Patterns of initial tooth displacements associated with various root lengths and alveolar bone heights

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The present study was designed to investigate the nature of initial tooth displacements associated with varying root lengths and alveolar bone heights. A three-dimensional model of the upper central incisor was developed for the finite element analysis. Tooth displacements were determined at various levels of the tooth and the apicogingival levels of the center of resistance and centers of rotation were calculated. The results showed that moment-to-force values at the bracket level for translation of a tooth decreased with shorter root length and increased with lower alveolar bone height. In addition, apicogingival levels of the center of resistance shifted more gingivally to the cervix, or the alveolar crest with a shorter root. Alveolar bone loss also shifted the center of resistance toward the alveolar crest, whereas its position was more apical relative to the cervix. Ratios of the center of resistance distances measured from the alveolar crest relative to the alveolar bone heights exhibited very slight changes in both cases. The centers of rotation from a single force varied substantially with a short root and alveolar bone loss. However, the relative distances of the centers of rotation from the alveolar crest in comparison with the alveolar bone heights were constant at 0.4 mm, with variations in the root length and alveolar bone height. Because this study showed that root length and alveolar bone height affect the patterns of initial tooth displacements both in the center of resistance and the centers of rotation and also in the amount of displacement, forces applied during orthodontic treatment should take into consideration the anatomic variations in the root length and alveolar bone height so as to produce optimal and desired tooth movement. (AM J ORTHOD DENTOFAC ORTHOP 1991;100:66-71.)

Initial tooth displacement, or mobility of a tooth, has been used for evaluating biophysical properties of the periodontium as a diagnostic aid to periodontal problems. In orthodontics the nature of tooth displacement is also of great interest in terms of an optimal force application and subsequent tooth movement.

Patterns of initial displacement of a tooth may be influenced by such anatomic variables as dimensions of the tooth and alveolar bone, widths of periodontal ligament (PDL) space, and mechanical properties of the periodontium. Since many adult orthodontic patients have altered crown-to-root ratios from alveolar bone loss induced by periodontal disease, the influence of these variables on the biomechanical behavior of a tooth may be more important in adults than in adolescents. In addition, variations in root length also modify the biomechanical behavior of the tooth when subjected to orthodontic forces. Thus it is of clinical significance to understand optimal force considerations for patients with altered crown-to-root ratios.

Although various studies have investigated these questions, the degree to which the biomechanical responses of the tooth are affected by tooth and bone geometry is not clear. Previous clinical studies have not fully described these variables with tooth displacements because of difficulties in quantifying precisely the variations in root length and alveolar bone height for patients or subjects.

The purpose of this study was to investigate the effects of root length and alveolar bone height on initial tooth displacements by means of a three-dimensional finite element analysis.

METHODS

A three-dimensional finite element method was applied using an analytic model of the upper central incisor. The model comprises the tooth, PDL, and alveolar bone, and consists of 1205 nodes and 920 solid elements (Fig. 1). Details of the modeling procedure are described in a previous publication. Root length of the model was changed in increments of...
Effects of varying root lengths and alveolar bone heights

Fig. 1. A three-dimensional finite element model of the upper central incisor. The model is restrained at the maxillary basal bone area as indicated by solid triangles.

0.5 mm from 10.0 to 15.0 mm on the basis of an average root length of 13.0 mm. The original model also was varied to produce different alveolar bone heights, maintaining the anatomic size and shape of the tooth. Apicogingival level of the alveolar crest (L) was originally the same as that of the cervix, or 13.0 mm high from the apex. In this analysis its height (L') was reduced to 10.5, 8.0, and 6.5 mm along the long axis of the root, simulating clinical alveolar bone loss (Fig. 2).

Mechanical properties of the three components of the model are defined in Table I and were based on previous studies. The model was restrained at the maxillary basal bone area to avoid rigid body motion (Fig. 1). A lingually directed 100 gm force was applied at a point on the labial surface of the crown (bracket position) 4 mm gingival to the incisal edge. Various labial crown couples were loaded with a constant 100 gm lingual force to determine the moment-to-force (M/F) value at the bracket for translation of a tooth in the lingual direction.

