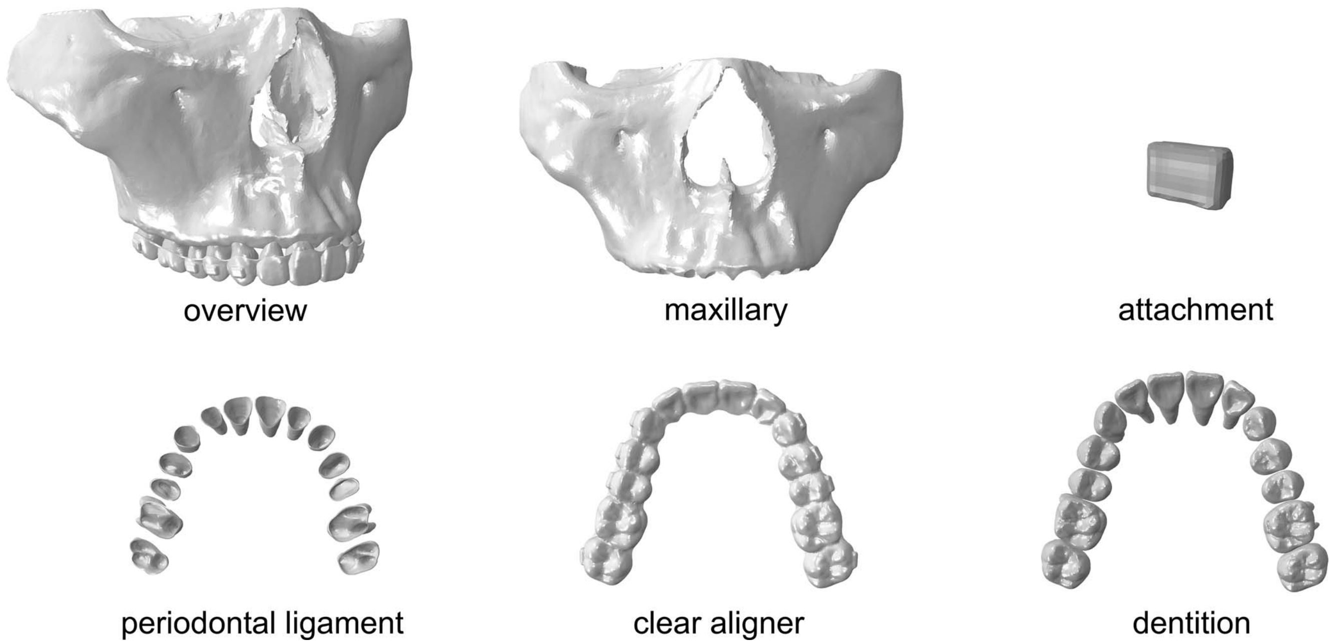

Figure 1. Model of maxilla, attachment, periodontal ligament, clear aligner and dentition.

and tooth displacement, three-dimensional (3D) finite element models have been used. Finite element models can be used to understand the biomechanics of different orthodontic treatment plans, such as to assess the stresses generated within the teeth, periodontal ligament, and alveolar bone.[9]

Most current studies of arch expansion with CAT are clinical studies in which authors measured the efficiency of tooth movement.[10–14] Due to differences in sample size and study objectives, no definitive conclusion on CAT overcorrection with arch expansion has been reached. Additionally, no authors have investigated the effect of attachment position on biomechanics during arch expansion. In this study, therefore, we focused on analysis of the biomechanics in CAT arch expansion through 3D finite element models to find an optimized attachment and overcorrection design for arch expansion.

MATERIALS AND METHODS

An adult patient in the Department of Orthodontics with complete dentition and normal dental anatomy who needed arch expansion treatment was selected as the study subject. Consent was obtained from the patient. The volunteer was a 24-year-old female with angle Class I mild crowding. To improve alignment, arch expansion treatment was performed to provide space. The patient's teeth and jaws were scanned by cone beam computed tomography before treatment. The study was approved by the Ethics Committee of West China Stomatology Hospital, Sichuan University (WCHSIRB-D-2022-478).

