3-Dimensional finite element analysis of stress distribution of dental implants on the bone tissue around the neck region of the implant and on the implant surface with respect to bone density

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Abstract
Aim: The aim of this study was to investigate the maximum Von Misses stress values of implants with different diameters in patients with different bone densities depending on the forces that are applied with different angles to the bone around the implant neck and implant surface, by using finite element analysis method.

Material and Methods: 3.8 mm and 4.6 mm diameter dental implants of an implant system that had an in vitro laser-microtextured neck design were used in this study. Computational models were generated for implants with different diameters which were placed in the maxillary and mandibular 1st molar teeth using flat and oblique (20° angled) abutments. Vertical and oblique (30° angled) forces of 300 N were applied to all models and the results were evaluated by finite element analysis.

Results: The results show that both vertical and oblique forces on the implants and placement of abutments in the flat and oblique position caused tension in the bone around the neck of the implant and the implant surface. When the oblique and vertical loads applied to the bone model were compared, the forces applied in the oblique direction exhibited a significant increase of Von Misses stress values in the cortical bone around the crest module of the implant compared to the other group. In our study, the minimum stress distribution with respect to the direction of the applied forces and placement positions of the abutments was obtained by applying the implant and the force in the same direction (abutment straight, force vertical). However, in the groups with the angled application of the force direction and the angled placement position of the abutments, the maximum Von Misses stress value increased in the bone around the implant neck and implant surface.

Conclusion: Placing the implants at the right angle and within bone tissues with adequate cortical bone density around the implant will ensure minimal stress values on both the supporting bone and the implant surface.

Keywords: Bone density; dental implant; finite element stress analysis; stress distribution

INTRODUCTION
The success of a dental implant is determined by the amount of tension applied to the surrounding bone. Many biomechanical factors have been identified for the long- and short-term success of the commonly used dental implants (1,2). Although the success rate of these implants is known to depend on the density and quality of the jaw bone, implant design, surface structure and surgical procedures, the importance of biomechanical factors on long-term success of implants is indisputable (2,3).

Several modifications have been made to the implants to increase the crestal bone levels and reduce its loss. One of these is to create a micro-turing ablated, micro-cavity containing implant surface on the neck of the implant by laser-microtexturing. The widths of these microcavities range between 8-12 µm (micrometer). Direct contact of connective tissue with the implant neck must be promoted in order to reduce the crestal bone loss by preventing epithelial tissue withdrawal (4).

Clinically, it has been shown that probing depths and crestal bone losses of the implants with laser-microtextured micro-cavities on the neck are lower than those of control implants with polished coronal parts (5,6). Finite element analysis (FEA) is a method that evaluates stress, tension and distortion in structures. The FEA
method is performed by dividing structures with complex
graphy into a number of smaller elements that show
similar characteristics to the original model (7,8). In oral
implantology, FEA method allows researchers to interpret
the stress distribution between the dental implants and
bone (9).

In the present study, we evaluated the stress distributions
of two implants of an implant system with different
diameters on the crestal bone around the implant neck
and on the implant surfaces by using the FEA method.

MATERIAL and METHODS

Laser-microtextured implants (Tapered Internal Laser-
Lok, Biohorizons®, USA) which are 3.8 mm or 4.6 mm in
diameter and 10.5 mm in length were used with two types
of abutments (20° angle (oblique) or straight). In order
to eliminate the effects caused by uneven deformation in
each region during modeling, images obtained through
MR or CT devices may be utilized (10). Thus, we also
utilized CT images for this purpose. Rhinoceros 4.0
software was used to transfer the CT images to the
computer. First, upper and lower jaw bones that are 20
mm in height, 30 mm in mesiodistal length and 10 mm
in buccolingual width were modeled (Figure-1a, b). In
this model, a cortical bone that was 2 mm thick in the
mandible and 1 mm thick in the maxilla was integrated.
The inner surface of the cortical bone was defined as
spongy bone. Maxillary and mandibular bone models in
which the implants will be placed were designed, scanned
with the Next Engine 3D laser scanner (NextEngine Inc.,
Santa Monica, California, USA), and endosteal implants,
abutments (straight and 20° angled) and prosthetic
upper-structures have been transformed into a 3D solid
model by using the Rhinoceros 4.0 software (Mc Neel &
Associates, Seattle, USA).