The analysis program used in this study was “ISAP,” provided by Nippon Electronic Company (Tokyo, Japan). The amount of tooth displacement was analyzed at various levels along the tooth. On the basis of tooth displacements, the apicogingival levels of the center of resistance (CRe) and the centers of rotation (CRo) from a single force were calculated to evaluate the nature of instantaneous tooth displacements. Further, apicogingival levels of the CRe and CRo were evaluated relative to varying root lengths and alveolar bone heights (Fig. 3).

RESULTS

Changes of tooth displacements at the incisal edge, cervix, and apex with various root lengths are shown in Table II, using relative displacements to those with a root length of 13.0 mm. Tooth displacements from a 100 gm lingual force increased gradually with a shorter root. Tooth displacement measured at the incisal edge was approximately 1.7 times (for a 10.0 mm root length) and 0.8 times (for a 15.0 mm root length) that of a tooth with an average root length. Changes of tooth displacements at the apex were similar to those at the incisal edge, whereas displacements at the cervix did not vary substantially.

Fig. 4 shows changes of M/F values at the bracket position for translation of the tooth and apicogingival levels of the CRe. The M/F value at the bracket and the distance (X) of the CRe to the cervix (or the alveolar crest) were 9.9 and 3.4 mm, with a root length of 10.0 mm, and 11.2 and 4.7 mm in the case of the root length of 15.0 mm. Ratios of the CRe distances to the various root lengths (X/L) increased slightly with a shorter root—i.e., 0.31 mm for a 15.0 mm root length, 0.33 mm for a 13.0 mm root length, and 0.34 mm for a 10.0 mm root length.
mm root length. However, these changes were minimal (Fig. 4).

Table III shows the position of the CRo produced by a single force on the crown. The position of the CRo became more gingival with a short root, whereas its ratios to the varying root lengths \( a/L \) were constant.

The pattern of tooth displacement was changed by different alveolar bone heights. The amount of tooth displacements from a lingually direct 100 gm force increased substantially with alveolar bone loss (Table IV). In particular, an increase of tooth displacements was pronounced at the cervix. An interesting finding was that changes of displacements at the apex were less than those at the incisal edge associated with alveolar bone loss.

The \( M/F \) value at the bracket for translation of a tooth with a 13.0 mm root length was 10.7 mm and increased to 12.3, 13.9, and 15.0 mm with 2.5, 5.0, and 6.5 mm alveolar bone loss, respectively (Fig. 5). Apicocingival levels of the CRe from a single force are evaluated in relation to the cervix and to the reduced alveolar bone heights (Fig. 3, B). Apicocingival levels of the CRe exhibited a shift to the apex with alveolar bone loss as noted by changes of \( X \) and \( X/L \) in Fig. 5. On the other hand, the distance \( (X') \) of the CRe to the alveolar crest decreased significantly with alveolar crest reduction, and ratios of the CRe distances to the varying alveolar bone heights \( (X'/L') \) decreased slightly—i.e., 0.32 mm (for a 13.0 mm alveolar bone height), 0.31 mm (for a 10.5 mm alveolar bone height), and 0.30 mm (for both 8.0 and 6.5 mm alveolar bone heights). However, these changes were negligible for clinical application (Fig. 5).

Apicocingival levels of the CRo from a single force ranged from 5.4 to 8.8 mm apical to the cervix and from 5.4 to 2.3 mm apical to the alveolar crest, in the cases of the alveolar bone height being varied from 13.0 to 6.5 mm, respectively (Table V). Although alveolar bone loss produced an apical shift of the CRo from a single force, as indicated by the changes of distance \( a \) and \( a/L \), apicocingival levels of the CRo relative to the varying alveolar bone heights \( (a'/L') \) were invariable as indicated in Table V.

