Analysis of a force system for upper molar distalization using a trans-palatal arch and mini-implant: a finite element analysis study

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SUMMARY The purpose of this study was to analyse distal movements of molars in a force system using a trans-palatal arch (TPA), fixed to the maxillary first molar, and mini-implants placed at the palatal midline, considering the diagnostic standard for placement site in association with variation in upper molar locations, using finite element (FE) analysis. Three-dimensional FE models, divided by the differing direction of traction force, mesiodistal locations of the left and right molars, and the lateral location of the mini-implant were constructed. (1) When a traction force was fixed from the height of alveolar crest to the mini-implant placed at the middle of palate, the molars underwent bodily movement. (2) When the location of the mini-implant was moved to the left of the midline, the amount of distal movement of the left molar increased. When the mesiodistal locations of the left and right molars differed, the amount of distal movement of the molar located mesially was larger than that of the contralateral molar, even when the mini-implant was located on the midline.

Introduction

In orthodontic treatment, headgear and inter-maxillary elastics are generally used to distalize upper molars in Angle class II malocclusion. The use of these devices, which depends on patient cooperation, is an important factor affecting successful treatment outcomes (Gray et al., 1983; Byloff et al., 2000). To avoid unreliability based on patient cooperation, new orthodontic appliances, such as the pendulum, Greenfield molar distalization, bimetric distalizing arch, and others, have been developed in recent years. However, anchorage loss accompanied by increases in overjet and clockwise rotation of the mandible caused by the elongation of molars may occur with these new devices (Chen et al., 1995; Ghosh and Nanda, 1996; Byloff and Darendileler, 1997; Byloff et al., 1997).

Some recent studies have introduced skeletal anchorage devices. Two types of skeletal anchorage devices—screw type and plate type—are used clinically as absolute anchorage devices. The plate type anchorage device acts as a fixed source when the maxillary teeth are distalized, but surgical invasion cannot be ignored. The use of the screw type mini-implant is widespread in clinical orthodontics because this device is simple and has low surgical invasion (Park et al., 2005; Motoyoshi et al., 2007).

The screw type mini-implant is generally placed into the posterior buccal alveolar bone in bicuspid extraction cases (Umal et al., 2011). To avoid bicuspid extraction and/or to distalize the entire maxillary dental arch, we often use mini-implants placed at the palatal midline and utilize traction force from the mini-implants to a TPA or lingual arch fixed to the maxillary first molars.

However, a force system for effective application of the screw-type mini-implant in cases of upper molar distalization has not been established. The purpose of this study was to establish a force system using the TPA and mini-implants, considering the diagnostic standard for placement site in association with variation in upper molar locations. The maxillary bone and the molars were reproduced using three-dimensional FE models. We simulated upper molar distalization using a traction force generated from the mini-implant, which was placed on the palatal midline, to the TPA.

Materials and methods

Preparation of FE models

FE models, including the maxillary bone (cortical and cancellous bone), maxillary first molar, periodontal membrane, TPA, and sheath of the TPA, were constructed (Figure 1) using a three-dimensional computer-aided design program (SolidWorks 2010; SolidWorks Japan K.K., Tokyo, Japan). An FE model of the maxillary bone was
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reconstructed, based on an East Indian skeletal specimen from the Department of Orthodontics at Nihon University School of Dentistry, and 1-mm computed tomographic slices were digitized. The depth of the palate was based on published data (Ash, 1984; Staley et al., 1992). The form of the maxillary first molar was constructed with reference to Ash (1984). The thickness of the periodontal membrane was fixed at 0.2 mm according to Natali et al. (2004).

