Comparison of tooth displacement between buccal mini-implants and palatal plate anchorage for molar distalization: a finite element study

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SUMMARY The purposes of this study were to mechanically evaluate distalization modalities through the application of skeletal anchorage using finite element analysis. Base models were constructed from commercial teeth models. A finite element model was created and three treatment modalities were modified to make 10 models. Modalities 1 and 2 placed mini-implants in the buccal side, and modality 3 placed a plate on the palatal side. Distalization with the palatal plate in modality 3 showed bodily molar movement and insignificant displacement of the incisors. Placing mini-implants on the buccal side in modalities 1 and 2 caused the first molar to be distally tipped and extruded, while the incisors were labially flared and intruded. Distalization with the palatal plate rather than mini-implants on the buccal side provided bodily molar movement without tipping or extrusion. It is recommended to use our findings as a clinical guide for the application of skeletal anchorage devices for molar distalization.

Introduction

Headgear has been a conventional modality for Class II malocclusion through distalization of molars or entire the maxillary dentition. However, its main disadvantage is its dependence on patient compliance, which is difficult due to social and aesthetic concerns (Egolf et al., 1990; Lima Filho et al., 2003).

To avoid this drawback, various non-compliance appliances have been developed including the Keles slider, repelling magnets, distal jet, and pendulum (Hilgers, 1992; Bondemark et al., 1994; Bussick and McNamara, 2000; Keles, 2001; Bolla et al., 2002; Bondemark and Karlsson, 2005). These devices applied continuous forces to distalize maxillary molars, which might lead to distal tipping and extrusion of the first molars, while the mesial reactive forces might cause anchorage loss and labial flaring of anterior teeth (Joseph and Butchart, 2000; Fuziy et al., 2006).

To overcome these unwanted side-effects, skeletal anchorage systems have been applied in previous studies for molar distalization (Keles et al., 2003; Escobar et al., 2007; Oncag et al., 2007; Kinzinger et al., 2009). Mini-implants have been combined with pendulums and distal jets to reinforce anchorage and prevent labial flaring. A different system is indirect anchorage that splints mini-implants to teeth between the canine and first premolar for relief of posterior discrepancy by distalization of molars and a direct anchorage using mini-implants between the second premolar and first molar to apply retraction force to hooks to prevent unwanted forward movement of the anterior teeth during molar distalization (Cornelis and De Clerck, 2007; Kim et al., 2008).

Recently, a mini-plate was applied on the palate to efficiently distalize maxillary molars without invasive procedures (Kook et al., 2010; Figure 1). However, the resultant tooth displacement due to molar distalization using skeletal anchorage has not been evaluated.

Therefore, the purposes of this study were to analyse the displacement of central incisors and molars according to the distalization modalities through the application of skeletal anchorage using finite element analysis.

Materials and methods

Construction of finite element model

Commercial teeth models (Model-i21D-400G; Nissin Dental Products, Kyoto, Japan) were three-dimensionally scanned to produce the teeth images. Then, the images were aligned on a broad dental arch form (Ormco®, Glendora, California, USA) without curves of Spee and Wilson.
The thickness of periodontal ligament was modelled as a 0.25 mm layer of uniform thickness according to Coolidge’s study (Coolidge, 1937). The alveolar bone was designed to follow the cemento-enamel junction gingivally and extended 1 mm beyond the apex (Block, 1987; Figure 2). Micro-arch® brackets (Tomy Co., Tokyo, Japan) were three-dimensionally modelled. In this study, the brackets and archwire were assumed to be in no-play and no-friction relationship, and all materials were considered to be homogenous, isotropic, and have linear elasticity. Materials’ properties (Young’s modulus and Poisson’s ratio) were reported by previous studies (Tanne et al., 1987; Sung et al., 2009; Table 1).

Determination of axes

Each model 3D co-ordinates [X, median (+) to lateral (−) direction; Y, anterior (+) to posterior (−) direction; and Z, supero (+) to inferior (−) direction]. For result presentation, the central incisor was modelled by the midpoint of the incisal edge and the apex while the first and second molars were demonstrated by the four cusps and the palatal root apex (Figure 2; Table 2).

Installation of simulated distalization modalities on finite element model

Models of three different distalization modalities were installed on finite element models (FEMs) to produce 10 different models according to the position of distalization arm.

