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A Finite Element Analysis for Mandibular Whole Arch Distalization According to Different Lengths of Retraction Hooks

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Abstract

Objectives: To compare the differences in displacement patterns and stress distribution in the periodontal ligament of whole mandibular dentition between distalization force vectors corresponding to retraction hooks of different lengths.

Methods: A cone beam computed tomography image of one 18-year-old female patient with Class III malocclusion was used to construct a finite element model. To simulate the whole arch distalization mechanics, a force of 200 g was applied to the miniscrews in the lower jaw using 1-, 3-, 6-, 9- and 12-mm retraction hooks. The displacement patterns of the teeth and the stress distribution in the periodontal ligament were analyzed on the x-, y-, and z-axes.

Results: At the retraction hook length of 6 mm, the incisors showed approximate bodily movement, the premolars showed slight extrusion, and the second molars showed slight intrusion. The von Mises stress in almost distalization patterns was highly distributed in the periodontal ligament of the teeth adjacent to the retraction hooks, especially when using hooks longer than 3 mm.

Conclusions: The 6-mm retraction hooks, used in conjunction with miniscrews on the mandibular buccal shelf area, caused mandibular dentition to move along the occlusal plane with minimal undesirable movement. The stress was highly distributed in the periodontal ligament of the teeth adjacent to the retraction hooks when hook length longer than 3 mm.

Keywords: distalization, finite element, mandibular whole arch, retraction hooks

Introduction

Class III malocclusion is among the most challenging skeletal problems. Treating adult patients without remaining growth commonly requires dentoalveolar compensation or camouflage treatment (for mild-to-moderate Class III patients) or orthognathic surgery (for severe Class III patients).(1) Camouflage treatment for Class III patients can be performed by distalization of the mandibular dentition.(2)

There are two types of orthodontic distalization (also known as orthodontic distal movement): movement of a single tooth (or segments of teeth) or the whole dental arch.(1) Moving the whole dental arch to distal is a way to solve a Class II or III malocclusion, which has the characteristics of the teeth that are positioned forwards of their skeletal base. The concept behind this technique is that a distalization force given to the anterior segment is passed along the archwire and proximal contact points to the posterior segment, causing the anterior teeth and posterior teeth to move together.(3) Although several intraoral and extraoral appliances can distalize teeth with acceptable treatment results, these appliances have many side effects and require patient compliance.(4) Additionally, moving the entire dental arch distally cannot be achieved using traditional orthodontic mechanics.

The temporary skeletal anchorage devices (TSADs) have enabled distalization of the entire dentition with fewer undesirable side effects.(5-9) TSADs usually refer to miniscrews or miniplates that provide absolute anchorage for tooth movement without patient compliance. Several recent clinical case reports have demonstrated the effectiveness of miniscrews or miniplates - aided mechanics in distalization of the mandibular dentition.(5-9) Miniscrews should be considered the first skeletal anchorage option due to the simple surgical placement without an incision or flap operation, which significantly decreases the pain and discomfort experienced by the patient after implantation.(10) Furthermore, miniscrews can be placed in various positions at a relatively low cost.

The pattern of the force system used for distalization depends on the positions of miniscrew anchorage and force application points on the archwire, which results in different force system characteristic, both horizontal and vertical components.(3) The relationship between the center of resistance (CRes) of the entire arch and the force vector can predict the displacement of the teeth and occlusal plane. Biomechanical principles indicate that when the line of action of the force passes through the CRes of the whole arch dentition, the teeth should move bodily without rotation of the occlusal plane.(11,12) However, if the force does not pass through the CRes of the whole arch dentition, a moment of force is produced that rotates the occlusal plane.

One of the methods used to describe force systems, analyze structural stress, and predict the resultant displacement patterns that occur in orthodontics, is the finite element method (FEM).(13,14) This method computes large numbers of equations to calculate the stress on the basis of the physical properties of the structures under analysis. In orthodontics, the FEM provides the orthodontist with quantitative data that can enable understanding of physiological reactions that happen within the dentoalveolar complex.

Many studies have investigated the displacement patterns in response to distalization force vectors with various angulations by varying the length of the retraction hook and the height of the miniscrew position in maxillary dentition.(3,15,16) However, few studies have applied this approach to mandibular dentition, which differs from the upper arch. Accordingly, this study compares the differences in displacement pattern and stress distribution in the periodontal ligament (PDL) of whole mandibular dentition between distalization force vectors corresponding to retraction hooks of different lengths.