The DICOM data of the maxilla and maxillary dentition were imported into Mimics version 17.0 (Materialise, Leuven, Belgium) software, and then a preliminary 3D model of the jaws and dentition was generated by selecting thresholds for appropriate grayscale values of the bone and teeth. The 3D model was then imported into Geomagic Wrap software version 2021 (3D systems, Rock Hill, SC), the surface of the model was smoothed, and a periodontal ligament model was generated at an average thickness of 0.30 mm on the surface of the root.

After the design of the skeletal and dental model, a postarch expansion dental model was obtained using ClinCheck@pro V.5 (Align Technology, Inc., San Jose, CA, USA). The canines, premolars, and molars were moved buccally by 0.3 mm, while the central and lateral incisors were left unchanged to simulate the clinical situation of arch expansion. The outer surface of the expanded crown model was then used as the inner surface of the aligner to create a 0.5-mm-thick clear aligner. The nodes of the outer surfaces of the teeth and the inner surfaces of the aligners in this process basically corresponded to each other, which allowed for better computational results to be obtained during finite element calculations. To control a single variable, only the attachments and tipping of the molars were changed to observe the effect of the program design. Rectangular attachments of $3 \times 2 \times 1$ mm were placed on the buccal crown surfaces of the canines, premolars, and second molars, followed by attachments in different positions on the first molar, including the no attachment, buccal attachment, lingual attachment, and buccolingual attachment groups (Figure 1). Then 1°, 2°,

Table 1. Material Properties

Component	Youngs Modulus (MPa)	Poissons Ratio
Teeth	1.96×10^4	0.30
Periodontal ligament	0.67	0.45
Bone	1.37×10^4	0.30
Attachment	1.25×10^4	0.36
Clear aligner	528	0.36

and 3° of buccal root torque were designed in combination with arch expansion on the first molar.

All models were then imported into finite element analysis software (Abaqus/CAE, version 2016; Dassault Systemes Simulia Corp, Providence, RI) to obtain calculations. Contact between the aligner and the corresponding area of the tooth was achieved by loading the aligner with the displacement control, followed by releasing the displacement control and obtaining the position of the aligner after releasing the elastic potential energy by mechanical calculation. The tangential direction of the contact surface was preset to a frictional contact with a friction coefficient of 0.2. The mechanical performance characteristics were derived from previous studies (Table 1).[15] The 3D model was meshed into finite elements with a modified tetrahedral quadratic cell type by applying an adaptive meshing algorithm.

The final calculated results included displacements and principal stress. The movement of the crown and root were linearly analyzed using GraphPad Prism version 9.4.1 (GraphPad, San Diego, CA, USA).

RESULTS

Effect of Arch Expansion on the Full Range of Teeth

When the arch from canine to molar was expanded with the most commonly used buccal attachments, the stress and displacement on teeth decreased from the mesial to the distal center. Also, labial tipping tendency was observed at the central incisors, while the lateral incisors showed a lingual tipping tendency (Figure 2).

Effect of Attachment Position on Molar Teeth During Arch Expansion

Displacement of the right first molar with different attachment position designs is exhibited in Figure 3. The position of the attachment did not change the tendency of buccal tipping movement on the first molar. Compared with the group without attachments, the addition of attachments increased buccal crown movement as well as lingual root movement. This was more pronounced in the group with lingual attachments. In the vertical direction, the more teeth were tipping buccally, the more pronounced the sagging of the palatal cusp. Additionally, the buccal attachment reduced the tendency of tooth mesial movement (Figure 3). The principal stress also showed that the stress on the crown and root was greater with both lingual and buccolingual attachments than with only the buccal attachment and no attachment (Figure 4). Based on the measured displacement of the crowns and roots, the angle of rotation of the tooth was calculated, and the data were organized in a table (Figure 5; Table 2).

Due to the asymmetry in the results of the above experiments, it was surmised that asymmetry in the dental arch was the cause. Therefore, the model was mirrored to simplify the modeling process. The magnitude and direction of the displacements and stresses on both sides of the arch were basically symmetric (Supplemental Figure 1). Therefore, the right side of the symmetric model was used in subsequent experiments.

