Intrusion of Maxillary Posterior Teeth with Miniscrew Anchorage: A Finite Element Study

Tangsumroengvong V Patanaporn V** Rungsiyakul C*** Chalermwong H *****

Abstract

The purposes of this study were to evaluate the displacement pattern of all maxillary teeth and the von Mises stress distribution in the periodontal ligament when using different maxillary posterior intrusion mechanics with miniscrew anchorage, analyzed using a finite element method. Finite element models of maxillary teeth with periodontal ligament and alveolar bone were constructed. For each pattern of mechanics, a 100-g of intrusion force was applied and distributed to the miniscrew on the buccal and palatal sides. In Model 1, one miniscrew was inserted between the roots of the first and second molar teeth on the buccal side. In Model 2, one miniscrew was placed on the buccal side and a transpalatal arch (TPA) connected the first molars. In Model 3, two miniscrews were placed between the roots of the first and second molar teeth, one on the buccal and one on the palatal sides. The stress distribution in the periodontal ligament and the displacement of the teeth were analyzed using ABAQUS software. The result showed that the posterior teeth in Model 1 were intruded and tipped buccally and the overall stress values were highest. In Model 2, the posterior teeth were intruded along the long axis with no tipping. The overall stress values were lower than in other models. In Model 3, the posterior teeth were intruded and slightly tipped palatally. In all models, the anterior teeth were slightly extruded and had a low stress concentration in the PDL. In conclusion, posterior tooth intrusion with one miniscrew on the buccal side with a TPA provided balanced intrusion with less concentration of stress in the PDL than did the other types of mechanics.

Keywords: *Posterior tooth intrusion/ Miniscrew/ Periodontal Ligament/ Finite element analysis*

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Introduction

Intrusion of posterior teeth is required for the closure of anterior open bite and the intrusion of extruded molar teeth.[1,2] Conventional methods of posterior tooth intrusion, such as high pull headgear, Multiloop-Edgewise-Archwire (MEAW) and posterior bite plane, often result in limited intrusion and depend on patient growth and compliance.[3,4] Nowadays, miniscrews are efficient tools to use as skeletal anchorage for molar intrusion without any side effects and do not require patient compliance. They also provide minimal invasiveness, are simple to use and cost less.[5]

Many case reports have shown satisfactory outcomes of posterior tooth intrusion using miniscrew anchorage.[6-11] The intrusive force varies among authors from 50-500 grams. Carrillo et al.[7] found that force ranging from 50 to 200 g produced clinically significant amounts of intrusion with no root resorption. The number of miniscrews is usually two or three, being placed buccally and palatally to produce counteraction to the applied force.[2,8,10] The placement locations of miniscrew on the buccal side include the buccal interradicular space and infrazygomatic crest, whereas the placement locations in the palate can vary from the midpalatal area, the paramedian area to the interradicular area.[12] The intrusion force is applied to the tooth through attachments on the tooth, such as brackets, buttons, soldered bands and through segmented or continuous archwires. When group intrusion is required, the whole group of teeth should be tied together.[1]

* *Master student, Master of Science Program in Dentistry, Division of Orthodontics, Department of Orthodontics and Pediatric Dentistry, Faculty of Dentistry, Chiang Mai University, Amphur Muang, Chiang Mai.*
** *Department of Orthodontics and Pediatric Dentistry, Faculty of Dentistry, Chiang Mai University, Amphur Muang, Chiang Mai.*
*** *Department of Mechanical Engineering, Faculty of Engineering, Chiang Mai University, Amphur Muang, Chiang Mai.*
**** *Dental Department, Lamphun Hospital, Amphur Muang, Lamphun.*

Currently, several protocols of maxillary posterior tooth intrusion mechanics are used, and differ in the number and positions of miniscrews, force patterns and magnitudes of force.[6-11,13] The referenced studies have reported the treatment steps for posterior tooth intrusion and the efficiency of clinical outcomes. However, the biomechanical effects of the whole maxillary teeth when using different number of miniscrews and force patterns for posterior tooth intrusion have rarely been studied.[14,15] Moreover, applying intrusive force to posterior teeth attached with a continuous archwire might affect the anterior teeth.[13] Previous biomechanical studies have reported the effect of intrusion on only the posterior teeth but did not reported the effects on the anterior teeth.[14-16]