Materials and Methods

A pre-treatment cone beam computed tomographic (CBCT) image was obtained from one healthy Thai orthodontic patient with Class III malocclusion and well-aligned mandibular dentition who was undergoing orthodontic treatment at the Department of Orthodontics and Pediatric Dentistry, Faculty of Dentistry, Chiang Mai University. The selected CBCT image was imported into Materialize Mimics software (Materialize, Wilfried, Leuven, Belgium) to generate digital biological structures comprising the mandible and all mandibular teeth (Figure 1). PDLs, brackets, archwire, retraction hooks, and miniscrews were built and assembled to previous biological models using SolidWorks software (Dassault Systèmes Americas, Waltham, Mass., USA) before being converted into solid models.

The PDL was modeled and assumed to have a uniform thickness of 0.2 mm, as indicated by previous FEM studies.[17,18] The gingival soft tissue was assumed to have an average thickness of 1 mm[19] to set the mini-screw head position. The brackets were constructed with a slot of 0.022x0.028 inches and were positioned in the middle of the clinical crown of all teeth.[20] The main archwire was modeled according to a 0.019x0.025-inch stainless steel (SS) wire and was engaged at all brackets.

The retraction hooks were created using 0.036-inch SS wire and located between the mandibular canine and first premolar. Hooks of lengths 1, 3, 6, 9 and 12 mm apical to the archwire represented short hooks (1 and 3 mm), medium hooks (6 mm), and long hooks (9 and 12 mm). The position of the miniscrew at the mandibular buccal shelf (MBS) was chosen to obtain the optimal anatomic characteristics: on the sagittal plane, it was placed on the buccal bone lateral to the distal root of the second molar;[21] on the transverse plane, it was placed about 4 mm buccal to the cemento-enamel junction (CEJ); on the vertical plane, its position depended on the contour of the buccal bone.

To create a finite element model, the assembled solid model was meshed into 2,276,246 elements and 522,239 nodes. The following model orientation was identified: the x-axis represented the labio-lingual direction of the anterior teeth and the mesio-distal direction of the posterior teeth; the y-axis represented the supero-inferior direction of all teeth; the z-axis represented the mesio-distal direction of the anterior teeth and the bucco-lingual direction of the posterior teeth (Figure 2). Positive X values indicated the labial direction of the anterior teeth or the mesial direction of the posterior teeth; positive Y values indicated the superior or incisal or occlusal direction of all teeth; positive Z values indicated the distal direction of the right anterior teeth, the mesial direction of the left anterior teeth, the buccal direction of the right posterior teeth, or the lingual direction of the left posterior teeth.

The boundary conditions in this study were defined at all peripheral nodes of bone with no movement (zero degrees of freedom) in any direction to prevent displacements from loading. All teeth were in contact with each other at the contact point as an independent object. The contact relationship between the brackets and the archwire was the surface contact with no play and friction because the archwire need not slide into the brackets. All materials except the PDL were assigned to be isotropic and homogeneous and featured linear elasticity. The material properties consisting of Young's modulus and Poisson's ratio were determined according to previous FEM studies (Table 1).[3,22] The PDL was defined as a non-linear elastic material in which the hyperelastic properties were determined according to the Ogden model from the study by Huang *et al.* (Table 2).[23] Where μi related to the initial shear modulus of the material, ai and Di were the material parameters.

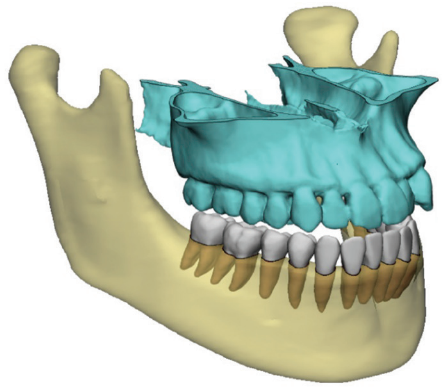

Figure 1: The geometric model with mandibular teeth, PDL and mandible.