We created eight types of FE models (Table 1) to evaluate the displacement of the teeth when traction force was applied from the hooks fixed to the TPA to the mini-implant. The first three types (Figure 2) were model A, in which the hook was fixed to the centre of the TPA; model B, in which the hooks were fixed at the height of the alveolar crest; and model C, in which the hooks were fixed at the height of the centre of the crown of the first molar. The next three types (Figure 3) were model I, in which the mini-implant was positioned at palatal midline; model II, in which the position was 2 mm left of the midline; and model III, in which the position was 4 mm left of the midline. The last two types of FE model were created using model B as the standard by which to evaluate displacement in cases in which the left tooth was located more mesially than the right tooth. These two types (Figure 4) were: model B’, in which the left tooth was located 2.5 mm mesially than the right tooth; and model B”, in which the left tooth was located 5 mm mesially.

Table 1 FE models constructed in this study.

<table>
<thead>
<tr>
<th>Models divided by</th>
<th>Description</th>
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<tbody>
<tr>
<td>The vertical location of the hooks on the TPA for traction</td>
<td>A Centre of the TPA</td>
</tr>
<tr>
<td></td>
<td>B Height of the alveolar crest</td>
</tr>
<tr>
<td></td>
<td>C Height of the centre of the crown of the first molar</td>
</tr>
<tr>
<td>The transverse location of the mini-implant</td>
<td>I Midline</td>
</tr>
<tr>
<td></td>
<td>II 2.0 mm left of the midline</td>
</tr>
<tr>
<td></td>
<td>III 4.0 mm left of the midline</td>
</tr>
<tr>
<td>The mesio-distal difference of the right and left molars</td>
<td>B’ Left molar located 2.5 mm more mesially than the right molar</td>
</tr>
<tr>
<td></td>
<td>B'’ Left molar located 5.0 mm more mesially than the right molar</td>
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TPA: trans-palatal arch.

Figure 1 Finite element (FE) models comprised the maxillary first molar, periodontal membrane, trans-palatal arch (TPA), sheath of the TPA, and maxillary bone elements.

Figure 2 Models A, B, and C reconstructed in this study. In model A, the hook was fixed to centre of the trans-palatal arch; in model B, the hooks were fixed at the height of the alveolar crest; and in model C, the hooks were fixed at the height of the centre of the crown of the first molar.

Figure 3 Models I, II, and III constructed in this study. In model I, the mini-implant was positioned at palatal midline; in model II, the position was 2 mm left of the midline; and in model III, the position was 4 mm left of the midline.
The bone, teeth, periodontal membrane, TPA, and sheath elements were assumed to be homogeneous, isotropic, and linearly elastic and the solution was determined with a static analysis. The material properties of the elements in all models were based on published data (Dorow et al., 2003; Dorow and Sander, 2005; Hohmann et al., 2011) (Table 2).

Each model was meshed automatically using the SolidWorks software. Each model consisted of approximately 250,000 nodes and 170,000 tetrahedral elements (Figure 1).

The first molar had to be displaced in the internal direction in the FE model when it was pulled in the internal direction. Clinically, however, the initial movement in the internal direction was considered negligible because continuous movement of the first molar resulted in the constriction of the upper arch, which is not seen during orthodontic treatment using a TPA. The TPA and sheath were then regarded as rigid materials in this study to reproduce the clinical situation (Table 2).

**Boundary conditions and solution**

Nodes at the upper surface of maxillary bone elements were restricted to three degrees (X, Y, and Z) of freedom. Traction force was attached from the hook of model A or other models (B, C, B', and B'') with model I (Figures 2 and 4), and force was applied to model II or III (Figure 3). The traction force was fixed at 2 N because the orthodontic force is usually applied at approximately 2 N clinically. Displacement for each model was calculated using a personal computer (CPU, Celeron 2.20 GHz; hard disk, 40.0 GB; RAM, 1024 MB) and an FE program (COSMOS/Works 2010). A linear structural analysis was performed to calculate the displacement of the molar.