The finite element method (FEM) has been widely used to study the mechanics of tooth movement in orthodontic research.[17,18] It is a computational technique used to study intraoral biomechanics, which is complex and difficult to study intra-orally. Therefore, FEM is beneficial for simulating living tissue and the mechanical characteristics of biomaterials, both of which are challenging to research *in vivo*.[19-21]

The purposes of this study were to investigate the displacement pattern of all maxillary teeth and von Misses stress distribution in the periodontal ligament (PDL) when using different maxillary posterior tooth intrusion mechanics analyzed by FEM.

Materials and Methods

A geometric solid model of maxillary teeth and maxillary bone was constructed from the scanned digital tooth image of a commercial model (Model-i21FE-400C; Nissin Dental Products, Kyoto, Japan), which was based on the average tooth dimensions of Asian adults with normal occlusion. In this process, the Nissin model was scanned via 3-D laser scanner (D800 3D Scanner, 3Shape, Warren, New Jersey, USA), and then was exported to SolidWorks software (Dassault Systèmes Americas, Waltham, Mass., USA) to construct and assemble structures of the solid model, including all maxillary teeth, PDL and maxillary bone. The periodontal ligament was assumed to have an even thickness of 0.2 mm, conforming to the root surface. The maxillary bone consisted of cancellous bone with 1.0 mm thickness of cortical bone. The alveolar crest was formed following the curvature of the cemento-emamel junction (CEJ), 1 mm apical to the CEJ.[22,23] The brackets with slot dimensions of 0.018 x 0.025 inches and a stainless-steel main archwire with dimensions of 0.017 × 0.025 inches were modeled, and it was assumed that there was no play and no friction between the brackets and the archwire. The brackets were attached to the midpoint of the facial axis of the crown and completely connected to each tooth. The buccal and palatal miniscrews were simulated 6 mm above the CEJ between the maxillary first and second molars in the interradicular space.

In the first model, miniscrews were placed in the buccal interradicular space between the first and second molars. An intrusive force of 100 g was applied from the miniscrews to the brackets on the first and second molars, the force divided equally, 50 g for each tooth (Figure 1).

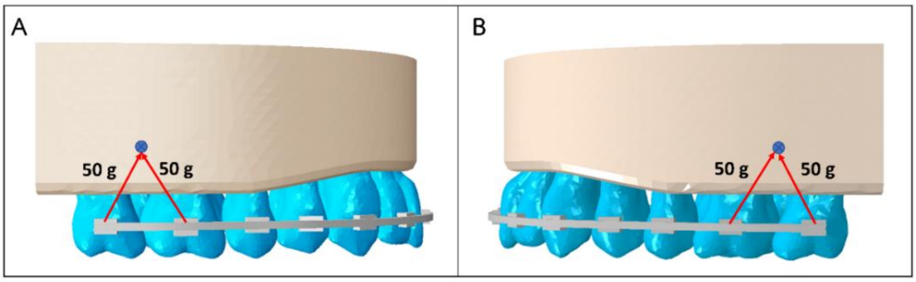

Figure 1 Schematic force diagram and miniscrew positions of the first model. Intrusive force (50 g) is applied from the miniscrews to the brackets of the first and second molars. A) Right B) Left

In the second model, miniscrews were placed in the same position, the buccal interradicular space between the first and second molars. In this model, a transpalatal arch (TPA) with a diameter of 1.4 mm was constructed connecting the right and left first molars. The TPA was modeled 5 mm away from the palatal bone to achieve clearance for intrusion. The intrusive force of 100 g was applied from the miniscrews to the brackets on the first and second molars, the force divided equally, 50 g for each tooth (Figure 2).

In the third model, miniscrews were placed buccally and palatally in the interradicular space between the first and second molars. In this model, buttons were modeled with a diameter of 2 mm. and attached to the midpoint of the palatal surface of the first and second molar crowns. An intrusive force of 100 g was applied from the miniscrews to the brackets and the buttons, the force divided equally, 25 g for each tooth (Figure 3).