DISCUSSION

The present study quantifies the effects of root length and alveolar bone loss on patterns of initial tooth displacement. Different patterns of tooth displace-
Table II. Changes in initial tooth displacements associated with various root lengths (Comparative displacements to those with an average root length shown)

<table>
<thead>
<tr>
<th>Root length (mm)</th>
<th>10.0</th>
<th>10.5</th>
<th>11.0</th>
<th>11.5</th>
<th>12.0</th>
<th>12.5</th>
<th>13.0*</th>
<th>13.5</th>
<th>14.0</th>
<th>14.5</th>
<th>15.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apex</td>
<td>1.74</td>
<td>1.57</td>
<td>1.42</td>
<td>1.30</td>
<td>1.19</td>
<td>1.09</td>
<td>1.00</td>
<td>0.92</td>
<td>0.85</td>
<td>0.79</td>
<td>0.73</td>
</tr>
<tr>
<td>Cervix</td>
<td>1.46</td>
<td>1.36</td>
<td>1.27</td>
<td>1.19</td>
<td>1.12</td>
<td>1.06</td>
<td>1.00</td>
<td>0.95</td>
<td>0.90</td>
<td>0.86</td>
<td>0.83</td>
</tr>
<tr>
<td>Incisal edge</td>
<td>1.74</td>
<td>1.56</td>
<td>1.41</td>
<td>1.28</td>
<td>1.17</td>
<td>1.08</td>
<td>1.00</td>
<td>0.93</td>
<td>0.87</td>
<td>0.82</td>
<td>0.78</td>
</tr>
</tbody>
</table>

*An average root length derived from Wheeler.17

Table III. Distances from the center of rotation, produced by a single force at the bracket, to the alveolar crest (a) and its ratio to the varying root lengths (a/L)*

<table>
<thead>
<tr>
<th>Root length (mm)</th>
<th>10.0</th>
<th>10.5</th>
<th>11.0</th>
<th>11.5</th>
<th>12.0</th>
<th>12.5</th>
<th>13.0*</th>
<th>13.5</th>
<th>14.0</th>
<th>14.5</th>
<th>15.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance a (mm)</td>
<td>4.0</td>
<td>4.3</td>
<td>4.6</td>
<td>4.8</td>
<td>5.0</td>
<td>5.3</td>
<td>5.5</td>
<td>5.8</td>
<td>6.0</td>
<td>6.2</td>
<td>6.4</td>
</tr>
<tr>
<td>Ratio a/L</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
</tr>
</tbody>
</table>

*a and L are indicated in Fig. 3, A.

In this study initial tooth displacements increased in response to the reduced root lengths and alveolar bone heights, with the change being more pronounced with alveolar bone loss. In orthodontic treatment force control is the most important factor to achieve an optimal tooth movement.6,8,22 This consideration may be even more critical for some patients because several clinical studies have reported slight loss of periodontal attachment in adults or adolescents during treatment with fixed orthodontic appliances.15,14,23,24 However, in...
these studies the applied forces may have been greater than optimal for altered periodontal tissues. For example, if the root length was reduced to 10.0 mm, an amount of tooth displacement at the incisal edge became 1.7 times greater than that with a 13.0 mm root length. The displacement of the tooth at the incisal edge increased from 2.3 to 6.9 and then to 16.5 times with approximately 19%, 38%, and 50% alveolar bone loss when compared with a tooth with no alveolar bone loss. Since an increase of tooth displacement generally leads to an increase in tooth mobility,13,18,19 force levels should be lowered in patients with short roots and/or substantial alveolar bone loss because mobility may become severe.