**Results**

1. **Difference according to the height of the hook**

   To examine three-dimensional movements of the crown and root of the first molar, displacements of the mesiolingual cusp and apex of the palatal root were evaluated, respectively. Figure 5 shows the displacement of the first molar in models A–C for various heights of the hook. In model A, in which the hook was fixed to the centre of the TPA, the mesial tip of the crown moved in the mesial direction because of negative displacement of the crown. Model B, in which the hooks were fixed at the height of the alveolar crest, approached bodily movement of the tooth because the orthodontic force is usually applied at approximately 2 N clinically. Displacement

**Table 2 Material properties.**

<table>
<thead>
<tr>
<th></th>
<th>Young's modulus (MPa)</th>
<th>Poisson's ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cortical bone</td>
<td>1000</td>
<td>0.3</td>
</tr>
<tr>
<td>Cancellous bone</td>
<td>500</td>
<td>0.3</td>
</tr>
<tr>
<td>Tooth (dentin)</td>
<td>18,600</td>
<td>0.3</td>
</tr>
<tr>
<td>Periodontal ligament</td>
<td>0.15</td>
<td>0.45</td>
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</table>

**Figure 4** Models B' and B'' constructed in this study. In model B', the left tooth was located 2.5 mm more mesially than the right tooth. In model B'', the left tooth was located 5 mm more mesially.

**Figure 5** Distal and vertical displacements of the crown and root when traction force was applied from the hooks of models A, B, and C to I.
at the height of the centre of the crown, the distal and vertical displacement of the crown were much greater than in other models, but the distal displacement of the root was much smaller than in other models. This means that model C showed mainly tipping movement. Model B was used as the standard model in subsequent examinations because it showed efficient bodily movement.

2. Distal displacement according to the transverse location of the mini-implant

Figure 6 shows the distal displacement of the crown for various locations of the mini-implant in models I–III and location of the first molar in models B–B'. When the mini-implant was located at the midline, the amount of distal movement of both first molars did not differ. On the other hand, when the location of the mini-implant was shifted to the left, the distal displacement of the left crown was increased, but that of the right crown was decreased. When the left molar was located in a mesial position compared with the right first molar, the larger difference in the mesiodistal positions of both molars increased the amount of distal movement of the left first molar and decreased that of the right molar. When the left first molar was located in a mesial position compared with the right first molar and the location of the mini-implant was moved to the left, a larger amount of distal movement was observed in the left first molar.

3. Lateral displacement according to the transverse location of the mini-implant

Figure 7 shows the lateral displacement of the crown for various locations of the mini-implant and first molars. When the mini-implant was located at the midline, the movements of the left and right first molars did not differ. When the location of the mini-implant was shifted to the left, lateral displacement of both molars increased. When the left first molar was located more mesially than the right molar, even when the mini-implant was located on the midline, lateral movement of both molars was observed. However, even when the left first molar was located 5 mm mesially, the amount of lateral movement was only one-thirtieth the amount of distal movement. Even when the left first molar was located mesially, the left-shifted mini-implant increased the amount of lateral movement of the molars. When the mini-implant was fixed at 4 mm left of midline, the amount of lateral movement of the molars was approximately one-fourth of the distal movement.

4. Vertical displacement according to the transverse location of the mini-implant

Figure 8 shows the vertical displacement of the crown for various locations of the mini-implant and first molar. When the mini-implant was located on the midline, the amount of depression of the right and left first molars was equal. When the mini-implant was located away from the midline, the vertical displacement of the left first molar increased, but that of the right first molar decreased. When the left first molar was located more mesially than the right first molar, the vertical displacement of the left crown decreased, but that of the right first molar increased in models II and III.
Discussion

The accuracy of results derived from FE models relates directly to the accuracy of the models. Although errors can be suppressed by reproducing the model as accurately as possible, it is impossible to create a model identical to a living human body, including the material properties. Therefore, the authors made an effort in this study to construct the shape of the maxillary bone, cortical and cancellous bone, the first molar, and the periodontal membrane as closely as possible to those in the living body. However, the material physical properties were assumed to be linear, the results were calculated in a static analysis, and an initial movement was expressible in this study. These factors should be given thorough consideration when interpreting the results derived from the FE models in this study.