Distalization modality 1: open-coil spring using indirect skeletal anchorage. Model 1. Brackets were placed on all teeth except the second premolar. A 0.019 × 0.025 inch SS archwire was engaged. To distalize the first molar, 150 g of force was applied by open-coil spring between the first premolar and the first molar. The first premolar was connected to alveolar bone with 0.019 × 0.025 SS wire in the FEM model to simulate the clinical application of the indirect anchorage of a mini-implant placed between the canine and the first premolar. The first molars were connected by a 0.9 mm SS transpalatal arch (TPA) to prevent rotation. The second molars were excluded because they sometimes have not erupted or have been strategically extracted (Figure 3A).

Distalization modality 2: open-coil spring and direct skeletal anchorage. Models 2, 3, and 4. Brackets were placed on all teeth except the second premolar. A 0.019 × 0.025 inch SS archwire was engaged. To distalize the first molar, 150 g of force was applied by open-coil spring between the first premolar and the first molar. To prevent labial movement of anterior teeth, a force of 150 g was applied between a virtual position of a mini-implant (8 mm apical to archwire

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s modulus (Mpa)</th>
<th>Poisson’s ratio</th>
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<tbody>
<tr>
<td>Periodontal ligament</td>
<td>$5.0 \times 10^{-2}$</td>
<td>0.49</td>
</tr>
<tr>
<td>Alveolar bone</td>
<td>$2.0 \times 10^{3}$</td>
<td>0.30</td>
</tr>
<tr>
<td>Tooth</td>
<td>$2.0 \times 10^{4}$</td>
<td>0.30</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>$2.0 \times 10^{5}$</td>
<td>0.30</td>
</tr>
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</table>

**Figure 1** (A) Schematic figure of palatal plate. (B) Schematic figure of maxillary molar distalization appliance using palatal plate.

**Figure 2** The finite element analysis model. (A) Teeth; (B) teeth and alveolar bone; Schematic line of axes (C) Y–Z plane; and (D) X–Z plane.
and 2 mm lateral to alveolar bone surface) and a 0.8 mm SS retraction hook attached to the archwire between the lateral incisor and canine. The first molars were connected by a 0.9 mm SS TPA to prevent rotation. The second molars were excluded. The vertical height of the retraction hook was decided to be 1, 4, and 7 mm in models 2, 3, and 4, respectively (Figure 3B).

**Distalization modality 3: palatal plate.** Models 5, 6, and 7. Brackets were placed on all teeth. A 0.019 x 0.025 inch SS archwire was engaged. A palatal plate was assumed to be at the level of the first molars centres, antero-posteriorly. The three notches on the lever arms of the palatal plate were selected for force application and were assumed to be at 4, 7, and 10 mm apical to the archwire vertically and 13, 12.5, 12 mm lateral to mid-palate horizontally, respectively. A 1.0 mm horseshoe SS palatal arch connected the first molars. Two stainless steel hooks (0.8 mm SS) were attached on the palatal arch close to the lingual position of canine (Figure 1). For the first molar distalization, a 150 g force was applied from one of the three indentation positions of the palatal plate arm to the palatal arch hook. The second molars were excluded for the same reasons noted for model 1. The power vectors for models 5, 6, and 7 were attached at the 4, 7, and 10 mm lever arm indentations, respectively (Figure 3C and 3D).

Model 8. This model was similar to model 7 but included the second molar (Figure 3E).

Model 9. This model was similar to model 7 but a cinch-back bend was applied in the archwire distal to the first molar tube to prevent sliding movement and imply en masse distalization.

Model 10. This model was similar to model 9 but included the second molar.

Non-linear analysis was performed by ANSYS Ver.11 (Swanson Analysis System, Canonsburg, Pennsylvania, USA) on HP XW6400 workstation (Hewlett-Packard Co., Palo Alto, California, USA).
Results

Distalization by modality 1 using indirect anchorage

The first molar was shown to expand laterally with mesial-out rotation (mesial side of the tooth is moved more laterally than distal side of the tooth), uncontrolled distally tipped, and extruded. The incisor was tipped anteriorly and intruded (Figures 4, 5, 6, and 7; Table 2).

Distalization by modality 2 using direct anchorage

The displacement of the first molar widened laterally with mesial-out rotation, uncontrolled distally tipped, and extruded. However, the results for the incisor position were relatively stable compared to model 1. However, flaring and intrusion of the incisors increased as the vertical height rose from 4 to 7 mm in models 3 and 4, respectively (Figures 4, 5, 6, and 7; Table 2).