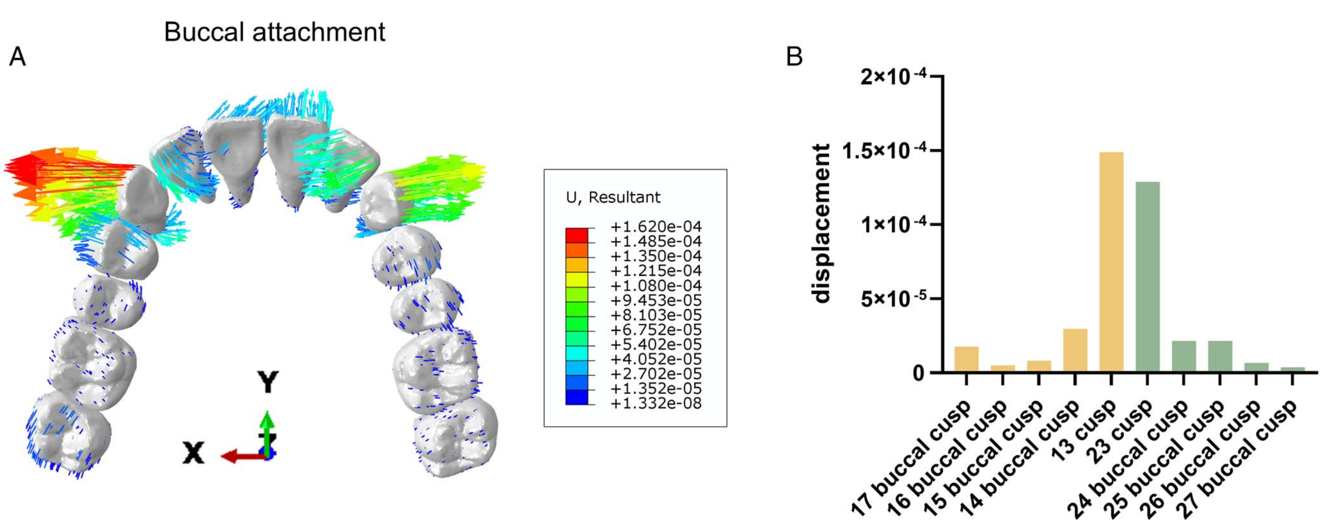

Figure 2. (A) Effect of arch expansion on the initial displacement of teeth in the full mouth. (B) Buccal cusp displacement for all teeth.