By mimicking centric occlusion; a total of 300 N (Newton)
force was applied as 100 N forces to each palatinal
tubercle, and mesial and distal fossa of the 1st molar tooth
of the maxillary both vertically (Figure 2a) and obliquely
with a 30° angle. Similarly, a force of 300 N (100 N each)
was applied to the buccal tubercle and mesial and distal
fossa of the 1st mandible molar tooth in a vertical (Figure
2b) and oblique direction and a total of 16 models were
obtained (Table 1).

<table>
<thead>
<tr>
<th>Models</th>
<th>Implant</th>
<th>Implant Diameter</th>
<th>Abutment Angle</th>
<th>Force Direction</th>
<th>Bone Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1</td>
<td>Laser-Lok</td>
<td>3.8 mm</td>
<td>straight</td>
<td>vertical</td>
<td>maxilla</td>
</tr>
<tr>
<td>Model 2</td>
<td>Laser-Lok</td>
<td>3.8 mm</td>
<td>straight</td>
<td>30° angled</td>
<td>maxilla</td>
</tr>
<tr>
<td>Model 3</td>
<td>Laser-Lok</td>
<td>3.8 mm</td>
<td>20° angled</td>
<td>vertical</td>
<td>maxilla</td>
</tr>
<tr>
<td>Model 4</td>
<td>Laser-Lok</td>
<td>3.8 mm</td>
<td>20° angled</td>
<td>30° angled</td>
<td>maxilla</td>
</tr>
<tr>
<td>Model 5</td>
<td>Laser-Lok</td>
<td>3.8 mm</td>
<td>straight</td>
<td>vertical</td>
<td>mandible</td>
</tr>
<tr>
<td>Model 6</td>
<td>Laser-Lok</td>
<td>3.8 mm</td>
<td>straight</td>
<td>30° angled</td>
<td>mandible</td>
</tr>
<tr>
<td>Model 7</td>
<td>Laser-Lok</td>
<td>3.8 mm</td>
<td>20° angled</td>
<td>vertical</td>
<td>mandible</td>
</tr>
<tr>
<td>Model 8</td>
<td>Laser-Lok</td>
<td>3.8 mm</td>
<td>20° angled</td>
<td>30° angled</td>
<td>mandible</td>
</tr>
<tr>
<td>Model 9</td>
<td>Laser-Lok</td>
<td>4.6 mm</td>
<td>straight</td>
<td>vertical</td>
<td>maxilla</td>
</tr>
<tr>
<td>Model 10</td>
<td>Laser-Lok</td>
<td>4.6 mm</td>
<td>straight</td>
<td>30° angled</td>
<td>maxilla</td>
</tr>
<tr>
<td>Model 11</td>
<td>Laser-Lok</td>
<td>4.6 mm</td>
<td>20° angled</td>
<td>vertical</td>
<td>maxilla</td>
</tr>
<tr>
<td>Model 12</td>
<td>Laser-Lok</td>
<td>4.6 mm</td>
<td>20° angled</td>
<td>30° angled</td>
<td>maxilla</td>
</tr>
<tr>
<td>Model 13</td>
<td>Laser-Lok</td>
<td>4.6 mm</td>
<td>straight</td>
<td>vertical</td>
<td>mandible</td>
</tr>
<tr>
<td>Model 14</td>
<td>Laser-Lok</td>
<td>4.6 mm</td>
<td>straight</td>
<td>30° angled</td>
<td>mandible</td>
</tr>
<tr>
<td>Model 15</td>
<td>Laser-Lok</td>
<td>4.6 mm</td>
<td>20° angled</td>
<td>vertical</td>
<td>mandible</td>
</tr>
<tr>
<td>Model 16</td>
<td>Laser-Lok</td>
<td>4.6 mm</td>
<td>20° angled</td>
<td>30° angled</td>
<td>mandible</td>
</tr>
</tbody>
</table>
The implants were placed symmetrically on the bone models and were assumed to be 100% osseointegrated into the bone models. In order to obtain optimum results, elastic modules and Poisson ratios of all materials to be used (cortical and spongy bone, titanium implants, chromium-cobalt alloy, feldspathic porcelain, polycarboxylate cement) were entered to the computer model as shown in Table 2 (11-15). Then, FEA results were evaluated and interpreted using ANSYS 14.0 (ANSYS Inc., Canonsburg) program on a computer (ASUS Intel Core i7; Asus Computer International, Fremont, CA, USA).