Distalization by modality 3 with palatal plate

The incisor position was very stable in models 5, 6, and 7 during distalization. The displacement of the first molar was distal-out rotation (distal side of the tooth is moved more laterally than mesial side of tooth), while modalities 1 and 2 were mesial-out. Controlled distal tipping and extrusion were found in model 5. However, as the indentation used was close to the midpalatal suture, extrusion was replaced with bodily movement. Finally, in model 7, which was closest to the midpalatal suture, bodily movement and intrusion were shown.

In model 8, the displacement of the first molar showed to widen laterally with distal-out rotation with translation and intrusion. However, the second molar showed to widen laterally and was tipped distally with extrusion (Figures 4, 5, 6, and 7; Table 2).

Model 9 showed the displacement of the first molar to widen laterally with distal-out rotation, translation, and intrusion. However, the incisor was slightly tipped lingually (Figures 4, 5, 6, and 7; Table 2).

Model 10 was similar to model 9, in that the maxillary second molar was tipped distally and extruded (Figures 4, 5, 6, and 7; Table 2).

Discussion

Molar distalization is recommended for correction of Class II malocclusion or maxillary crowding cases without extraction. For better treatment results, in spite of development of several intraoral appliances, it does not perfectly prevent reciprocal mesial movement of anchorage.

Figure 4  Contour image of the maxillary dentition in X-axis displacement. Original model (white mesh) and deformed model (colour). (A and B) Contour plot of models 1 and 2, respectively, was 10 times magnified. As the orthodontic force is applied at buccal side, the mesial-out rotation of the first molar (mesial side of the tooth is moved more laterally than distal side of the tooth) was observed. (C) Contour plot of model 7 was 20 times magnified. As the orthodontic force is applied at palatal side, the distal-out rotation of the first molar (distal side of the tooth is moved more laterally than mesial side of tooth) was observed. (D) Contour plot of model 8 was 40 times magnified. The second molar is moved laterally without large rotation because the distal-out rotation of the first molar and rearward force are transferred to contact point between the first molar and the second molar. (E) Contour plot of model 9 was 40 times magnified. The second premolar is moved medially by virtue of the distal-out rotation of the first molar. (F) Contour plot of model 10 was 40 times magnified. The distal-out rotation of the first molar, median movement of the second premolar, and lateral movement of the second molar are observed.
### Table 2  Values of displacement of teeth. MIE, middle incisal edge; RA, root apex; MBC, mesio-buccal cusp; MPC, mesio-palatal cusp; DBC, disto-buccal cusp; DPC, disto-palatal cusp; PRA, palatal root apex.

<table>
<thead>
<tr>
<th>Central incisor</th>
<th>The first molar</th>
<th>The second molar</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MIE</td>
<td>RA</td>
</tr>
<tr>
<td>Model 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Δx</td>
<td>6.30 × 10⁻³</td>
<td>-5.86 × 10⁻⁴</td>
</tr>
<tr>
<td>Δy</td>
<td>2.72 × 10⁻²</td>
<td>-1.29 × 10⁻²</td>
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<tr>
<td>Model 2</td>
<td></td>
<td></td>
</tr>
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<td>Δx</td>
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<td>-1.05 × 10⁻²</td>
</tr>
<tr>
<td>Δy</td>
<td>1.52 × 10⁻⁵</td>
<td>-2.39 × 10⁻⁵</td>
</tr>
<tr>
<td>Δz</td>
<td>2.09 × 10⁻⁵</td>
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</tr>
<tr>
<td>Model 3</td>
<td></td>
<td></td>
</tr>
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<td>Δx</td>
<td>4.86 × 10⁻²</td>
<td>-1.08 × 10⁻²</td>
</tr>
<tr>
<td>Δy</td>
<td>8.56 × 10⁻⁵</td>
<td>-2.39 × 10⁻⁵</td>
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<tr>
<td>Δz</td>
<td>3.07 × 10⁻⁵</td>
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</tr>
<tr>
<td>Model 4</td>
<td></td>
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<td>Δx</td>
<td>5.65 × 10⁻²</td>
<td>-1.24 × 10⁻²</td>
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<td>Δz</td>
<td>4.17 × 10⁻²</td>
<td>1.15 × 10⁻²</td>
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COMPARISON OF BUCCAL AND PALATAL APPROACHES FOR MOLAR DISTALIZATION