According to Tanne et al. (1987), the centre of resistance is located two-third along the apical side of the root. Considering their findings and the results of this study, the force vector in models A–I passed to the apical side, which is comparable with the centre of resistance in the tooth, and mesial inclination was observed by distal movement of the root apex. In models B–I, the force vector passed two-third of the way around the apical side of the root, which corresponds to the centre of resistance, and bodily movement in the distal and depressive directions was observed. In models C–I, the force vector passed across the cervical area of the crown side compared with the centre of resistance, and distal inclination was observed. These results suggest that traction from the hook placed at the height of the alveolar crest is effective for the correction of Angle class II malocclusion with a high mandibular plane angle.

According to Squeff et al. (2009), when the mesiodistal positions of the right and left molars differ, various asymmetric face-bows were designed to produce optimal molar movement. Yu et al. (2011) and Kook et al. (2010) analysed maxillary molar movement, when a mini-implant was applied at the middle of the palate. However, no published study has clarified the asymmetric influence of the placement site of the mini-implant. When the location of the mini-implant was moved to the left of midline, the amount of distal movement of the left molar increased. When the mesiodistal locations of the left and right molars differed, the amount of distal movement of the molar located mesially was larger than that of the contralateral molar, even when the mini-implant was located on the midline. To increase the amount of distal movement of a molar located mesially, the mini-implant should be placed near the molar.

Movements in the buccal–palatal direction are generally undesirable and very difficult to control (Wohl et al., 1998; Altug et al., 2005). According to Yoshida et al. (1998), movement in the lateral direction is directly proportional to the asymmetry in the orthodontic force. However, these studies were carried out using traditional orthodontic treatment without mini-implants. In the present study, when the left molar was located more mesially than the right molar, lateral movement of the molar can be clinically ignored if the mini-implant is located at the midline. However, when the location of the mini-implant was moved 4 mm to the left to increase the amount of distal movement of the left molar, the amount of lateral movement was one-fourth the amount of distal movement. This should not be clinically ignored. A physical phase occurring in this assumption can be explained by the diagram shown in Figure 9. When Y elements (distal direction) of the right and left molars are compared, the Y element of the left molar (Yb) is larger than the Y element of the right molar (Ya; Yb > Ya). In the X elements (lateral direction), however, the X element of the right molar (Xa) is larger than the X element of the left molar (Xb; Xa > Xb). Thus, orthodontic force in the left direction acts on the left and right molars because of rigid fixation by the TPA. This result corresponds to the result shown in Figure 7. It is useful to enlarge the orthodontic force (b) loaded to the left molar so that Xa = Xb, to counterbalance the orthodontic force to this lateral direction. To examine the degree of this enlargement of the force against the left molar to counterbalance the lateral force, FE was performed using model B”–III. A 1.4-fold enlargement was required to omit the lateral force, and approximately 3 N of orthodontic force should be applied to the left molar when 2 N of orthodontic force to the right molar and a mini-implant location 4 mm left of midline are assumed.

In clinical situations, when the lateral inclination of the occlusal plane is accompanied by vertical deformity of the maxillary dental arch, it would be useful to place the mini-implant near the molar with excessive extrusion. Considering vertical displacement using the theoretical relationship shown in Figure 9, it would be possible to eliminate the lateral force by enlargement of the orthodontic force on the extruded molar. In this case, however, it is important to consider the direction and strength of the orthodontic force in an individual because the force in the distal direction also increases.

Conclusion

1. In Angle class II malocclusion with a high mandibular plane angle, the traction force should be fixed from
the hook placed at the height of the alveolar crest to the mini-implant located in the median palatal suture to create bodily movement in the distal and depressive directions.

2. When the mesiodistal positions of the right and the left molars differ, it is useful to place the mini-implant near the mesial molar to increase the amount of distal movement of this molar.

The optimal orthodontic force and placement site of the mini-implant should be considered in an individual because various palate depths and vertical and horizontal asymmetry of molar positions are usually present clinically.

Funding


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