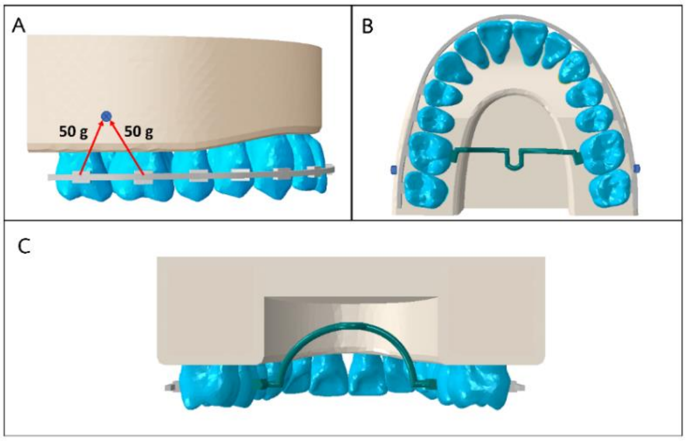

Figure 2 Schematic force diagram and miniscrew positions of the second model. A) Intrusive force (50 g) is applied from the miniscrews to the brackets on the first and second molars. B) Occlusal view that shows the transpalatal arch connecting the first molars. C) TPA is 5 mm. away from the palatal bone

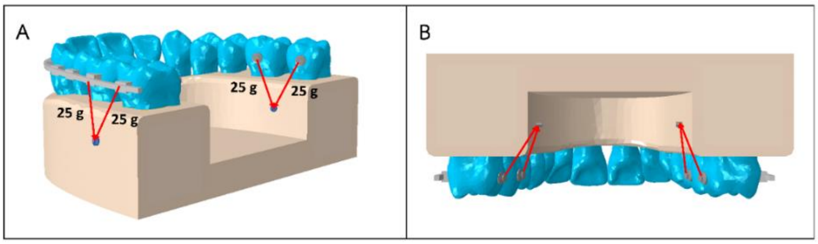

Figure 3 Schematic force diagram and miniscrew positions of the third model. A) Intrusive force (25 g) is applied from the miniscrews to the brackets on the buccal side and the buttons on the palatal side. B) Posterior view of the model showing the intrusive force vector from the miniscrews to the buttons on the palatal side

The properties of all materials followed the same values as used in other previous finite element studies (Table 1).[20,24-29] All materials were assigned as isoparametric, homogeneous, and linear elastic properties, except for the PDL, which was defined as having non-linear elasticity. The property values of the Ogden model were assigned to describe the non-linear elastic behavior of the PDL (Table 2).[30]

Table 1 Material properties of dentin, cortical bone, cancellous bone and stainless steel required within the FE model.[20,24-29]

Material	Young's modulus (MPa)	Poisson's ratio
Dentin	19600	0.3
Cortical bone	13700	0.26
Cancellous bone	1370	0.3
Stainless steel	200000	0.3

Table 2 Coefficients of the third order Ogden model property values describing non-linear elasticity of the PDL.[30]

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

The constructed finite element model was meshed into 148,914 nodes and 651,810 elements. The teeth, PDL and alveolar bone were constructed into tetrahedron elements. The brackets, buttons, and archwire were constructed into hexahedron elements. The interactions between teeth were tie contact with no friction. The boundary conditions were defined at the top and posterior surface of the maxillary bone. The orientation of this model was established with the x axis representing the mesio-distal direction of the anterior teeth and the bucco-palatal direction of the posterior teeth. The y axis represented the supero-inferior direction. The z axis represented the antero-posterior direction, which was the labio-palatal direction of the anterior teeth and the mesio-distal direction of the posterior teeth (Figure 4).

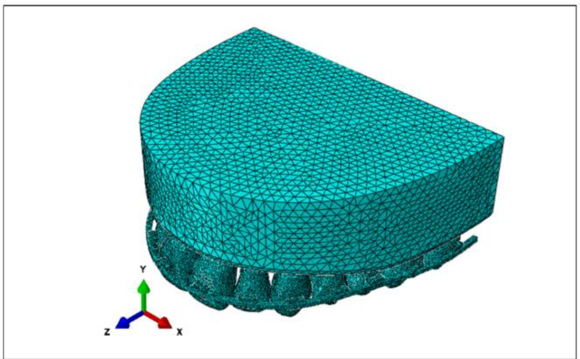

Figure 4 The orientation of the model in x, y and z axes.