Figure 5 Contour image of the maxillary dentition in Y-axis displacement. Original model (white mesh) and deformed model (colour). (A) Model 1 contour plot was 10 times magnified. The first molar was showed uncontrolled distal tipping, and the incisor was tipped anteriorly. (B) The displacement of the first molar showed uncontrolled distal tipping in model 2. (C) Contour plot of model 7 was 20 times magnified. The incisor position was very stable and the first molar showed bodily movement. (D) Contour plot of model 8 was 40 times magnified. The first molar was translated but the second molar was tipped distally. (E) Contour plot of model 9 was 40 times magnified. The first molar was translated and the incisor was slightly tipped lingually. (F) Contour plot of model 10 was 40 times magnified. The first molar was translated but the second molar was tipped distally.

Figure 6 Contour image of the maxillary dentition in Z-axis displacement. Original model (white mesh) and deformed model (colour). (A) Model 1 contour plot was 10 times magnified. The first molar was extruded. The incisor was intruded. (B) The displacement of the first molar was extruded in model 2. (C) Contour plot of the model 7 was 20 times magnified. The incisor position was very stable and the first molar was intruded in model 7. (D) Contour plot of model 8 was 40 times magnified. The displacement of the first molar showed intrusion. However, the second molar showed extrusion. (E) Contour plot of model 9 was 40 times magnified. The first molar was intruded. (F) Contour plot of model 10 was 40 times magnified. The first molar was intruded but the second molar was extruded.

teeth, the extrusion and distal tipping of the maxillary molars (Joseph and Butchart, 2000; Fuziy et al., 2006; Escobar et al., 2007).

Recently, studies have been directed towards the use of skeletal anchorage devices. An example of indirect anchorage used a mini-implant splinted to a tooth to counter
Figure 7 Tooth axies graph (incisor: midpoint of incisal edge to root apex; canine: cusp tip to root apex; and molar: mesio-palatal cusp tip to palatal root apex) magnified tooth displacement 70 times. A solid line means before displacement and a dotted line means after displacement (circles, central incisor; squares, the first molar; and triangles the second molar). (A) The first molar showed uncontrolled distal tipping and extruded and the incisor was tipped anteriorly and intruded. (B, C, and D) The displacement of the first molar showed uncontrolled distal tipping, and the incisor was intruded and preclined as the vertical height rose from 1 to 7 mm in models 2, 3, and 4, respectively. (E, F, and G) Axies graph of the models 5, 6, and 7, respectively. The incisor position was very stable in models 5, 6, and 7. The displacement of the first molar was controlled distal tipping and extruded in model 5. However, as the indentation used was close to the midpalatal suture, extrusion and distal tipping were replaced with intrusion and bodily movement in model 7. (H) Axies graph of model 8, the first molar was translated and intruded. However, the second molar was tipped distally with extrusion. (I) Axies graph of model 9, the displacement of the first molar was translation and intrusion and the incisor was slightly tipped lingually. (J) Axies graph of model 10. Model 10 was similar to model 9 in that the second molar was tipped distally and extruded.
reciprocal mesial force (Kim et al., 2008). A direct anchorage method to counter such force applied a mini-implant connected with an elastic chain to a hook placed to the anterior position on the archwire (Cornelis and De Clerck, 2007). A third method placed a plate or mini-implant in the palate to make the force direction pass through the centre of resistance as closely as possible to distalize the first molars (Kook et al., 2010).

Desirable treatment outcomes vary with the presence or absence of molar inclination, rotation, and other factors. For example, distal movement of the crown portion only can effectively treat mesially tipped molars. But our study’s model was assumed to have normal alignment, so bodily movement was the primary concern for evaluation during distalization. Occlusal relations can worsen if molar extrusion during treatment causes open bite or clockwise mandibular rotation. Distal tipping of the first molar can cause premature contact, which in turn might lead to a relapse. Therefore, the clinician should ensure intrusion or maintenance of the pre-treatment molar position during distalization.

Conventional measuring points for evaluating tooth displacement have been imprecise, for example, the crown centroids or cusp tips. Treatment results will be different depending on the measuring points chosen to evaluate the amount of teeth movement. If the first molar was tipped distally, the mesial tips of the crown might show extrusive movement, while the distal tips could intrude. In our study, therefore, the functional mesio-palatal cusp tip and palatal root apex of the first molar were the measuring points for analysis of displacement (Table 2).