Table 2. Material properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Elasticity modulus (Gpa)</th>
<th>Poisson ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Implant&amp;Abutment</td>
<td>11.5</td>
<td>0.342</td>
</tr>
<tr>
<td>Cortical bone</td>
<td>13.7</td>
<td>0.3</td>
</tr>
<tr>
<td>Spongy bone</td>
<td>1.1</td>
<td>0.3</td>
</tr>
<tr>
<td>Feldspathic porcelain</td>
<td>82.8</td>
<td>0.35</td>
</tr>
<tr>
<td>Cr- Co alloy</td>
<td>218</td>
<td>0.33</td>
</tr>
</tbody>
</table>

The reason that we used two bone models with different densities was to see how the stress distribution in the implants with different diameters occurs in the bone around the implant neck and surface with respect to the forces applied at different angles and to analyze the bone resorption depending on the stress distribution.

RESULTS

Laser-pretextured implants that were 3.8 mm and 4.6 mm in diameter (Tapered Internal Laser-Lok, Biohorizons®, USA) were placed in the maxilla and mandible at different positions and force was applied at different angles. The maximum Von Misses stress values were calculated when the implant abutments were placed at an angle of 20° and when the force was applied at 30° oblique angle. These values were 67.10 MPa in the maxillary bone (crest module) around the implant neck in the application of an implant with a diameter of 3.8 mm, 57.72 MPa in the case of application of an implant with a diameter of 4.6 mm. In the mandible, the 3.8 mm diameter implant was determined to exert a 74.62 MPa force in the bone tissue around the implant neck, while this force was calculated to be 46.49 MPa for the 4.6 mm diameter implant. Maximum Von Misses stress values on the surface of the implant were obtained by oblique application of the angled force of the abutment. In the maxillary bone, the maximum Von Misses value was 239.2 MPa for the implant with 3.8 mm diameter and 108.15 MPa for the 4.6 mm diameter implant (Figure 3, Figure 4). We observed that the maximum Von Misses stress values for the 4.6 mm diameter implant was lower than that of the 3.8 mm diameter implant, on the bone tissue both around the implant neck and the implant surface (Figure 3).

The minimum Von Misses stress value was calculated and when the implant application direction and the force direction was the same for both implant diameters and in both types of bones: That is, it was observed when the abutment was placed straight and the force was applied vertically. Von Misses stress values calculated after vertical application of the force on a straight placed 3.8 mm diameter implant into the mandible was 9.33 MPa in the bone around the implant and 21.34 MPa on the implant surface.
For the 4.6 mm diameter implant placed in the mandible, the Von Mises stress values that occur were 6.2 MPa in the bone around the implant neck and 14.34 MPa on the implant surface when the force was applied vertically (Figure 5). The maximum Von Mises stress values were observed to increase as the implant position and the angle of application of the force diverged from the vertical angle.

