Three-dimensional finite element analysis of the stability of mini-implants close to the roots of adjacent teeth upon application of bite force

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To investigate the cause of mandibular implant loss, we evaluated the stress distribution in the bone under bite force when the mini-implant was near the root using three-dimensional finite element analysis. Our analysis involved four finite element models with different distances between the implant and adjacent tooth root and three loading conditions. With loading of the tooth only or both the tooth and implant, the peak stress within the bone around the implant neck, displacement, and stress surrounding the bone near the root increased as the distance between the implant and root decreased. However, with separate loading of the implant, the stress did not correlate with the distance between the implant and root. Application of bite force increases stress within bones surrounding mini-implants near the roots of adjacent teeth and may threaten implant stability, but simple orthodontic loading has little effect on the stress distribution at the mini-implant–bone interface.

Keywords: Anchorage, Finite element analysis, Mini-implant, Implant stability

INTRODUCTION

Anchorage is critical for the success of orthodontic treatments, and implants can provide stable and effective anchorage. In particular, the mini-implant offers multiple advantages, including its small size and convenience, and greatly expands the scope of orthodontic treatments. Therefore, it is often preferred by orthodontists and patients and has been widely used over the past decade. However, the mini-implant cannot always offer sufficient stability, and the clinical success rate for use of mini-implants has been reported to be approximately 80%¹², with most cases of failure occurring in the posterior region of the mandible¹³⁴. Studies also have shown that implant loss occurs most often within 1–2 months after implantation⁵⁶, and Moon et al.⁷ observed that the probability of the mini-implant touching the tooth root is 20% during implantation because space is limited⁷. Even when implantation is performed by skilled oral surgeons, this probability of contact between the mini-implant and root remains 13.5%⁸. Multiple studies have demonstrated that placement of the mini-implant in contact with the tooth root significantly affects the stability of the implant⁹¹⁰. Motoyoshi et al. noted that a mandible with 2 mm of cortical bone thickness may pose a higher risk for loss of mini-implants close to the roots of adjacent teeth¹¹. The implant surface treatment technology can increase the total surface area of the implant and enhance bone formation around the implant¹²¹⁴. In recent years, surface modification techniques have been applied to the mini-implants to improve the initial stability¹⁰. Kim et al.¹⁶ observed the stability of a surface modified implant (1.8 mm in diameter) that was closer to the root and considered that the proximity of the implant to the tooth root only does not necessarily lead to mini-implant loss, and the underlying cause for implant loosening when close to the root remains unclear. Mini-implants may not remain in the same position under orthodontic force. The biomechanical principles of mini-implants close to the roots of adjacent teeth are still unknown. The implant tail can move in the direction of load force⁶. Therefore, near-root implants possibly could be removed from the adjacent root by the load force.

The main cause of implant loss is a stress concentration at the bone–implant interface that exceeds the tolerance of the bone. The loading scheme applied to a mini-implant will be determined by the goal of the orthodontic treatment and may be single loading or combined loading, with a variable loading direction¹⁷. The peak values of stress and displacement within the bone around the implant neck and the surrounding bone close to the tooth root increase significantly as the distance between the implant and the root decreases. However, when a load is applied to the implant separately, the relationship between implant stability with the proximity of the mini-implant to the adjacent root is unclear¹⁸. To date, no studies have evaluated the effects of different loading conditions on the clinical stability of mini-implants close to tooth root.

Finite element analysis has been used in the study of biomechanical property of orthodontic mini-implant and stress distribution of surrounding bone in recent years. With the development of three-dimensional finite
element method, it has become a way to simulate various clinical problems. In this study, finite element analysis was used to simulate different conditions according to the location of the mini-implant relative to the tooth root and analyze the effects of bite force and different loading situations on the stress distribution at the implant–bone interface in order to identify causes for the high failure rate of mini-implants close to the root and provide a theoretical basis for improved clinical application of mini-implants.

MATERIALS AND METHODS

Sixteen-slice helical computed tomography (Light Speed, GE Healthcare, Cleveland, OH, USA) scanning was performed on the jawbone of a healthy young volunteer (male, 20 years old). Referring to the Frankfort horizontal plane and parallel to the occlusal plane, cross-sectional scanning was carried out with 0.5-mm layer thickness in the implant area and 1-mm layer thickness in other areas and 0.875-mm screw pitch. Then the mandible was reconstructed three-dimensionally, and the CT images were stored in DICOM format. Mimics software (10.1, Materialise Company, Leuven, Belgium) and Catia Software (V5, BM, Kingstone, NY, USA) were used to establish the mandible model, in which the first molar existed in isolation on the right side of mandible and the periodontal ligament thickness was set as 0.25 mm.