In modality 1, model 1, the incisor was tipped labially with distortion of 019 × 025 inch SS wire and the first molar was rotated mesial-out, extruded with uncontrolled distal tipping. We thought this result occurred because the distalization force was applied through a bracket level below the furcation area, which has been reported to be a centre of resistance (Dermant et al., 1986; Figures 4, 5, 6, and 7; Table 2).

In modality 2, models 2, 3, and 4, the displacement of the first molar was similar to model 1 but the incisor results varied according to the vertical height of the hook (Figures 4, 5, 6, and 7; Table 2). In model 2 (short hook), the incisor was slightly intruded. If the distalization force had been heavier, the incisor might have tipped lingually. However, as the hooks’ vertical height increased, there was anchorage loss resulting in labial tipping of the incisors.

In modality 3, models 5, 6, and 7, the anterior teeth were stable. This was the most favourable outcome compared with modalities 1 and 2, which applied mini-implants on the buccal side. The first molar in modality 3 had a tendency to rotate mesial-in because it was distalized on the palatal site. The displacement of the first molar changed from controlled tipping to bodily movement as the force vector was applied to lever arm indentations vertically farther from the bracket level. Therefore, model 7, showed the most desirable result of bodily movement with intrusion during distalization (Figures 4, 5, 6, and 7; Table 2).

Model 8 was assumed to include second molars. The tooth movement was similar to model 7 but the second molar was tipped distally and widened laterally without rotation (Figures 4, 5, 6, and 7; Table 2). This movement might be because the distalization force was applied through the contact point between the first and second molar by bodily movement of the first molar.

In modalities 1 and 2, the mini-implant was assumed to be placed buccally to distalize the molar. As the molar distalizing force was applied at the level of the bracket, the first molar was tipped distally. After the first molar was moved distally in modality 2, if the second premolar needed to be moved distally, the mini-implant must first be moved because of the narrow inter-radicular space.

In contrast, modality 3 used a palatal plate on the palatal side instead of a mini-implant on a buccal site, and it applied force through near the center of resistance of the first molar. The plate was placed on the non-tooth-bearing area near the midpalatal suture, avoiding the problem of narrow inter-radicular space on the buccal side for placing mini-implants (Lee et al., 2009). Also, the thick cortical bone enabled heavy force to be loaded (Lombardo et al., 2010; Moon et al., 2010).

In model 8, the second molar was seen to widen laterally and was tipped distally with extrusion. To avoid this unwanted movement, the second molar needs to be first bodily moved with a TPA before distalization of the first molar. Moreover, models 9 and 10 were simulated group distalizations. Park et al. (2005) reported a group distalization using buccal mini-implants. These skeletal anchorage devices ensure whole arch movement without distalizing molars and anterior teeth separately. This movement could improve molar occlusal relationship and correct mild protrusion cases.

Placing the mini-implants between the buccal roots limits the distal movement of the dentition (Lee et al., 2009). Also, this movement causes tipping, especially in the molars, as demonstrated in additional studies (Park et al., 2005).

Our report suggested that model 7 has the ideal vertical height of 10mm, which indicates the indentation closest to the midpalatal arch. The first molar showed distal bodily movement, but its movement on the buccal side was limited due to distal-out rotation. Also, movement of the anterior portion was not as great as was expected. Therefore, to minimize first molar distal-out rotation, we recommend reinforcement of the TPA with a heavy wire to reduce distortion, a modified lingual retractor by splinting all teeth to minimize individual tooth movement (Kim et al., 2004) or by placing a mini-implant buccally to apply additional buccal force (Oberti et al., 2009).

This study has some limitations, including only calculating initial tooth displacement with finite element
analysis. In addition, the following clinical factors such as occlusal force, differences in mechanical properties between virtual models and biological tissues, and elastic recovery force of archwires over time were not applied. However, our findings could serve as a diagnostic and treatment guide for clinicians in the application of skeletal anchorage devices for molar distalization.

Conclusions

This study used finite element analysis to evaluate teeth displacement according to three modalities of molar distalization with skeletal anchorage devices. Modalities 1 and 2 placed mini-implants in the buccal side, and modality 3 placed a plate on the palatal side. Distalization with the palatal plate showed bodily molar movement and insignificant displacement of the incisors. Placing mini-implants on the buccal side caused the first molar to be distally tipped and extruded, while the incisors were labially flared and intruded. It is recommended that our findings serve as a diagnostic and treatment guide for clinicians in the application of skeletal anchorage devices for molar distalization.

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