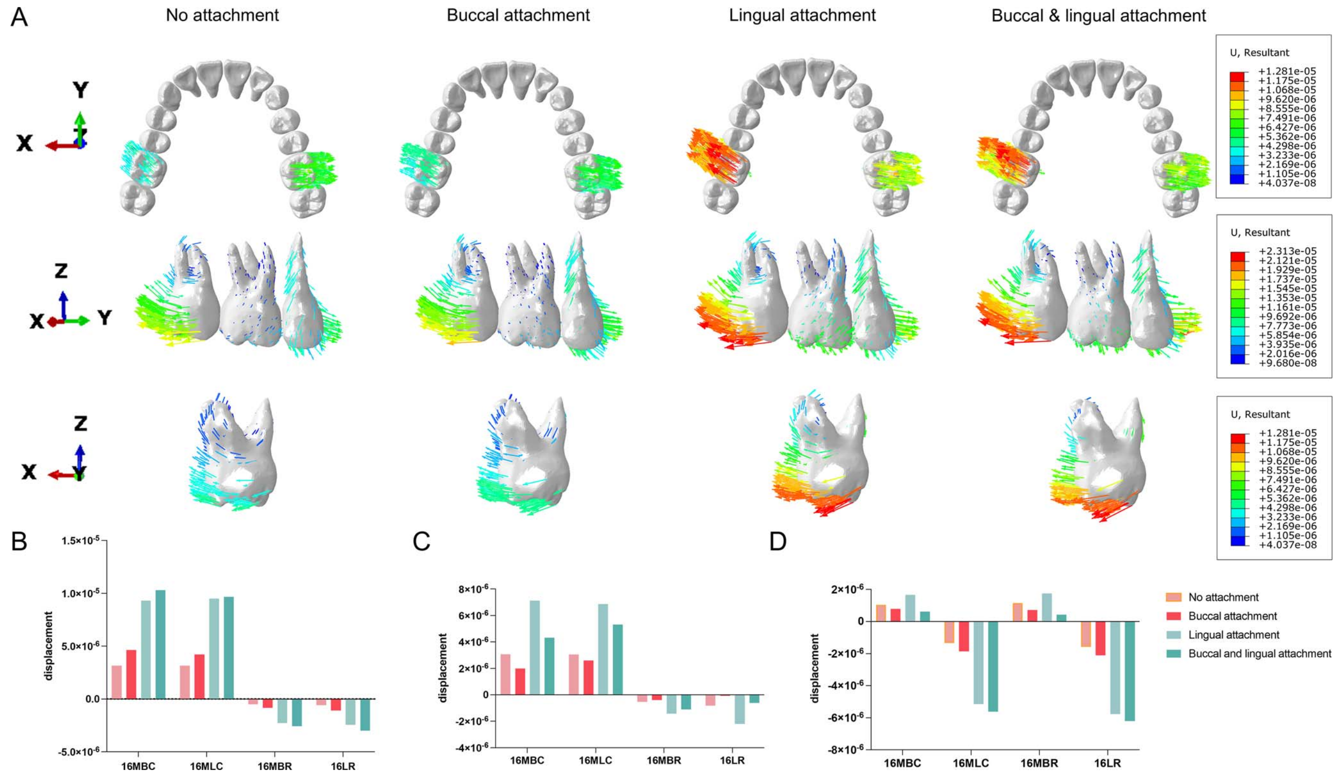

Figure 3. (A) Effect of different attachment positions on buccolingual displacement of first molars. (B) Buccolingual displacement of different locations on tooth 16. (C) Mesiodistal displacement of different locations on tooth 16. (D) Vertical displacement of different locations on tooth 16. (MBC indicates mesial buccal cusp; MLC, mesial lingual cusp; MBR, mesial buccal root; and LR, lingual root.)

Effect of Torque on the Initial Displacement in the Buccolingual Direction of the Molar

The specific tooth movements shown in Supplemental Tables 1 through 4 demonstrate that the use of attachments increased not only the bodily movement of the teeth but also buccal tipping during arch expansion. Different attachment positions and overcorrections were designed, followed by a linear analysis to find a suitable root torque for each attachment design (Table 3). The root and crown moved buccally at approximately 1.5° of buccal root torque without attachments. The overcorrection value changed after the addition of attachments on the first molar. With the buccal attachment, only 0.5° of buccal root torque was needed. The lingual attachment group required 1.8° of buccal root torque. In contrast, the buccolingual attachment group needed 0.9° of buccal root torque for bodily movement (Figure 6).

Teeth Moved Bodily With Proper Overcorrection

A simple validation of the above results was performed. A 1.5° orthodontic treatment overcorrection was set for the no attachment group and showed that both crown and root movement were toward the buccal direction (Figure 7). Other groups, after applying the corresponding torque, also exhibited a trend of overall buccal movement both the crown and root.

DISCUSSION

CAT allows digital design of arch expansion using a combination of two types of tooth movement (tipping movement and bodily movement). However, more tipping than bodily movement was observed in clinical trials.[16,17] It was also found that the rate of accuracy is higher in canine areas and lowest in first molar areas.[5] Tooth movement efficiency in CAT was recently improved with material innovations and proper treatment plan design.[4] Researchers found that the greater the amount of expansion planned, the less predictable it was in clinical outcomes. Authors of studies have also found that, even with innovative aligner materials, the orthodontic efficiency of arch expansion in CAT remains unsatisfactory. Authors of one study reported that 40% of the expansion group did not achieve ideal occlusal contact at the end of treatment due to unexpected buccal tipping movement.[18] Buccal root torque is commonly added to the virtual setup in the CAT plan design by clinicians as overcorrection; however, reckless or excessive overcorrection was found to reduce the accuracy of the simulated treatment plan.[18] Research findings regarding how much overcorrection should be designed into arch expansion in CAT to