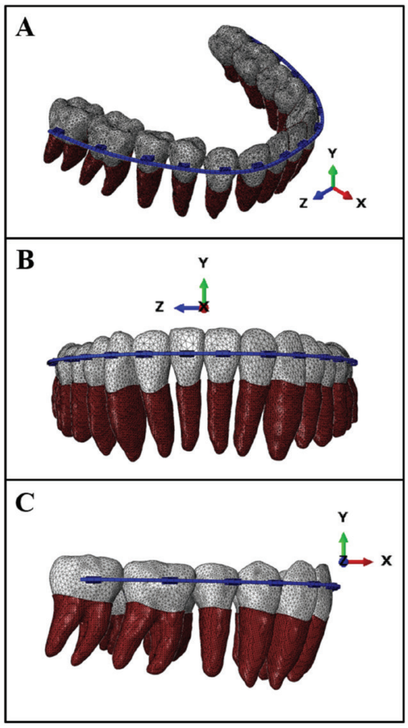

Figure 2: The orientation of the model: (A) overall, (B) frontal and (C) lateral views.

Table 1: Material properties required by the finite element model.

Material	Young's modulus (MPa)	Poisson's ratio
Alveolar bone	2.0E+03	0.30
Teeth	2.0E+04	0.30
Bracket	2.0E+05	0.30
Stainless steel wire	2.0E+05	0.30

Table 2: Coefficients of the third order Ogden model.

i	μ_i	a_i	D_i
1	-24.4237106	1.99994222	4.87164332
2	15.8966494	3.99994113	0.00000000
3	8.56953079	-2.00005453	0.00000000

To simulate the distalization of whole mandibular dentition, a single force vector (200 g)[2,24] was applied from the retraction hook to the miniscrew for all of the different hook lengths (Figure 3). The patterns of stress distribution in the PDL and displacement of the teeth were evaluated based on the color of graphic outputs and the superimposition of before and after loading conditions using Abaqus software (Dassault Systèmes, MA, USA). The reference points were defined for each tooth to interpret the displacements of the teeth: the midpoint of the incisal edge and root apex of the central and lateral incisors, the cusp tip and root apex of the canine, the buccal cusp tip and root apex of the premolars, and the mesiobuccal cusp tip and mesial root apex of the molars.

Results

The resultant force vectors and superimposition of all mandibular teeth with the retraction hooks of each length appear in Figures 4 and 5. The translucent magenta images show the positions of the teeth before applying the force, and the green images show the subsequent displaced positions. The direction of the arrows adjacent to the teeth represents the direction of tooth movement. The length and color of the arrows represent the degree of tooth movement, with the long red arrows indicating large amounts of displacement and the short blue arrows indicating small amounts of displacement.

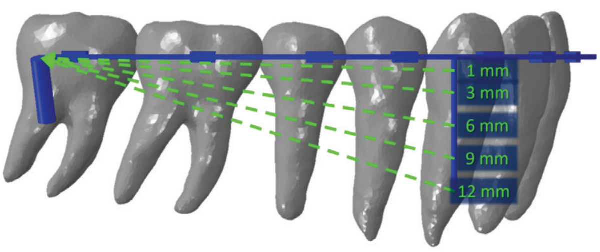

Figure 3: Distalization pattern: the force vector (200 g) from the anterior retraction hook (1, 3, 6, 9 and 12 mm in length) to the MBS miniscrew.

After applying force to the 1-mm and 3-mm retraction hooks, all teeth were displaced distally, as both the sagittal and occlusal views show. The sagittal view shows that the anterior teeth were retracted, extruded, and tipped lingually, except for the canines in the case of the 3-mm hooks, which were lingual-bodily displaced and extruded. The posterior teeth were distalized, intruded and tipped distally (Figure 4 A&B). The occlusal view shows that the crowns of the anterior teeth moved lingually, whereas the crowns of the posterior teeth were distalized and tipped slightly in the lingual direction (Figure 5 A&B).

After applying force to the 6-mm retraction hooks, all teeth were still displaced distally, as both the sagittal and occlusal views show. The sagittal view shows that all incisors were slightly retracted, extruded, and lingual-bodily displaced, whereas the canines were slightly extruded and lingual root torqued. The posterior teeth were distalized and tipped distally. All premolars were slightly extruded, but the second molars were slightly intruded (Figure 4 C). The occlusal view shows that the crowns of the anterior teeth moved slightly lingually, whereas the crowns of the posterior teeth were distalized and tipped in the lingual direction (Figure 5 C).

After applying force to the 9-mm and 12-mm retraction hooks, the crowns of the anterior teeth, especially the canines, were close to their original position and were slightly intruded while their root apices displaced lingually, which was lingual root torque. The posterior teeth were distalized and tipped distally. Vertically, the posterior teeth were extruded from the first premolars (most extruded) to the first molars (least extruded), and the second molars were slightly intruded (Figure 4 D&E). The occlusal view shows that the crowns of the anterior teeth were close to their original position, whereas the crowns of the posterior teeth were distalized and considerably tipped in the lingual direction (Figure 5 D&E).