The Abaqus software (Dassault Systèmes Americas) was used to calculate and visualize the initial tooth displacement and the PDL von Mises stress distribution of all maxillary teeth for the intrusion of the maxillary posterior teeth. To precisely determine the tooth displacement, the same nodes of the incisal edges, the cusp tips, and the root apices of teeth in each model were assessed, and superimpositions were used.

Results

Tooth displacement

The displacement patterns of all maxillary teeth in each pattern of intrusion mechanics are shown in Figures 5-7. The translucent yellow tooth images show the positions of the teeth before applying the force, and the blue tooth images show the displaced positions afterwards. With all mechanics, the amounts of initial tooth movement in the posterior segment were larger than in the anterior segment.

In the first model, the posterior teeth, especially the first and second molars, were intruded and tipped buccally. The buccal roots showed considerably greater intrusion than did the palatal roots. Extrusion was observed at the palatal cusps, as the result of prominent buccal tipping movement of the posterior teeth. The anterior teeth were slightly extruded and tipped palatally (Figure 5).

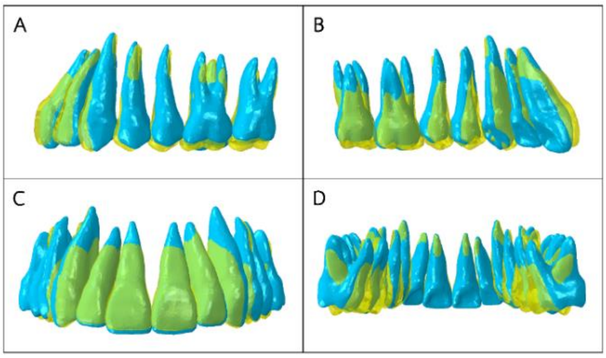

Figure 5 Displacement of the maxillary teeth in first model indicated by superimposition of teeth before (yellow) and after (blue) application of the intrusion force. A) Sagittal view (buccal), B) Sagittal view (palatal), C) Frontal view, D) Posterior view

In the second model, the posterior teeth were intruded along the long axis with no tipping movement, representing bodily movement or pure intrusion. The amounts of intrusion movement of buccal and palatal roots of the molars were nearly equal. The premolars were intruded less than the molars. The anterior teeth were also slightly extruded and tipped palatally, as in the first model (Figure 6).

In the third model, the posterior teeth were intruded and slightly tipped palatally. Intrusion of the palatal roots was slightly greater than that of the buccal roots. The anterior teeth were also slightly extruded and tipped palatally, as in the first and second models (Figure 7).

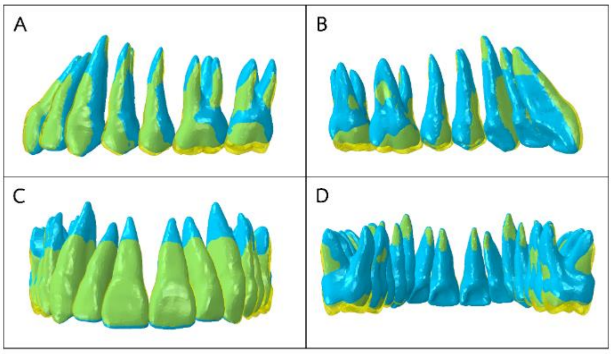

Figure 6 Displacement of the maxillary teeth in the second model. A) Sagittal view (buccal), B) Sagittal view (palatal), C) Frontal view, D) Posterior view