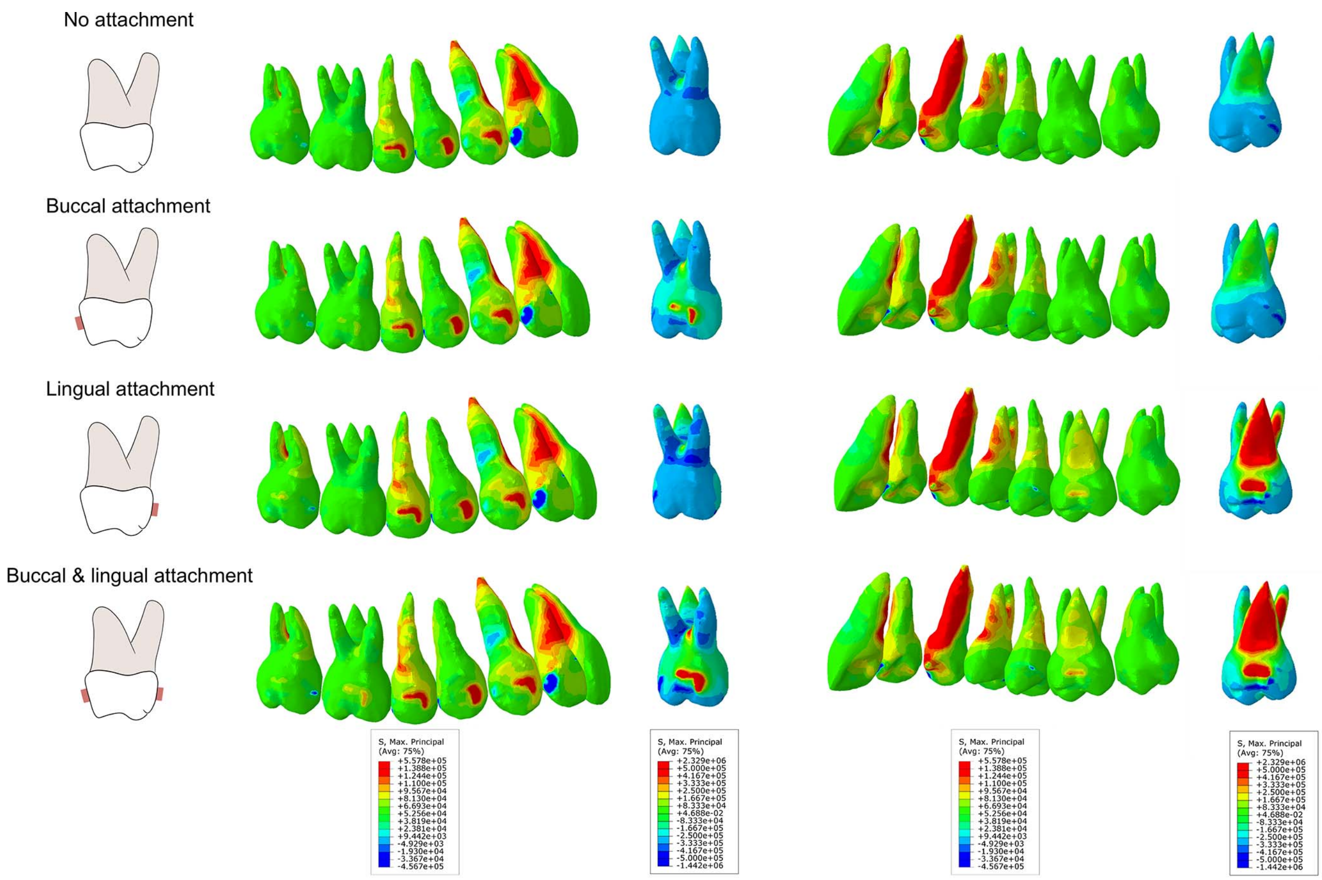

Figure 4. Stress cloud of right dental arch and the first molar.

achieve bodily movement and avoid unexpected buccal tipping movement are beyond clinical needs. Therefore, an appropriate amount of overcorrection is required. Although bodily movement was not found to be achieved by using attachments alone despite their positions, the use of attachments is still necessary because of higher expansion efficiency.

The degree of initial buccal-lingual tipping of teeth is worthy of more attention during arch expansion treatment plan design in CAT. If the teeth are more lingually tipped, it is possible to place lingual attachments to achieve early and rapid arch expansion. If the initial tipping of the teeth is more upright, it is recommended to design a small amount of crown lingual torque as overcorrection on the posterior teeth while expanding to achieve better bodily movement. If the initial presentation of the posterior teeth is more buccally tipped, it is necessary to design sufficient buccal root torque in the case of sufficient buccal bone.