The von Mises stress distribution in the PDL was calculated in N/mm^2 (Megapascal or MPa). The level of stress is shown on the color-coded map in Figures 4 and 5, where red represents the area of maximum stress and dark blue represents the area of minimum stress. For the 1-mm retraction hooks, high-stress areas were concentrated in the distal root of the second molar (Figure 4 A). For the 3-mm retraction hooks, high-stress areas were concentrated in the apical third of the first premolar and the distal root of the second molar (Figure 4 B).

For the 6-mm retraction hooks, high-stress areas were concentrated in the root of the canine and first premolar, which were close to the position of the retraction hook (Figure 4 C). Additional high-stress areas were observed in the apical third of the second premolar. For the 9-mm retraction hooks, high-stress areas were concentrated in a pattern similar to the 6-mm retraction hooks, but the stress was more concentrated (Figure 4 D).

For the 12-mm retraction hooks, high-stress areas were concentrated in a pattern similar to the 9-mm retraction hooks, but the stress was even more concentrated (Figure 4 E). Additionally, high-stress areas were observed in the apical third of mesial root of the first molar and the cervical third of the second molar.

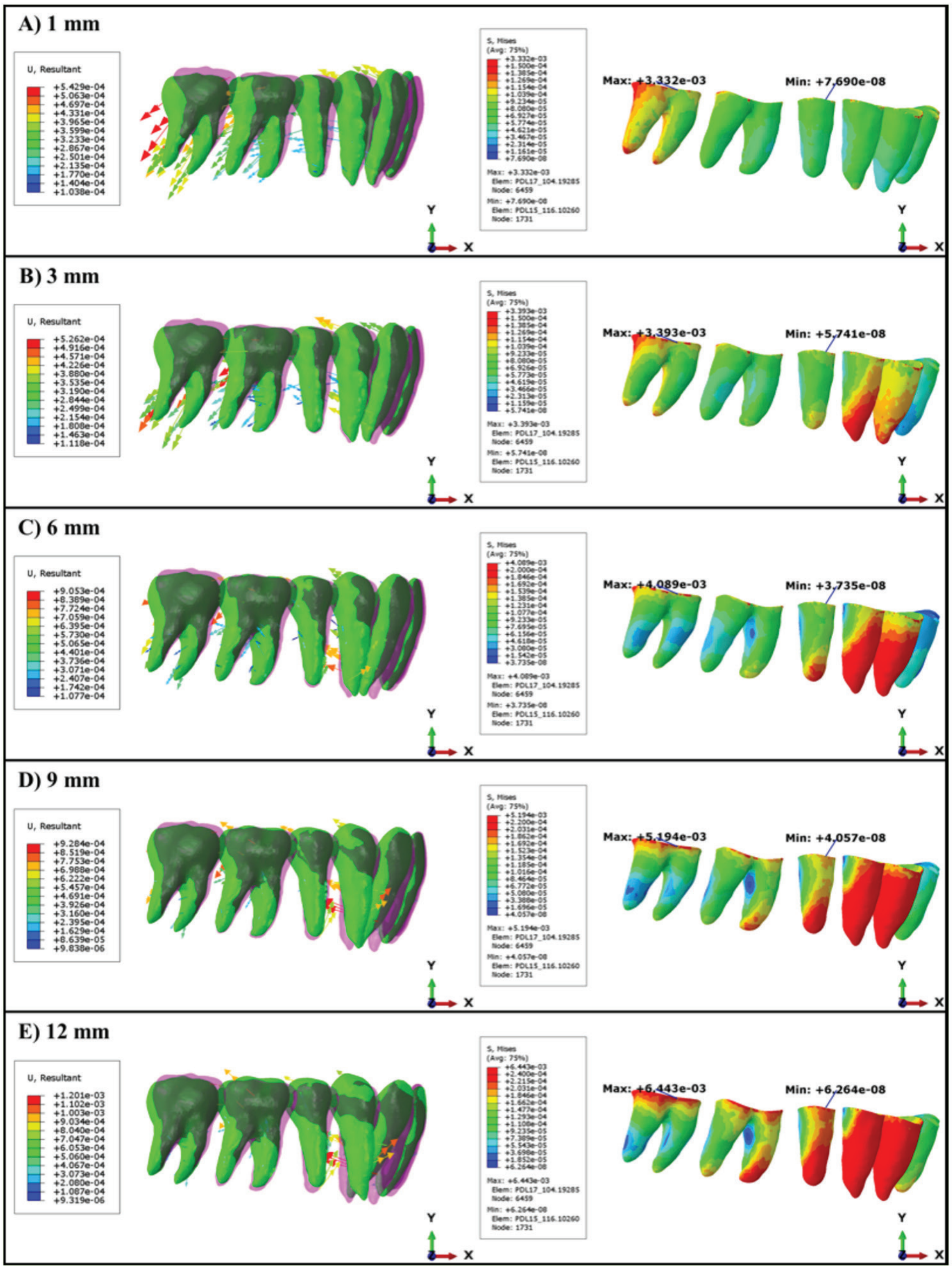

Figure 4: Superimposition of right mandibular teeth with the resultant force vectors and color-coded map of von Mises stress distribution in the right quadrant of the PDL for (A) 1-mm, (B) 3-mm, (C) 6-mm, (D) 9-mm and (E) 12-mm retraction hooks.

