Use of 3D finite element models to analyze the influence of alveolar bone height on tooth mobility and stress distribution

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Abstract Background/purpose: In this study, we investigated the von Mises stress distribution on three types of teeth with different peripheral alveolar bone heights and displacements in the vertical and lateral directions of the teeth when forces were applied to it. When a tooth was bearing an occlusal force, the alveolar bone height affected tooth movement, but previous research seldom analyzed the relationship of alveolar bone height and tooth mobility with a three-dimensional finite element method. Material and methods: We chose a mandibular molar (Type A), canine (Type B), and premolar with two roots (Type C) for our samples. A force of 10 N to simulate a biting force was applied to these teeth with different alveolar bone heights, and a three-dimensional finite element model was used to record the degree of tooth mobility and stress distributions on the various tooth-root types. The corresponding numbers of nodes used were 9161, 9261, and 5841, respectively. The tooth material was assumed to be enamel with a Young’s modulus of $E = 84,100$ MPa and Poisson ratio of $\nu = 0.2$. Various alveolar bone heights were considered to explore the effects of alveolar bone height on the contact displacement and von Mises stress distribution. Results: Results showed that a tooth with a higher alveolar bone height had less lateral and vertical displacements. They also revealed that with a lower alveolar bone height, an increase in the von Mises stress produced maximum shear stresses at the root apex for the molar, canine, and premolar. Conclusions: Tooth mobility and stress distributions are highly correlated to the alveolar bone height, and there is a greater chance of injury with alveolar bone loss.

KEYWORDS
alveolar bone height; finite element model; tooth mobility; von Mises stress
Introduction

Occlusal trauma is considered one of the important etiologic factors in clinical attachment apparatus loss. Several studies indicated that alveolar bone suffers from pathological microbial destruction, gradually resulting in tooth mobility. Then progressive tooth mobility combined with active occlusal forces accelerates loosening of the teeth, ultimately leading to tooth loss.1-6 These co-destructive factors not only frequently enhance the rate of periodontal apparatus destruction, but also result in hypermobility of the teeth.3,5,7 The majority of previous studies documented a positive relationship between secondary progressive occlusal trauma and active advanced periodontitis in human and animal models.3,5,7 Other researchers also stated that remarkable increases in tooth mobility exhibited progressive loss of periodontal support.10,11 However, there are controversies over the role of occlusal trauma in the etiology of early, moderate, and severe periodontitis and its therapy. The majority of investigators stated that abnormal occlusal forces causing tooth mobility require further studies.12-14 There is little research regarding the relationship among the alveolar bone height, root shape, and vertical and lateral displacements of the teeth. We used a three-dimensional (3D) finite element analysis to investigate the influence of alveolar bone height upon tooth mobility and von Mises stress distributions.

Materials and methods

Root types

In this study, a 3D finite element model (FEM) was used to simulate the behavior of tooth movement with application of an occlusal force. Three different root types were investigated to explore the effects of the stress distribution on the teeth. The samples were divided into three groups: a mandibular molar (Type A), a premolar with two roots (Type B), and a canine (Type C). The dimensions and geometrical configurations of the teeth used in this study are shown in Fig. 1. Tooth lengths of Types A, B, and C were 19.96, 21.13, and 25.18 mm, respectively.

Variations in alveolar bone height

Various alveolar bone heights were designed to explore the effects of alveolar bone height on the displacement and von Mises stress distribution. The height of the alveolar bone, h, as shown in Fig. 1, was defined from the cementoenamel junction to the apex and gradually reduced. Heights which are discussed in this study are listed in Table 1. A vertical load of 10 N was applied at the occlusal surface in the Y direction, and a lateral load of 10 N in the X direction was applied at the assumed highest contour, h = 17 (Type A), 16.2 (Type B), and 19.5 mm (Type C).

3D FEM

The FEM is shown in Fig. 2. The contact behavior between the teeth was modeled using contact elements. A mesh was constructed using eight-node 3D brick elements. The numbers of elements used in the simulations were 8000, 8000, and 5060 for Types A, B, and C, respectively. The corresponding numbers of nodes used were 9161, 9261, and 5841, respectively. The tooth was assumed to be made of enamel and to have a Young’s modulus of $E = 84,100$ MPa ($1\text{MPa} = 10^6 \text{N/m}^2 = 1 \text{N/mm}^2$) and a Poisson ratio of $\nu = 0.2$.12 Various finite-element mesh sizes were used for the convergence test of von Mises stresses at the portion of the root that was assumed to be embedded in the alveolar bone. After completing the convergence test, the mechanical analysis was begun. The analyses were performed on a personal computer, using ABAQUS software (vers. 6.9, Dassault Systems, Lowell, MA, USA).