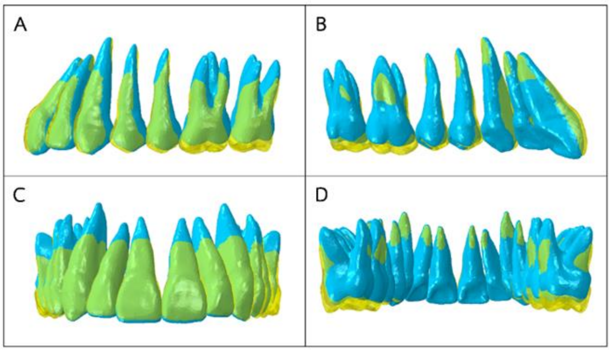

Figure 7 Displacement of the maxillary teeth in the third model. A) Sagittal view (buccal), B) Sagittal view (palatal), C) Frontal view, D) Posterior view

Stress distribution in PDL

The von Mises stress distribution in the PDL was calculated in N/mm^2 (MegaPascals or MPa). The color-coded map of von Mises stress distribution in the PDL with all models is shown in Figure 8. The levels of stress are shown in the map, in which the red color represents the areas of maximum stress and the dark blue color represents the areas of minimum stress.

In the first model, the maximum von Mises stress was 5.653x10^{-3} MPa, which was the highest maximum stress value in all the models. The buccal roots of the first and second molars showed that the high stress was concentrated in the apical third of the first molar and all surface areas of the second molar. The minimum von Mises stress was 2.492x10^{-8} MPa and areas of low stress were found in the anterior teeth, decreasing progressively from the posterior to the anterior segments (Figure 8A).

In the second model, the maximum von Mises stress was 1.276x10^{-3} MPa. High stress values were observed in the root tip of the disto-buccal root of the first molar. The buccal root and the apical third of the palatal root of the second molar also showed high stress values. The minimum von Mises stress was 5.373x10^{-9} MPa and areas of low stress were also found in the anterior teeth (Figure 8B).

In the third model, the maximum von Mises stress was 2.464x10^{-3} MPa. High stress values were identified in all surface areas of the palatal root of the first molar and the buccal and palatal roots of the second molar. The minimum von Mises stress was 9.521x10^{-9} MPa and areas of low stress were also found in the anterior teeth (Figure 8C).

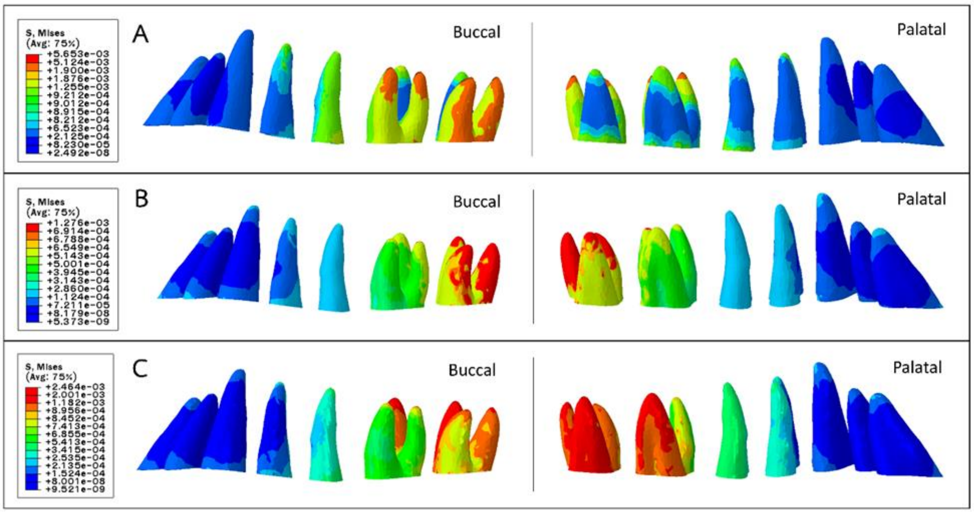

Figure 8 Color-coded maps of von Mises stress distribution of the left maxillary quadrant PDL in the buccal and palatal views. A) Model 1, B) Model 2, C) Model 3

Discussion

This finite element study was carried out to evaluate the effects of various patterns of posterior tooth intrusion mechanics with miniscrew anchorage. It was found that the displacement and stress distribution were different in each pattern of mechanics and was influenced by the force pattern and miniscrew position.