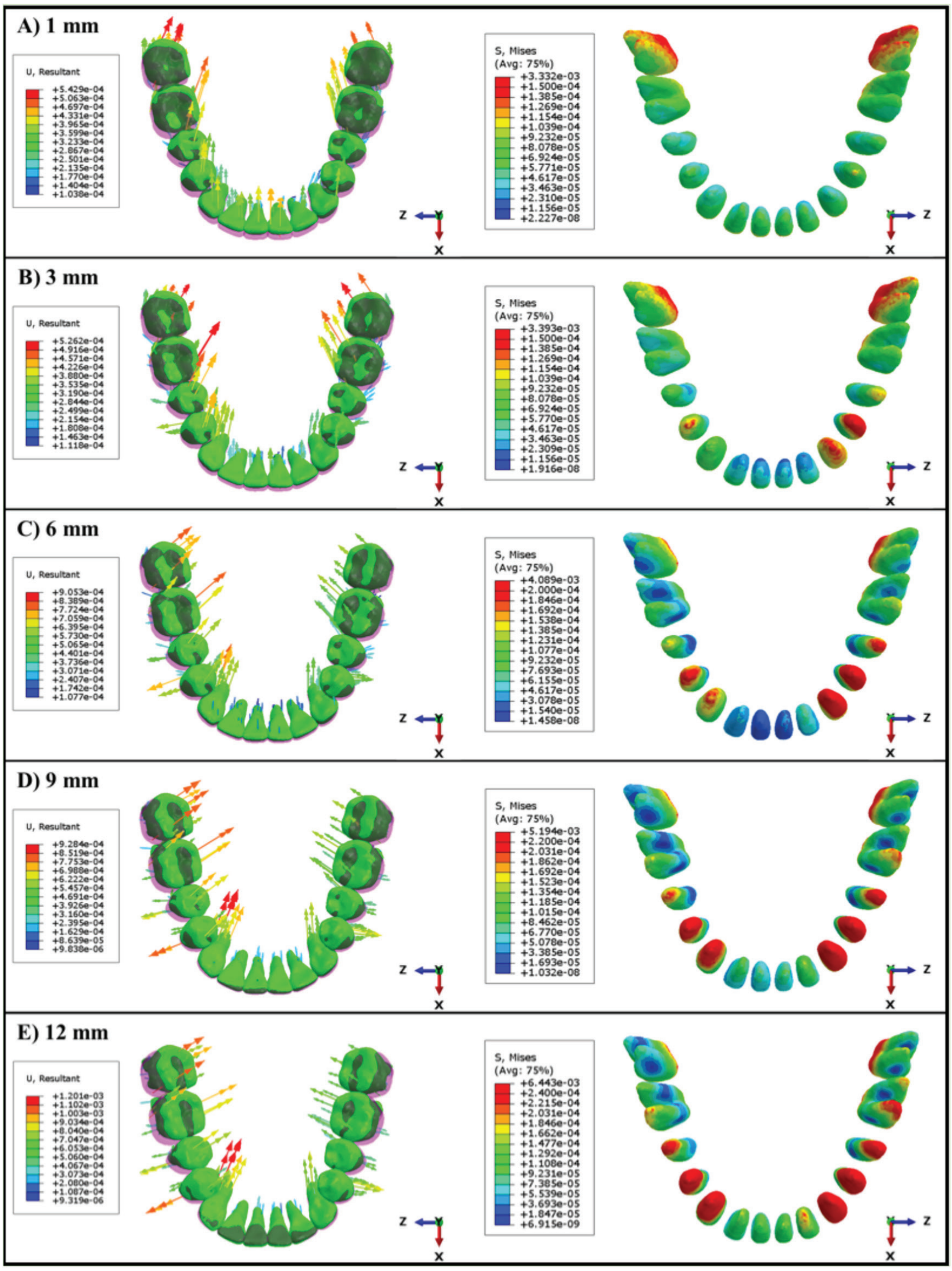

Figure 5: Occlusal view of superimposition of all mandibular teeth with the resultant force vectors and bottom view of the color-coded map of von Mises stress distribution in the PDL for all mandibular teeth for (A) 1-mm, (B) 3-mm, (C) 6-mm, (D) 9-mm and (E) 12-mm retraction hooks.

In the bottom view of the PDL, for all retraction hook lengths, the color-coded map of von Mises stress distribution in the PDL is shown in Figure 5, revealing high-stress areas concentrated in the canines, premolars, and second molars. For the 1-mm and 3-mm hooks, the stress was concentrated in the cervical third of the second molars. For the 6-mm, 9-mm, and 12-mm hooks, the stress was concentrated in the root of the canines and premolars.

Discussion

This study used the FEM to predict the tooth displacement and stress distribution in the PDL of mandibular teeth upon application of distalization force. The precision of the outcome is largely due to how well the model is constructed in terms of anatomy, material properties, and boundary conditions. In most published finite element studies in dentistry, the finite element model has been constructed using commercial dental model basing the dimensions and alignment of the teeth of adult populations with normal occlusion. However, this study constructed the finite element model from the CBCT image of one patient undergoing orthodontic treatment, enabling the model naturally realistic anatomy. Additionally, the analysis results can compare clinical outcomes in cases where the patient must undergo the same mechanic for orthodontic treatment.

The elastic material was defined as the property of the archwire used in this study. Although it distorted upon application of force, causing the whole arch to not move in one direction as a single unit, a rigid archwire could be considered unrealistic. Moreover, there were differences in the shape and position of the left and right teeth which were not the mirror image, meaning the analysis results were not exactly the same for both sides. Nonetheless, the differences in values were slight.

The mechanical factors that determine the differences in the displacement of mandibular dentition upon application of distalization force can be clarified by the FEM simulation. In this study, the displacement patterns of the mandibular dentition were influenced by the direction of distalization force, the relationship between the force vector and the CRes of the mandibular dentition, and the elastic deflection of the archwire. The details are as follows.