Four models were established according to the distance between the implant and the adjacent tooth root: Model 1, the mini-implant touched the root surface after implantation; Model 2, part of the screw thread of the implant was embedded in the periodontal ligament after implantation; Model 3, the mini-implant touched the surface of periodontal ligament after implantation; and Model 4, the mini-implant was located 1.0 mm away from the surface of the periodontal ligament (Fig. 1).

Referring to the geometrical morphology of a commercial cylindrical, threaded mini-implant, the segment within the bone was 8 mm in length and 1.6 mm in diameter, the thread height was 0.3 mm, the apex angle of the blade thread was 60°, and the thread pitch was 0.6 mm. The mini-implant was implanted in the buccal alveolar bone between the second premolar and first molar of the mandible at a distance of 5 mm from the alveolar crest and at an angle of 45° from the plane of the mandible, wherein the thickness of the cortical bone was 1.62 mm (Fig. 2).

The elastic modulus and Poisson’s ratio of each material present in the modeled system are listed in Table 1. The mechanical parameters of materials come from

Fig. 1 Different models for evaluating stress distribution at implant–bone interface with the mini-implant: Model 1, touching the root; Model 2, partially embedded in the periodontal membrane; Model 3, touching the periodontal membrane; and Model 4, located 1.0 mm away from periodontal membrane surface.

Mini-implant (medium blue), periodontal membrane (lavender), tooth root (turquoise), cortical bone (brown), cancellous bone (orange).

Table 1 Mechanical properties of constituent materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s modulus (MPa)</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Titanium</td>
<td>110,000</td>
<td>0.35</td>
</tr>
<tr>
<td>Cortical bone</td>
<td>13,700</td>
<td>0.30</td>
</tr>
<tr>
<td>Cancellous bone</td>
<td>1,370</td>
<td>0.30</td>
</tr>
<tr>
<td>Tooth (dentin)</td>
<td>18,600</td>
<td>0.30</td>
</tr>
<tr>
<td>Periodontal membrane</td>
<td>68.9</td>
<td>0.45</td>
</tr>
</tbody>
</table>

Fig. 2 The finite mesh model of the jaw. (a) Mini-implant, (b) periodontal membrane, (c) tooth, and (d) assembled structures with loading directions illustrated.
the reported literature\textsuperscript{20-22}. Pure titanium was selected as the implant material. The deformation patterns of the mandible with isotropic material property appeared to be very similar to those with orthotropic material properties\textsuperscript{23}. Therefore, the model assumed that the materials were homogeneous and isotropic linear elastic materials and that material deformation was small. The models were meshed and divided in Hyperworks (12.0, Altair Engineering, Troy, MI, USA), with an average mesh size of 0.01 mm in the area surrounding the screw surface and an average mesh size of 0.3 mm in other parts of the mandible. The total number of meshes was 208,049, and the total number of pitch points was 56,081. In Abaqus-software (version 6.13, Dassault Systems, Providence, RI, USA), the frictional contact connection was made on the contact surface between the mini-implant and mandible, and the friction coefficient was set as 0.3\textsuperscript{24}, with relative sliding allowed. All degrees of freedom were constrained at the nodes at the bottom of the cortical bone elements.

Three loading situations were modeled: Load A, the tooth was loaded separately; Load B, the mini-implant was loaded separately; and Load C, the tooth and mini-implant were loaded simultaneously. The teeth were loaded with a simulated bite force. The occlusal surface of the tooth was loaded with 300 N parallel to the long axis of the teeth, which was referred to the study on the function and bite force of the mandibular first molar\textsuperscript{25}. The mini-implant was loaded with 2 N Load-a, Load-b, or Load-c individually or in combination to simulate the clinical situations for anterior tooth retraction, a molar moving mesially, and intrusion of a molar intrusion with mini-implant, respectively. For example, Load-B-ab was loaded with Load-B-a and Load-B-b simultaneously, Load-C-abc was loaded with Load-B-a, Load-B-b and Load-B-c simultaneously (Fig. 2). As a result, each model included a total of 15 simulated conditions designated: Load-A; Load-B-a, Load-B-b, Load-B-c, Load-B-ab, Load-B-ac, Load-B-bc, and Load-B-abc; Load-C-a, Load-C-b, Load-C-c, Load-C-ab, Load-C-ac, Load-C-bc, and Load-C-abc. The four models included a total of 45 simulated conditions.