In the first model, the intrusive force was applied only from the buccal side, resulting in buccal crown tipping. This tipping was the result of the buccal crown moments caused by the intrusive forces through only the buccal molar tubes.[2,31] Thus, the most severe buccal tipping and highest stress magnitudes among the three models were observed in this model. In addition, high stress was mostly found in the buccal roots of the molars because these roots were more intruded than the palatal root (Figure 5 & 8A).

The most balanced intrusion with no buccal or palatal crown tipping was identified in the second model, which had a TPA connecting the first molars. The TPA was used to balance the produced moments and inhibit buccal crown tipping. The highest stress magnitudes of this model were less than the magnitudes of the other two models. The area of high stress was found in both buccal and palatal roots, since they were intruded equally (Figure 6 & 8B).

In the third model, the applied force from miniscrews on the buccal and palatal sides led to slight palatal crown tipping of the posterior teeth. One explanation for this tipping is the inequality of the angles of buccal and palatal force vectors in this finite element model due to the difference in slope anatomy of the buccal and palatal sides of the alveolar bone. The palatal force vectors were angulated 13 degrees to the long axis of the maxillary molar teeth, whereas the buccal force vectors were angulated 30 degrees. Consequently, there was more resultant force in the palatal direction, leading to slight palatal tipping. However, the posterior teeth had a balanced intrusion, similar to that in the second model due to the counterbalancing force on the buccal and palatal sides. Whereas the high stress was found in both buccal and palatal roots of the molars, the stress was slightly higher in the palatal root, which was more intruded than the buccal root (Figure 7 & 8C).

In all models, high von Mises stress and large amounts of displacement were observed in the first and second molars and gradually decreased from the molar to the premolar and anterior teeth. The anterior teeth were slightly extruded because the lever effect in the reciprocal force system produces an extrusive force when applying intrusive force to the posterior teeth.[2,31,32] This extrusion movement may improve the anterior open bite by closing the overbite. The von Mises stress in the PDL of the anterior teeth was low, since the extrusion effect occurred in them. Moreover, the tooth adjacent to the force application site showed relatively high stress, whereas minimum stress was observed in the anterior teeth, which were away from the force application point. Hence, the chances of root resorption were high in the posterior teeth and low in the anterior teeth. These findings are consistent with those of Cifter et al.[14] and Pekhale et al.,[15] who reported that the stress was more concentrated on the teeth close to the point of force application than on other teeth in positions farther away.

Cifter et al.[14] studied three models of posterior tooth intrusion in which the combinations of miniscrews and TPA varied. They reported on only the posterior teeth but did not mention the anterior teeth. They found that the application of force from the miniscrew on the buccal and palatal sides leads to a more uniform stress distribution and balanced intrusion than does the pattern of mechanics with a TPA. In our study, balanced intrusion was observed when using one miniscrew on the buccal side and a TPA. These results agree with the finding of Pekhale et al.,[15] who suggested that using three mini-implants with a TPA showed the most balanced intrusion.

In clinical situations, extrusion of the palatal cusps of the posterior teeth can create interferences between the opposing teeth and lead to more severe open bite.[8,14] Thus, in most patients with open bite, it is important to prevent buccal crown tipping during posterior tooth intrusion. Previous studies have reported that the use of four miniscrews on the buccal and palatal sides is biomechanically ideal, but it can be difficult to apply clinically and obtain acceptability from patients because four miniscrews can be too much for them.[13,15] Using four miniscrews is more invasive and costly than using only one miniscrew on the buccal side. Buccal interradicular areas are commonly used in anchorage because of their ease of access and patient comfort compared to palatal areas, which require some complicated auxiliary tools for loading the force.[33,34] In our study, where one miniscrew on buccal side and a TPA were used, the results obtained were effective intrusion with no buccal crown tipping. The stress concentration in the PDL was also lowest when compared with the other patterns of mechanics. However, it is essential to apply unique mechanics and force systems for each patient because of the variations in tooth morphology and inclination of the buccal and palatal slopes of the alveolar bone that can affect stress distribution and the displacement pattern of the posterior tooth intrusion.[15] Even though perfect patterns of mechanics and force systems are used, the biomechanical effect of the force systems can change after the initial tooth movement, and some modifications might be required during the treatment.