It was also noted that the first molar tended to move mesially during expansion in the current study. This may have been due to the space created by arch expansion and consequent closure of that space, resulting in a reduction in arch length (Supplemental Figure 2).

In the current study, attachments on the first molar were routinely placed in the middle of the buccal or lingual surfaces of the teeth rather than at different occlusal-gingival heights. Like paired optimized attachments to control tooth tipping and labial power ridges with

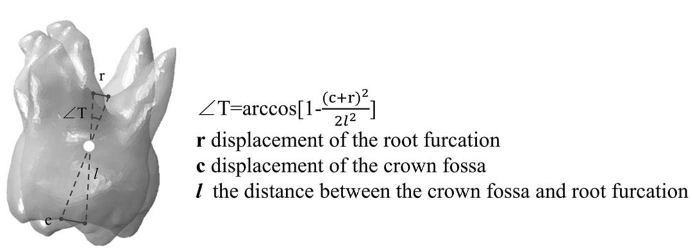

Figure 5. Calculation of the variation of tooth torque angle.

Table 2. Effect of Different Attachment Positions on Tooth Movement of the First Molar

	No Attachment	Buccal Attachment	Lingual Attachment	Buccal and Lingual Attachment
Extrusion/intrution (E/I), (10^{-3} mm)	0.348E	0.560E	2.07E	2.51E
Crown buccal/lingual movement (B/L), (10^{-3} mm)	2.72B	3.54B	7.78B	7.98B
Crown mesial/distal movement (M/D), (10^{-3} mm)	2.52M	1.84M	5.76M	3.87M
Root buccal/lingual movement (B/L), (mm) (10^{-3} mm)	8.24L	1.14L	1.91L	2.12L
Root mesial/distal movement (M/D), (10^{-3} mm)	0.648D	1.34D	2.06M	0.559D
Torque (B/L), (°)	0.0120B	0.0160B	0.0372B	0.0384B
Tipping (M/D), (°)	0.0117M	0.00769M	0.0281M	0.0178M

lingual pressure applied to control tooth torque, placing the two adjacent groups of attachments on the buccal and lingual surfaces at different occlusal-gingival heights or in a mesiodistal position may be a better way to modify the torque or rotation of the teeth.[19,20] This result was also supported, from another perspective, by the current findings that the buccal root torque needed for overcorrection decreased after the placement of buccal or lingual attachments.

Zhou and Gou[5] found that the accuracy of arch expansion from the canine to the molar region progressively decreased. The current results showed that the initial displacement from the canine to the molar zone decreased gradually when the same amount of arch expansion was designed. This may have been due to the curved shape of the arch, and the closer the tooth is to the mesial center, the shorter the moment and the greater the force, while the molar in the distal center has a longer moment and less force. Therefore, it is recommended that, when multiple teeth are expanded at the same time, the anterior teeth should be expanded less than the posterior teeth or that different teeth should be expanded in different stages to reduce the stress concentration phenomenon.

When teeth are expanded by the same amount, the efficiency of the expansion is also related to the morphology of the teeth and arch. Because the model used in this study was derived from a clinical volunteer, the tooth morphology of the first molars and their relationship to the adjacent teeth was not perfectly symmetrical. Although the same amount of expansion was designed, slight differences on different sides of the arch were noted due to asymmetry of the dental arch. However, the general trend was the same, and this difference was considered acceptable. It also suggests that clinicians should carefully check the adjacent tooth relationships and the degree of rotation before performing arch expansion to prevent large mesial and mesially tipping tooth movement during expansion.

In this study, we also found that, although no movement was designed on the incisors, there was no way to avoid greater stress on the central and lateral incisors, as the appliance is a single unit and the lateral incisors are subjected to lingual orthodontic forces, while the central incisors are subjected to labial forces. Therefore, when designing arch expansion in patients with narrow arches and labially tipped incisors, clinicians should control the position of the central incisors since the arch length increases with expansion and the incisors need to be retracted. The purpose of controlling the incisors during arch expansion is to prevent unnecessary repeated movement of the incisors.

The movement of multiple teeth was designed to simulate, as closely as possible, actual arch expansion clinically, which made the 3D finite element analysis model more complex.[21] In this study, we theoretically provided the overcorrection torque in upper arch expansion, and this needs to be validated by further clinical studies.