The calculation results were examined and viewed in Hyperworks12.0 software. Von-Mises stress and displacement values for the mini-implant, cortical bone and cancellous bone under various working conditions were collected at intervals of 0.5 mm along the direction of the long axis of the mini-implant.

RESULTS

When the tooth was loaded separately (Load-A), the values of stress and displacement within the bone around the implant neck decreased significantly as the distance between the implant and the root increased. The peak values of stress within the bone around the implant neck were 17.55, 16.98, 15.37, and 11.28 MPa in Models 1–4, respectively (Fig. 3). The peak values of displacement were 4.21, 4.57, 4.49, and 3.61 \( \mu \)m in Models 1–4, respectively (Fig. 4). Notably, the area showing obviously increased stress and displacement was located within the surrounding bone close to the implant root in Models 1 and 2. The peak values of
stress within the surrounding bone close to the implant root were 9.51, 6.95, 3.96, and 2.70 MPa in Models 1–4, respectively (Fig. 3).

When the mini-implant was loaded separately (Load-B), the peak values of stress and displacement within the bone around the implant neck showed no direct relationship with the distance between the implant and the tooth root. For example, application of load-B-a resulted in peak values of stress within the bone around the implant neck of 2.89, 4.47, 3.31, and 3.79 MPa in Models 1–4, respectively. Moreover, no area with obviously increased stress appeared within the surrounding bone close to the implant root in Models 1–4 (Fig. 5). Overall, the scheme of implant loading affected the stress distribution within the cortical bone around the implant neck. The stress peaks of the bone around the implant neck are different in different directions of single load and composite loads in different directions.

When the tooth and mini-implant were loaded simultaneously (Load-C), in addition to the increase in stress within the implant neck as the distance between the mini-implant and tooth increased, a second area with high peak stress appeared where the implant was close to the tooth root. When the tooth and mini-implant were loaded with Load-C-b, the peak values of stress within the bone around the implant neck were 17.02, 18.36, 17.48, and 12.81 MPa in Models 1–4, respectively, and the peak values of stress in the area where the implant was close to the tooth root were 9.51, 6.95, 3.98, and 2.72 MPa, respectively (Fig. 6). Moreover, we found that the peak values of stress at the implant neck–bone interface with applications of Load-A and Load-C were obviously higher than those with only application of Load-B (Fig. 7). The internal stress peak values of the surrounding bone close to the root of Load A and Load C were obviously greater than that of Load-B, but there was no obvious difference between Load A and Load C in the internal stress peak values of the surrounding bone close to the root (Fig. 8).

**DISCUSSION**

In this study, after establishment of models in which mini-implants were located at different distances from the tooth root, different conditions were applied including separate loading of the tooth, separate loading of the implant with different schemes, and simultaneous loading of the tooth and implant. The results showed that as the implant was placed closer to the tooth root, the peak values of stress and displacement within the bone around the implant neck, and the surrounding bone close to the implant root were increased obviously when the tooth was loaded separately or the tooth and implant were loaded simultaneously. When the mini-implant was loaded separately, the peak values of stress within the bone around the implant neck and the surrounding bone
close to the implant root showed no direct relationship with the distance between the implant and tooth root. Finally, changing the loading scheme had no obvious effect on the stress distribution within the bone close to the root.

In general, mini-implant loading stress is distributed mainly in the cortical bone around the implant neck, and the stress and displacement within the bone around the implant root are very small. Ammar et al. proposed that the 2–3 mm anterior cortical bone segment of the mini-implant neck is essential for bearing the orthodontic load. The results of the present study showed that the stress was mainly distributed in the bone around the implant neck when the load was applied to only the mini-implant (Load-B), and the peak value of stress was significantly lower than those when loading was applied to only the tooth (Load-A) or to both the tooth and mini-implant (Load-C). For example, the stress peak value of the bone around the implant neck when the Load-A was applied was 232 times than that of Load-B-c. Even if the implant touched the tooth root (Model 1), the stress and displacement within the bone around the implant root were not obviously increased. This finding indicated that 2 N orthodontic force had little effect on the stability of a mini-implant placed close to the root. The reason is that the orthodontic force that can be loaded on the mini-implant is lower, and the stress is mainly borne by the cortical bone around the implant neck, causing the stress and displacement at the implant root to be much lower. Therefore, placement of the implant increasingly close to the root has no significant effect on the stress distribution over the implant–bone interface. The study of Lee et al. also confirmed that in most cases, mini-implants close to the root can remain stable after 300 gf orthodontic force is applied for 16 weeks, indicating that mini-implant placement close to the root can achieve clinical success. In 1992, Brunski proposed the micro-motion theory, which claimed that a micromotion of less than 100 µm between implant and bone tissue would not significantly affect bone osseointegration. In this study, when the implant was close to the tooth root, the peak
value of displacement at the implant–bone interface increased to 4.6 μm, which should not be enough to lead to implant loosening. Kim et al.20 also reported that placement of an implant simply in close proximity to the tooth root is not responsible for loosening and loss of the implant, but rather, the area of the region where the mini-implant contacts the tooth root is a greater determinant of its stability.