In the finite element method, the accuracy of the result is largely attributed to how well the model is constructed in terms of anatomy, material properties and boundary conditions.[35] In this study, a commercial dental model was used to create the external geometry of the finite element model, based the dimensions and alignment of teeth of adult populations with a normal occlusion.[23,36,37] All materials were assigned as linear elastic properties, excepting the PDL, which was defined as having non-linear elasticity because of its hyper-elastic behavior. Previous studies have proved that the PDL is generally perceived to be nonlinearly elastic in its behavior.[38,39] Therefore, the Ogden model of non-linear properties proposed by Huang et al.[30] was used to express the elastic response of this biological soft tissue.

This finite element study showed initial displacement and stress distribution in the PDL of maxillary teeth during posterior tooth intrusion. The results may not reveal actual clinical outcomes because the human body continually undergoes biological responses after force is applied to the tooth. Therefore, orthodontic tooth movement might differ from the calculated initial movement, since the periodontal ligament and alveolar bone are remodeled before changing their shapes and positions, according to individual biological responses.[40,41] Another factor should be considered was the floor of maxillary sinus, which may interfere the maxillary molar intrusion. However, orthodontic movement through maxillary sinus can be possible when applying constant and light to moderate forces with temporary anchorage devices (TADs).[42,43] Yao et al.[44] and Kravitz et al.[8,45] used TADs to intrude maxillary molar within the maxillary sinus. They reported that bone remodeling of the sinus floor was observed following the maxillary molar intrusion. Moreover, the thickness of the PDL is in fact non-uniform, having an hour-glass shape with the mid-root level having the narrowest width,[46] but in this study, it was assumed to be uniform (0.2 mm.). The cortical bone in this finite element model was also created with uniform thickness (1 mm.), but the thickness of the cortical bone varies in the jaws.[47,48] These limitations can cause differences between clinical applications and simulation studies. However, in conjunction with other relevant clinical, biological, and biomechanical research, our findings can provide a treatment guide in the clinical application of miniscrew anchorage for intrusion of the maxillary molar teeth.[23]

Conclusion

Posterior tooth intrusion with miniscrews placed on only the buccal side resulted in buccal flaring of the posterior teeth, whereas placing miniscrews on the buccal side with a TPA, or placing buccal and palatal miniscrews, produced balanced intrusion and uniform stress distribution.

- Applying intrusive force to the posterior teeth also produced an extrusive force on the anterior teeth, resulting in slight extrusion of the anterior teeth.

- Areas of high stress concentration were particularly found in the intruded roots, thus it should be taken into consideration that these areas are prone to apical root resorption.

Acknowledgment

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Corresponding author

Virush Patanaporn
Department of Orthodontics and Pediatric Dentistry,
Faculty of Dentistry, Chiang Mai University,
Amphur Muang, Chiang Mai, 50200
Tel: +66 53 944 440-1
Fax: +66 53 222 844
E-mail: vr167420@hotmail.com