CONCLUSIONS

- Different positions of attachments exhibit the same trend of tooth movement in CAT expansion, all with a buccal tipping movement.
- If bodily movement of teeth is needed in the expansion process, different torque designs should be applied based on the attachment position to achieve overall tooth movement.

Table 3. Prediction of Overcorrection Angles for Different Attachment Positions Based on Linear Equations

Attachment	*Y* (crown)	*Y* (root)	*X* (Overcorrection)	*Y* (Displacement)
No	$Y = -2.324 \times 10^{-6}X + 3.780 \times 10^{-6}$	$Y = 7.326 \times 10^{-7}X - 6.889 \times 10^{-7}$	1.5°	3.81×10^{-7}
Buccal	$Y = -8.660 \times 10^{-6}X + 4.430 \times 10^{-6}$	$Y = 3.004 \times 10^{-6}X - 8.194 \times 10^{-7}$	0.5°	5.33×10^{-7}
Lingual	$Y = -4.366 \times 10^{-6}X + 8.171 \times 10^{-6}$	$Y = 1.386 \times 10^{-6}X - 2.030 \times 10^{-6}$	1.8°	4.28×10^{-7}
Buccal & lingual	$Y = -9.779 \times 10^{-6}X + 9.133 \times 10^{-6}$	$Y = 3.370 \times 10^{-6}X - 2.275 \times 10^{-6}$	0.9°	6.49×10^{-7}