![Figure 1](image-url) Geometrical configuration of three different tooth types; Type A (mandibular molar), Type B (canine), and Type C (premolar with two roots).
Data collection and analysis

Fig. 2 shows the 3D FEM of the mandibular molar as an example. It was used to determine how a decrease in the alveolar bone heights would affect lateral and vertical displacements of the three different tooth types. The behavior of the teeth was modeled using contact elements. A mesh was constructed using eight-node 3D brick elements. The value of the X-direction displacement was estimated at the assumed highest contour of the tooth, and the Y-direction displacement was measured at the root apex. Then the relationship of alveolar bone height to the von Mises stress distribution was calculated and analyzed with the FEM.

Results

Effect of alveolar bone height on contact displacement

Fig. 3 shows the effects of various alveolar bone heights on the tooth lateral displacement at the highest contour for the three different root types. In this figure, only the lateral force (in the X-direction) was applied. Results showed that the lateral displacement was decreased with an increasing alveolar bone height, \( h \), and Type A exhibited a smaller displacement compared to the other two groups. Fig. 4 shows variations in tooth vertical displacements in the Y-direction at the apex for different alveolar bone heights. Results revealed that a larger alveolar bone height resulted in a smaller apical vertical displacement. The results also showed that compared to the vertical displacement calculated for Types B and C, a smaller displacement was obtained for Type A with the same alveolar bone height.

Effects of alveolar bone height on the von Mises stress distribution

Effects of alveolar bone height on the von Mises stress at a point with equal height to the apex of the alveolar bone are shown in Fig. 5. Only a lateral force was applied for this condition. The von Mises stress, \( \sigma_{\text{Mises}} \), is an effective stress and can be expressed as:

\[
\sigma_{\text{Mises}} = \sqrt{\frac{1}{2} \left( (\sigma_{xx} - \sigma_{yy})^2 + (\sigma_{yy} - \sigma_{zz})^2 + (\sigma_{zz} - \sigma_{xx})^2 + 6(\tau_{xy}^2 + \tau_{yx}^2 + \tau_{yz}^2 + \tau_{zy}^2 + \tau_{zx}^2 + \tau_{xz}^2) \right)}
\]

Table 1  The assumed alveolar bone heights for the three type of teeth.

<table>
<thead>
<tr>
<th>Alveolar bone height (h)/mm</th>
<th>Type A</th>
<th>Type B</th>
<th>Type C</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.50</td>
<td>9.18</td>
<td>7.81</td>
<td></td>
</tr>
<tr>
<td>5.25</td>
<td>10.10</td>
<td>8.59</td>
<td></td>
</tr>
<tr>
<td>6.00</td>
<td>11.01</td>
<td>9.38</td>
<td></td>
</tr>
<tr>
<td>7.50</td>
<td>11.93</td>
<td>10.16</td>
<td></td>
</tr>
<tr>
<td>8.25</td>
<td>12.85</td>
<td>10.94</td>
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<td>9.75</td>
<td>13.77</td>
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<td>14.69</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.00</td>
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</tr>
</tbody>
</table>

Figure 2  Finite element model of mandibular molar.

Figure 3  Effect of alveolar bone height on the von-Mises stress at contact point (lateral force applied only).

Figure 4  Effect of alveolar bone height on the tip normal displacement at contact point (vertical force applied only).
Finite element models analyse alveolar bone height

Discussion

We attempted to determine more-reliable relationships among the bone height, different root shapes, and stress distribution. That is, at any point within the body there are stresses acting in different directions, and the direction and magnitude of the stresses change from point to point. The von Mises criteria are a formula for combining these three stresses into an equivalent stress at a given point. This is why we selected von Mises stress distributions in the model instead of only principle stresses.

The above results revealed that the molar exhibited less displacement than the canine and premolar in both the X- and Y-directions. This can be attributed to the tooth lengths of the molar (19.96 mm) being shorter than those of the premolar (21.13 mm) and canine (25.18 mm). Under the condition of a constant alveolar bone height, the molar tooth had a shorter free portion above the climax of the alveolar bone, and this perhaps resulted in smaller apical and lateral displacements.