First, the study's miniscrews were constructed as a cylinder, rather than a point, to be as realistic as possible. The head of the miniscrew emerged from the bone and the soft tissue thickness was compensated. Therefore, from the anatomy of the finite element model used, the position of the miniscrew head was positioned higher towards the occlusal plane. Because the miniscrew and retraction hook were not at the same level vertically, the force vector was obliquely directed upward to distal, meaning, especially for greater hook lengths, the force would be directed more obliquely.

This study determined the relationship between the line of action of the force and the CRes of the mandibular dentition by the retraction hook lengths and miniscrew position. The precise location of the CRes is highly important for predicting movement and guaranteeing the effective displacement of teeth groups during treatment. Jo *et al.*[25] observed that the position of the CRes of the whole mandibular dentition in their finite element model was 13.5 mm apical and 25.0 mm posterior to the incisal edge of the mandibular central incisors. However, their model was constructed using a commercial dental model based on average tooth shape and size, meaning the CRes found might not be able to be applied precisely to each patient's dentition. According to Reimann *et al.*[26], the CRes is a range, not a point, and it is affected by the root shape and the wire size, which impacts the play between the bracket and the wire and the distortion of the wire.[27] Therefore, caution is advised before using the CRes from the previous study to refer to the model in this study.

When using the 6-mm retraction hook length, the line of action of the force possibly passed quite close to the CRes of the whole mandibular dentition, causing a relatively slight rotation of the occlusal plane (Figure 6 B), moderately affected by the deflection of the archwire. Consequently, all mandibular teeth were displaced to distal with minimal change in other directions and minimal rotation of the occlusal plane compared to hooks of other lengths. Therefore, in conjunction with the miniscrews at the MBS, 6 mm was a hook length for effectively distalizing the whole mandibular arch.