การดันเข้าของฟันหลังบนด้วยหลักยึดหมุดฝังในกระดูก: การศึกษาโดยวิธีไฟไนต์เอลิเมนต์

วณิชชญา ตั้งสำริงวงศ์ วิรัช พัฒนาภรณ์** ชาย รังสิยากูล*** หัสมนัญ เฉลิมวงศ์*****

บทคัดย่อ

การศึกษานี้มีวัตถุประสงค์เพื่อประเมินลักษณะการเคลื่อนที่ของฟันทุกซี่ในขากรรไกรบนและกระจายความเค้นแบบวอนมิสเซสในเอ็นยึดปริทันต์เมื่อใช้กลไกการดันเข้าของฟันหลังบนที่แตกต่างกันด้วยหลักยึดหมุดฝังในกระดูก วิเคราะห์โดยวิธีไฟไนต์เอลิเมนต์ โดยทำการสร้างแบบจำลองไฟไนต์เอลิเมนต์ของฟันบนทุกซี่ พร้อมทั้งเอ็นยึดปริทันต์ และกระดูกเบ้าฟัน ในแต่ละรูปแบบของกลไกมีการให้แรงดันเข้าขนาด 100 กรัม และแบ่งกระจายแรงไปยังหลักยึดหมุดฝังที่ด้านแก้มและด้านเพดานปาก ในโมเดลที่ 1 มีหลักยึดหมุดฝังหนึ่งตัวอยู่ที่ทางด้านแก้ม ระหว่างรากของฟันกรามซี่ที่หนึ่งและสอง ในโมเดลที่ 2 มีหลักยึดหมุดฝังหนึ่งตัวอยู่ที่ทางด้านแก้ม และมีแท่งยึดผ่านเพดานเชื่อมระหว่างฟันกรามซี่ที่หนึ่ง ในโมเดลที่ 3 มีหลักยึดหมุดฝังสองตัวอยู่ระหว่างรากของฟันกรามซี่ที่หนึ่งและสอง โดยอยู่ที่ด้านแก้มหนึ่งตัวและด้านเพดานปากอีกหนึ่งตัว ทำการวิเคราะห์การกระจายความเค้นในเอ็นยึดปริทันต์และการเคลื่อนที่ของฟันโดยโปรแกรมอาบาคัส ผลการศึกษาพบว่าในโมเดลที่ 1 ฟันหลังถูกดันเข้ากระดูกเบ้าฟันและล้มเอียงไปทางด้านแก้ม ค่าความเค้นโดยรวมมีค่าสูงสุด ในโมเดลที่ 2 ฟันหลังถูกดันเข้ากระดูกเบ้าฟันไปตามแนวแกนฟันโดยไม่มีการล้มเอียง ค่าความเค้นโดยรวมต่ำกว่าในโมเดลอื่นๆ ในโมเดลที่ 3 ฟันหลังถูกดันเข้ากระดูกเบ้าฟันและล้มเอียงไปทางด้านเพดานปากเล็กน้อย ในทุกโมเดลพบว่าฟันหน้าถูกดันออกจากกระดูกเบ้าฟันเล็กน้อยและมีความเค้นในเอ็นยึดปริทันต์ต่ำ จากการศึกษาสรุปว่าการดันเข้าของฟันหลังเข้าไปในกระดูกด้วยการใช้หลักยึดหมุดฝังหนึ่งตัวร่วมกับแท่งยึดผ่านเพดานทำให้เกิดการดันเข้าอย่างมีสมดุลและมีความเค้นในเอ็นยึดปริทันต์ต่ำกว่าที่พบในกลไกแบบอื่นๆ

คำไขรหัส: *การดันเข้าของฟันหลัง/ หลักยึดหมุดฝังในกระดูก/ เอ็นยึดปริทันต์/ ไฟไนต์เอลิเมนต์*

ผู้รับผิดชอบบทความ

วิรัช พัฒนาภรณ์

ภาควิชาทันตกรรมจัดฟันและทันตกรรมสำหรับเด็ก

คณะทันตแพทยศาสตร์ มหาวิทยาลัยเชียงใหม่

อำเภอเมือง จังหวัดเชียงใหม่ 50200

โทรศัพท์: 053 944 440-1

โทรสาร: 053 222 844

จดหมายอิเล็กทรอนิกส์: vr167420@hotmail.com

* นักศึกษาระดับปริญญาโท หลักสูตรวิทยาศาสตรมหาบัณฑิต (สาขาวิชาทันตแพทยศาสตร์) สาขาวิชาทันตกรรมจัดฟัน ภาควิชาทันตกรรมจัดฟัน และทันตกรรมสำหรับเด็ก คณะทันตแพทยศาสตร์ มหาวิทยาลัยเชียงใหม่ อำเภอเมือง จังหวัดเชียงใหม่

** ภาควิชาทันตกรรมจัดฟันและทันตกรรมสำหรับเด็ก คณะทันตแพทยศาสตร์ มหาวิทยาลัยเชียงใหม่ อำเภอเมือง จังหวัดเชียงใหม่

*** ภาควิชาวิศวกรรมเครื่องกล คณะวิศวกรรมศาสตร์ มหาวิทยาลัยเชียงใหม่ อำเภอเมือง จังหวัดเชียงใหม่

**** แผนกทันตกรรม โรงพยาบาลลำพูน อำเภอเมือง จังหวัดลำพูน