The present study also showed that various patterns of tooth displacements were induced by different root lengths and alveolar bone heights, producing variations in the CRe and CRo under the same force condition. It is very interesting that relative levels of the CRo to the alveolar crest heights were invariable, although varying root lengths and alveolar bone heights produced various levels of the CRo between the alveolar crest and apex. This finding indicates an important role of the alveolar crest in determining relative CRo position or patterns of subsequent tooth movements. From the results on the M/F value and the CRe, it was shown that a precise control6,8,16,21 of couples with a constant force is more important for adult patients with reduced periodontal support than those with normal periodontal conditions. For example, if the root lengths are 13, 10, and 15 mm, then 1070, 980, and 1120 gm-mm labial crown couples are needed with a constant 100 gm lingual force for translation of the teeth with three different root lengths. If the alveolar bone height ranges from 13.0 to 6.5 mm, then 1070 and 1500 gm-mm couples are required to produce translation of the tooth. Orthodontic treatment occasionally induces an injury of the periodontium that is clinically observed as root resorption and/or alveolar bone loss.20,24 Therefore orthodontists must take steps to alter the force system precisely if root resorption and/or alveolar bone loss is recognized before or during active treatment.

The present study is based on a numerical finite element analysis that had been used previously for biomechanical investigations in dentistry and/or orthodontics.16,18,20,25-29 Since the analyzed results are dependent on the model used,15,28 the model was examined repeatedly for geometric and mechanical equivalences.16 As is usually the case with finite element analyses, boundary conditions of the model were established at the peripheral region of the bone to eliminate unreasonable motion of the whole model. At the root-PDL and PDL-alveolar bone interfaces, a node was located on the apexes of two adjacent elements facing these interfaces to allow the PDL to deform coordinately with tooth and bone displacements. This may have generated the mechanical behavior of the tooth in such a way that it was almost equivalent to an actual tooth displacement described below. However, a refinement of the interfaces in the model may be needed for a more natural tooth displacement as reported in a previous study.29

With respect to the mechanical behavior of the model, patterns of initial tooth displacements expressed by the CRo from a single force and the CRe were almost coincident with a previous study,21 indicating a validity of the model in terms of biomechanical behavior. Furthermore, analyzed findings should be verified by suitable clinical experiments. As indicated previously, it is difficult to make clinical experimental models that account for the effect of only one variable to the exclusion of other variables because many variables interact to produce various biomechanical behaviors of a tooth. Until that time, present results will serve as one criterion for varying both force magnitude and M/F value on the crown when different anatomic structures of root and alveolar bone are observed.

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### Table IV. Changes in initial tooth displacements with varying alveolar bone heights
(Comparative displacements to those with no alveolar bone loss shown)

<table>
<thead>
<tr>
<th>Alveolar bone height (mm)</th>
<th>6.5</th>
<th>8.0</th>
<th>10.5</th>
<th>13.0*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apex</td>
<td>9.09</td>
<td>4.69</td>
<td>2.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Cervix</td>
<td>21.00</td>
<td>9.01</td>
<td>2.66</td>
<td>1.00</td>
</tr>
<tr>
<td>Incisal edge</td>
<td>16.48</td>
<td>6.93</td>
<td>2.32</td>
<td>1.00</td>
</tr>
</tbody>
</table>

*No alveolar bone loss.

### Table V. Apicogingival levels of the center of rotation by a single force at the bracket associated with varying alveolar bone heights

<table>
<thead>
<tr>
<th>Alveolar bone height (mm)</th>
<th>6.5</th>
<th>8.0</th>
<th>10.5</th>
<th>13.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>a (mm)</td>
<td>8.8</td>
<td>7.9</td>
<td>6.5</td>
<td>5.4</td>
</tr>
<tr>
<td>a/L</td>
<td>0.7</td>
<td>0.6</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>a' (mm)</td>
<td>2.3</td>
<td>2.9</td>
<td>4.0</td>
<td>5.4</td>
</tr>
<tr>
<td>a'/L'</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
</tr>
</tbody>
</table>

a, Distance of center of rotation to the cervix; L, average root length of 13.0 mm; a', distance of center of rotation to the alveolar crest; L', varying alveolar crest heights.

NOTE: a, a', L, and L' are indicated in Fig. 3, B.
REFERENCES


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