When using shorter retraction hook lengths (i.e., 1 mm and 3 mm), the line of action of the force was likely to pass above the CRes of the whole mandibular dentition, causing the counterclockwise rotation of the occlusal plane (Figure 6 A). This rotation occurred in the 1-mm hooks more than in the 3-mm hooks because the line of action of the force was further from the CRes that making the moment of force greater. Additionally, using shorter hooks resulted in less deflection of the archwire. Consequently, the anterior teeth showed lingual crown tipping and extrusion, whereas the posterior teeth showed distal crown tipping and intrusion.

When using the longer retraction hook lengths (i.e., 9 mm and 12 mm), the line of action of the force was likely to pass below the CRes of the whole mandibular dentition, suggesting, theoretically, that the occlusal plane would rotate clockwise (Figure 6 C). However, using long retraction hooks was greatly affected by the deflection of the archwire, which caused the teeth anterior and posterior to the retraction hooks to not rotate in the same direction as a single unit. Consequently, the anterior teeth showed lingual root torque and intrusion, whereas the posterior teeth showed distal crown tipping and extrusion, except for the second molars, which showed slight intrusion.

When force was applied to the retraction hook, a high bending moment occurred at the junction between the archwire and the hook, causing deflection of the archwire.[15] An increased high bending moment in the archwire related directly to increasing hook length, meaning the greater the length of the retraction hook, the greater the bending moment (Figure 7). Beyond an increase in hook length, the factors that increase deflection of the archwire are the archwire's strength and size and the magnitude of distalization force.[28] The deflection of the archwire produced lingual root movement and intrusion of the anterior teeth, with the posterior segment extruded and tipped lingually. Tominaga *et al.*[29] found that even when the line of action of the retraction force passed below the CRes of the anterior segment, the anterior teeth were bodily moved because they derived the effect of the archwire deflection, indicating that the deflection of the archwire literally affects the movement patterns of the teeth. Reducing archwire deflection can be achieved by loading the orthodontic force periodically to allow sufficient time for the archwire to rebound or by using a more rigid archwire.[3]

In lateral displacement, the crowns of the posterior teeth were tipped lingually, an effect that grew gradually as the length of the retraction hooks was increased. This displacement of the posterior teeth aligned with the observations of Tangsumroengvong *et al.*[30], who simulated the maxillary whole arch distalization with miniscrew anchorage. Although the position of the miniscrew was located buccally, the posterior teeth did not tip buccally due to the high bending moment and deflection of the archwire, both of which caused a twisting of the posterior segment of the archwire. This twisting of the archwire is similar to a third-order bend or torque on an archwire bent with pliers, which produces the same effect on the teeth.

Following several previous studies[3,31,32], this study has used the term von Mises stress to describe the overall stress distribution in the PDL upon the application of distalization force. The teeth close to the retraction hook, the point of force application, demonstrated higher concentrations of stress in their PDL than teeth located further from the hook. Therefore, this study observed stress concentrated in the PDL of the canines and first premolars, especially when using long retraction hooks, because these teeth were close to the hooks.

For the 1-mm and 3-mm hooks, stress was concentrated at the posterior teeth, especially in the distal aspect of the PDL of the second molar, due to the counterclockwise rotation of the occlusal plane that produced distal crown tipping and intrusion of the posterior teeth (Figure 4 A&B). Additionally, in the case of the 3-mm hooks, stress occurred at the apical third of the PDL of the first premolars due to a slight deflection of the archwire that produced stress on the teeth adjacent to the retraction hooks.

Longer hooks were associated with decreased stress in the PDL of the posterior teeth because the line of action of the retraction forces was closer to the CRes of the whole mandibular dentition, reducing rotation of the occlusal plane. Instead, stress was concentrated on the canines and first premolars, adjacent to the retraction hooks, due to the greater deflection of the archwire along the length of the hook, which began having a noticeable effect when using hooks of 6 mm and longer.