According to the study by Li et al.29, overload cortical bone resorption would occur in areas with von Mises stresses greater than 25–28 MPa. In this study, the peak value of stress at the implant–bone interface increased to 17.6 MPa as the implant was close to the tooth root. However, Motoyoshi et al.13 reported that peak value of stress of a mandible with 2 mm of cortical bone thickness reached up to 140 MPa. The reason for the difference may be the different locations of implants close to tooth roots and different placement angles of implants. The study by Motoyoshi et al.13 also showed that the mandible with 2 mm of cortical bone thickness had a higher peak value of stress compared with those with 1 or 3 mm of cortical bone thickness when the mini-implant was close to tooth roots, but the peak values of displacement did not show a similar trend. On the contrary, a mandible with 1 mm of cortical bone thickness had the highest peak value of displacement. Therefore, for the mandible, the cortical bone thickness is not the major factor causing the implant to fall off.

The tooth root is connected to the alveolar bone via the periodontal ligament, which is mainly composed of collagen fibers. The loading force on the tooth is transmitted to the alveolar bone through the periodontal tissue, and then movements occur in the periodontal ligament and root. When the mini-implant touched the root surface and penetrated the periodontal ligament in the present study, the stress within cancellous bone was significantly increased, with the peak value of stress reaching 9.5 MPa. Li et al.29 also reported that cancellous bone resorption would occur under such conditions and might be a contributing factor to loosening and loss of mini-implants placed close to the root. When the tooth and mini-implant were loaded simultaneously (Load-C), the stress distribution along the implant–bone interface was similar to that observed with load-A. As the distance between the implant and the tooth root decreased, the peak values of stress and displacement increased, indicating the effect of bite force was greater for mini-implants located closer to the root. This relationship between the location where the mini-implant is inserted relative to the root and the effect of bite force should be studied further.

The movement of teeth roots during chewing can cause micro-scale movement of mini-implants, and thus, if the mini-implant is in contact with the tooth root, its mechanical stability is seriously affected. Multiple studies have shown that close proximity to and invasion into the adjacent tooth root are major risk factors for clinical failure of mini-implants20,31. Therefore, it is believed that mini-implants should be placed a certain distance from the tooth root. Jung et al.31 reported that the shortest distance between the mini-implant and tooth root surface should be at least 0.49 mm for success of the implant. Our simulation results showed that a mini-implant located 1 mm from the periodontal ligament surface was less affected by the bite force. Janson et al.6 also proposed that the mini-implant needs to be surrounded by at least 1 mm of alveolar bone for periodontal health to be maintained. Thus, we recommend that mini-implants should be placed at least 1 mm away from the periodontal ligament. The maximum movement of the tail ranged up to 2 mm in the loading direction29. Therefore, the mini-implants close to the roots of adjacent teeth can move away from the root of the teeth under the orthodontic force.

The loading scheme and direction of mini-implants often vary in clinical application according to different treatment goals, and single loading or combined loading may be applied13. This study showed that differences in the loading scheme corresponded to differences in the stress distribution within the bone around the implant neck, whereas the stress within the surrounding bone close to the root was less affected. These results suggest that a mini-implant not affected by bite force is more likely to be able to withstand orthodontic loading of appropriate force from different directions without the occurrence of tissue damage.

In summary, the closer the mini-implant is to the tooth root, the greater the effect of the bite force on the stress distribution over the mini-implant–bone interface is, which is not conducive to the stability of the implant. However, simple orthodontic loading of the mini-implant has little effect on the stress distribution over the mini-implant–bone interface even for mini-implants located close to the tooth root. Thus, it is recommended that the implant placement or angle should be adjusted if the distance between the roots is too small, the implant should be loaded early to be removed from the root, or the composite adhesive should be bonded onto the surface of other molars in order to reduce the occlusal force if the implant is closer to the root.

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CONFLICT OF INTEREST

We declare that we have no conflict of interest.
REFERENCES