Although this 3D finite analysis model did not consider periodontal ligament effects and was not perfect, it still provides the following direction to ponder. According to the above results of von Mises stress distributions, the mandibular molar showed less stress in the lateral direction compared to the canine and premolar. This led to a smaller bending moment created at the force contact point and resulted in a smaller von Mises stress distribution when only a lateral force was applied to the teeth. This hypothesis needs more data to be confirmed in the future.

Although Fig. 6 shows that the molar had the greatest von Mises stress distribution in the vertical direction compared to the other two tooth types, the factors of a stronger root type, crown-root ratio, and trunk shape might have caused the molar to exhibit less displacement in the vertical direction. We still need more evidence to confirm that.

Persson and Svensson15 used force sensors to examine differences in tooth mobility between patients with and without periodontal disease, and concluded that tooth mobility might not only result from loss of alveolar bone, but also from changes in the periodontal apparatus. Ericsson and Lindhe16 found the simultaneous clinical phenomenon of periodontal connective tissue, alveolar bone loss, and tooth mobility increasing in animals predisposed to periodontal damage. More-recent research in humans and animals documented the apparent relationship between tooth mobility and periodontitis with a lower alveolar bone height.17–23

Wang et al. concluded that a strong relationship exists between the amount of alveolar bone and tooth stability.24 There is limited information available about the relationship between tooth mobility and variations in the alveolar bone height for different tooth types with a 3D FEM analysis. The present study is the first to use a 3D FEM to examine the influence of lateral and vertical forces on the simulated reaction phenomena of tooth mobility, stress distribution, and different alveolar bone heights for different tooth types. Our results indicated that tooth mobility is highly correlated to the alveolar bone height, regardless of the tooth type. Even though another model

\[
\sigma_{\text{Mises}} = \sqrt{\frac{(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2}{2}},
\]

where \(\sigma_x\), \(\sigma_y\), and \(\sigma_z\) are principal stresses. According to the von Mises criterion, yielding initiates when the von Mises stress reaches the yield stress.

Fig. 5 indicates that the von Mises stress decreased as the alveolar bone height (h) increased. It was also observed that for a constant alveolar bone height, the von Mises stress obtained from the molar (Type A) was less than those obtained from the premolar (Type B) and canine (Type C).

In Fig. 6, variations in the von Mises stress distributions with different alveolar bone heights of the three different groups are plotted when only a vertical force was applied. The simulation indicated that von Mises stresses decreased with an increasing alveolar bone height. However, the results also showed that the von Mises stress observed for the canine was less than those observed for the molar and premolar at the same bone height.

Figure 5  Effect of alveolar bone height on the von-Mises stress at tooth fixed end for three different tooth types (lateral force applied).

Figure 6  Effect of alveolar bone height on the von-Mises stress at tooth fixed end for three different tooth types (vertical force applied only).
including the periodontal ligament effect should be established in the future to further clarify this issue, our results led us to believe that the increasing stress is related to a reduction in the alveolar bone height. It was very possible that greater stresses result in increased tooth mobility and loss of alveolar bone, inducing progression of periodontal disease. Moreover, these stresses also lead to a vicious cycle of destruction of the periodontal apparatus. Therefore, our results support earlier conclusions that the close relationship between alveolar bone height and stress is an important etiologic factors in the development of secondary occlusal trauma.2,12,15,25,26

Although it is known that the 3D FEM cannot provide practical predictions of the effects of external forces on the alveolar bone height and stress distribution, it may be reasonable to apply external forces to alveolar bone of different heights and evaluate the stress distribution. Causative relationships between occlusal force patterns and their influence on the periodontium remain poorly defined because of several contradictory reports. Therefore, the most effective manner to reduce stress is to increase the cross section of the tooth crown and root, and add alveolar bone height and levering force. However, there are other teeth in the mouth, not merely a single tooth. Occlusal discrepancies can lead to individual teeth being loaded with greater stresses, possibly resulting in the progression of periodontal disease.24,27 We suggest that proper occlusal treatment to reduce occlusal discrepancies appears to be a favorable way to resolve the problem regarding individuals with advanced periodontal disease and occlusal trauma.

Conclusions
The present study, using a 3D FEM of different tooth types, investigated the influence of various alveolar bone heights on a numerical simulation of tooth mobility and von Mises stresses with periodontitis. The 3D FEM analysis of tooth geometry characteristics and stress relationship under different alveolar bone heights suggested that von Mises stresses might increase with less periodontal support. This means that teeth could possibly sustain more stress corresponding to a lower alveolar bone height, and that is why teeth are more predisposed to occlusal trauma.

References