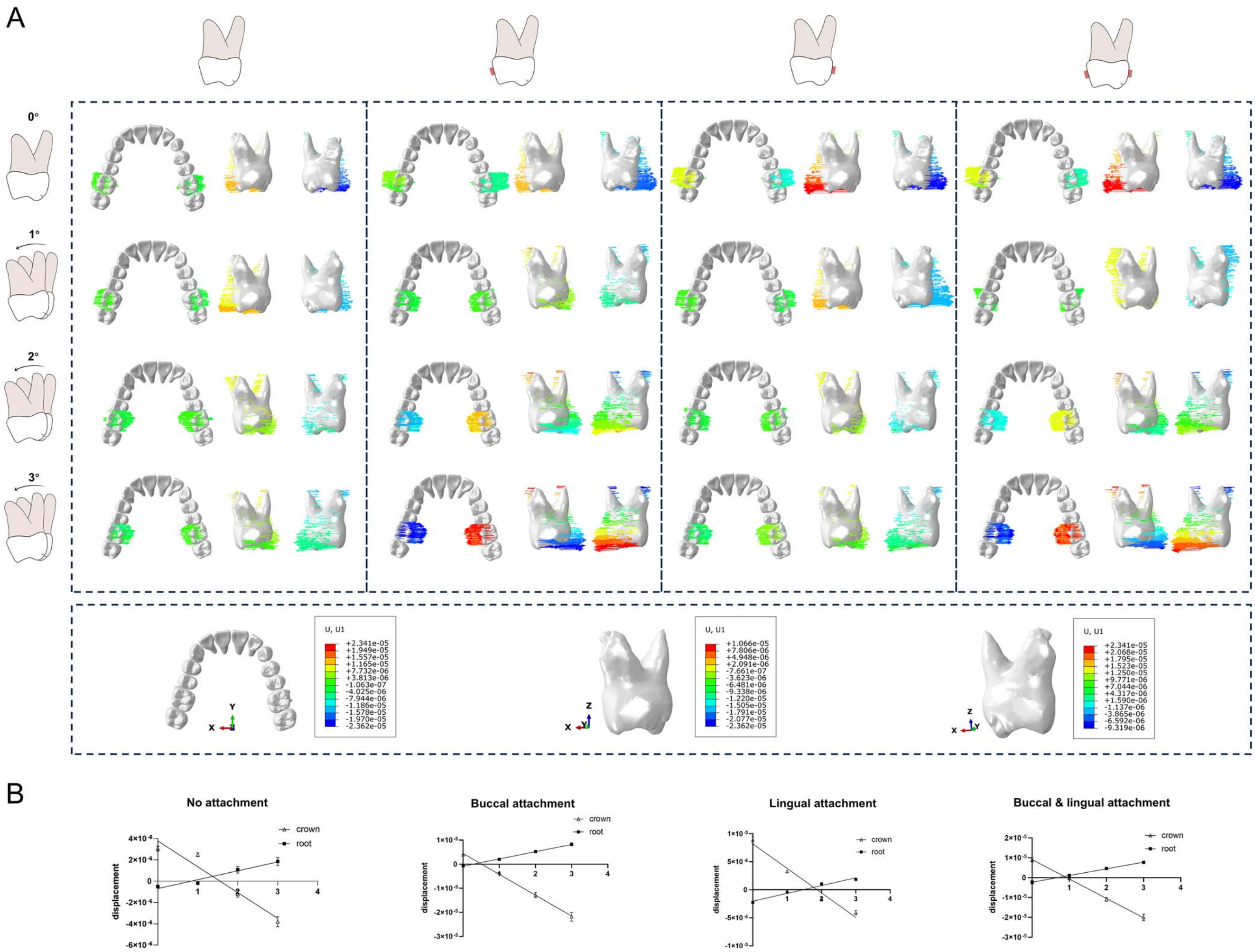

Figure 6. (A) Effect of attachment position and different torques on displacement of the first molar in buccal/lingual movement (0°: asymmetry model; 1–3°: symmetry model). (B) Different points on the crown and root were selected to measure the buccolingual displacement in the models of 0°, 1°, 2°, and 3° and then fitted with a straight line.

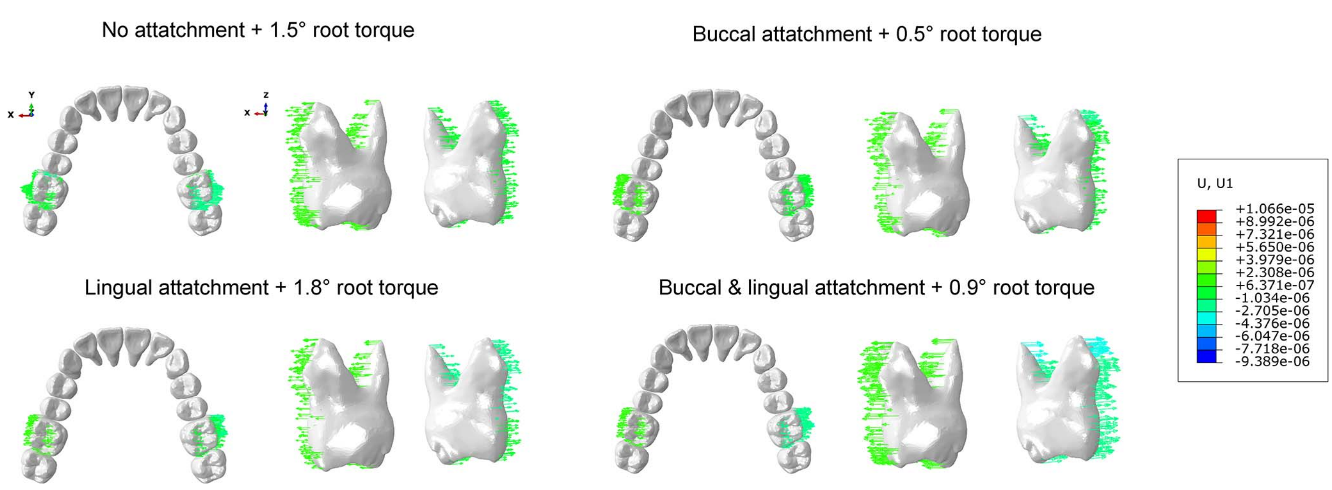

Figure 7. Different buccal root torque values should be applied based on attachment positions.

SUPPLEMENTAL DATA

Supplemental Tables 1 through 4 and Supplemental Figures 1 and 2 are available online.

Supplemental Figure 1. (A) Displacement of teeth in symmetric models. (B) Displacement of teeth in a symmetric model with right side teeth. (C) Displacement of teeth in a symmetric model with right side teeth.

Supplemental Figure 2. (A) The tendency for the first molar to move mesially after arch expansion. (B) Closing the space after arch expansion leads to shortening of the dental arch. (Blue: before arch expansion. Orange: after arch expansion.)

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