**Figure 5.** Von Misses stress values that occur in the bone around the neck and implant surface as a result of the vertical application of the abutments with straight force.

**DISCUSSION**

Dental implants have been successfully used in the treatment of dental deficiencies for the last two decades (16). However, dental implants are not 100% successful in the long term. Clinical and experimental studies have showed that the stress transmitted to the bone around the implant may lead to bone resorption and consequently loss of implants (17,18). Functional and parafunctional forces generated in the intraoral area are transmitted to the implants via the upper-structures of the implants and from there to the adjacent bone. These forces cause stress and deformation in the implant-bone contact area, and may affect remodeling of the bone around the implant (17).

In a study by Papavasiliou et al., stress occurring around a single dental implant at different bone densities was evaluated by using the FEA method. They reported that the stress was concentrated on the compact bone and that the oblique loads on the occlusal surface increased the stress on the bone around the implant by ten times (13). In another study, Sevimay et al. examined the distribution of stress in bones with different densities by finite element analysis and reported that the stress increased in the bone around the neck of the implant in low-density bones (19). In their study using different implant designs and bone models with different densities, Yalcın et al. reported that as bone resorption progresses, increased stress in the cancellous bone and implant under lateral load may fail the implant (24). In many studies, it has been reported that the greatest tension was observed in the bone region around the implant's neck (25-29). In our study, with the vertical application of the force in the mandible, the stress levels in the bone in the neck region of the implant was 6.215 MPa, whereas the oblique application of the force in the same region resulted in an increase to 46.49 MPa. In the maxilla, it increases from 12.96 MPa to 57.72 MPa. Our results, which are in parallel with other studies, showed us that direction of the force and bone quality affect the stress value.

Himmelova and colleagues examined the distribution of Von Misses stress value around implants with different diameters and lengths by finite element analysis, and they reported that the diameter of the implant is more important than the length of the implant to reduce the Von Misses stress levels (30). Petrie et al. reported that long diameter and long implants will have longer life in low density bones (31). Raaj et al. reported that when in axial and non-axial loads, amount of stress distribution around implant-bone interface is influenced by diameter and length of implant in cortical and cancellous bone, respectively. In addition, increased diameter of the implant produced the minimum stress in cortical bone (32). Pelizzer et al. evaluated implants with different diameters with FEA under standard force and reported that the stress distribution became more efficient as the implant diameter increased (33). Implant dimensions are very important in transmission of the force to surrounding tissues. Considering that the maximum stress is concentrated around the neck region of the implant, the length/diameter ratio is an important parameter (34). In their study where they applied forces mimicking chewing muscles, Ding and colleagues reported that stress and tension in the neck of the implant decreased as the diameter increased (35). Eazhil et al. reported that there was a statistically significant decrease in Von Misses stress as implant diameter increased (36). Anitua et al. found that the use of wider implants would be better to dissipate impact forces and thus reduce stress in the bone surrounding the implant (37). Mohammed et al. analyzed the stress distributions of implants with different designs and diameters and reported that the stress in the peri-implant area decreases with increasing implant diameter (38). In our study, especially in the mandible where the cortical bone density is high, the stress levels in the crestal bone around the implant decreased as the implant diameter increased. In the maxilla, as the diameter increased, the stress levels decreased both on the surface of the implant and on the bone around the implant.
Among the models created in our study, the minimum Von Misses stress values were calculated by applying the implant and force in the same direction. In contrast, in models obtained with angled application of force and angled abutment, we observed the maximum Von Misses stress values on the bone around the neck of the implant, which we think will clinically increase crestal bone resorption.

CONCLUSION

Increased maximum Von Misses stress values on the bone around the implant neck and the implant surface indicates that bone resorption will be increased. We believe that stress analysis studies related to commonly used implant types will guide the clinicians in terms of implant surface, neck characteristics and application protocols and increase awareness in implantology and the success rate of dental implants.

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REFERENCES