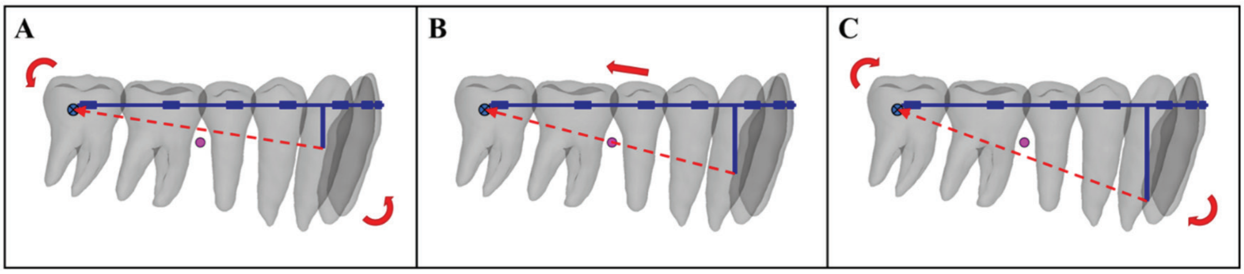

Figure 6: Schematic diagram of whole arch distalization with retraction hooks and miniscrews. A pink dot indicates the approximate position of the CRes. Red dotted lines indicate the distalization force. Red solid curved arrows express the moments that originated from the force. (A) Short hook: the red dotted line passes above the CRes and a counterclockwise moment is generated. (B) Optimal hook: the red dotted line passes through the CRes and a moment is not generated. (C) Long hook: the red dotted line passes below the CRes and a clockwise moment is generated.

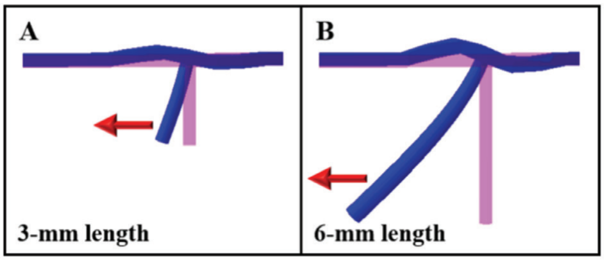

Figure 7: Comparison of archwire deflection obtained by (A) 3-mm and (B) 6-mm retraction hooks. The pink archwire shows the shape before the application of force; the solid blue archwire shows the distorted shape after the application of force.

According to the observed stress distribution pattern in the PDL, von Mises stress was highly concentrated in the PDL of the teeth adjacent to the retraction hook, consistent with the findings of Sung *et al.*[3] and Li *et al.*[33] Additionally, histological findings by Tomizuka *et al.*[34] and Böhl *et al.*[35] revealed that heavy stress in the PDL would lead to hyalinization. The formation of a large hyalinized area in the PDL decreases the rate of tooth movement and increases the possibility of root resorption. Therefore, the roots of the teeth close to the retraction hooks were subjected to higher levels of stress from the whole arch distalization mechanism, creating a root resorption risk.

Caution should be exercised when selecting the length of the retraction hook for whole arch distalization, which should depend on the individual patient's malocclusion and treatment objectives. When using miniscrews in the MBS area, shorter hooks should be used for lingual crown tipping of the anterior teeth and intrusion of the posterior teeth, procedures that are useful for patients with flared incisors and openbite. The 6-mm hooks would be suggested for distalizing the mandibular teeth along the distal direction with minimal change in other directions and minimal rotation of the occlusal plane, meaning that this length is suitable for patients with a normal bite.

Longer hooks could be effective for lingual root movement or protraction of the anterior teeth and minor extrusion of the posterior teeth, procedures that are appropriate for patients with retroclined incisors and deepbite. In clinical practice, long hooks may cause discomfort due to gingival impingement and deflection of the archwire and hook upon application of retraction force.[29]

Future studies should consider introducing a treatment time factor into FEM simulations to produce more accurate outcomes. Dynamic finite element studies could provide different and more realistic results concerning orthodontic tooth displacement and stress distribution than static finite element analysis.[36,37]

Conclusions

This study's FEM simulations showed that retraction hook length contributed to differences in the displacement patterns of the mandibular dentition and differences in the stress distribution patterns in the PDL for the whole arch distalization mechanism.

Used in conjunction with miniscrews on the MBS area, the 6-mm retraction hooks caused mandibular dentition to move distally with minimal change in other directions and minimal rotation of the occlusal plane, as indicated by the incisors showing approximate bodily movement and the posterior teeth showing slight vertical movement.

The occlusal plane rotated counterclockwise when using the shorter retraction hooks (1 mm and 3 mm) and clockwise when using the longer retraction hooks (9 mm and 12 mm).

For the shorter hooks, von Mises stress was highly concentrated in the distal aspect of the PDL of the second molars.

For the longer hooks, von Mises stress was highly concentrated in the PDL of the teeth adjacent to the retraction hooks, with greater degrees of concentration observed for longer hooks.

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Conflicts of interest

The authors declare no conflicts of interest.

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