The placement of dental implants in place of missing teeth is becoming an increasingly common treatment model. Implants of different sizes, designs, and structures are produced in order to manage different clinical scenarios. Dependent on the increasing demand of dental implants, many manufacturers are entering the dental implant industry by prioritizing the advantages of their different designs. Thus, there are now many special designs available that allow the implant manufacturer to distinguish themselves from others.¹⁻³

Several studies have been conducted to understand the factors that affect implant success. These factors are the biocompatibility of the material, implant design, surface structure of the implant, surgical technique, and loading conditions, and they have been shown to affect the osseointegration of implants.³ Another factor that affects success is the quality of the bone in which the implant will be placed. It is known that poor bone quality affects long-term implant success.³ Poor bone quality is not a feature that can be easily changed. Changing the implant design and its surface structure to allow for proper stress distribution in the implant-bone interface and cortical bone plays a key role in successful implant treatment by reducing bone loss around the implant.⁵,⁶

**Purpose:** The aim of this study was to evaluate the effect of implant designs with different lengths and diameters on the stress distribution in abutments, implants, and cortical and trabecular bone of the edentulous mandible via three-dimensional finite element analysis. **Materials and Methods:** Eight different finite models (cylindrical 3.5 × 6; cylindrical 3.5 × 10.5; cylindrical 4.5 × 6; cylindrical 4.5 × 10.5; triple cylindrical 3.5 × 6; triple cylindrical 3.5 × 10.5; triple cylindrical 4.5 × 6; and triple cylindrical 4.5 × 10.5) were created. Abutments, abutment screws, and metal-retained porcelain crowns were modeled on the implants. A 200-N oblique load was applied on the buccal cusp of the crown. The highest maximum principal ($P_{\text{max}}$) and minimum principal ($P_{\text{min}}$) stresses were calculated for trabecular and cortical bone, and von Mises stress values were calculated for the implant and abutment. **Results:** The triple cylindrical implant abutments showed lower stress values than cylindrical implant abutments. The highest von Mises stress values were observed in the cervical third of the abutments. The stress values on implants were found at the neck of the implants, and cylindrical implants showed higher stress values than triple cylindrical implants. The peak $P_{\text{max}}$ and $P_{\text{min}}$ values in cortical bone were detected around the implant neck. For implants with a 3.5-mm diameter, the triple cylindrical implant design showed lower stresses in cortical bone than the cylindrical implant design; however, similar stresses were observed in 4.5-mm implants for both designs. Implant length did not affect the stresses in cortical bone. Implants with a 10.5-mm length showed lower $P_{\text{max}}$ values than implants with a 6-mm length in trabecular bone. For $P_{\text{min}}$ values in trabecular bone, the triple cylindrical implant design had lower values than did the cylindrical implant design. **Conclusion:** Within the limitations of this study, the triple cylindrical implants, with a new implant design, showed appropriate results in terms of abutment, implant, and bone tissue stress. Int J Oral Maxillofac Implants 2020;35:257–264. doi: 10.11607/jomi.7760

**Keywords:** dental implants, finite element analysis, implant design, stress distribution
While the surface structure of the implant is mostly related to osseointegration, it affects the implant-bone interface by its implant design, mechanical stability, and occlusal loads.3

Some of the implant body designs reduce biomechanical loading and bone loss.5 It was also emphasized that implant design is important for achieving successful osseointegration by providing mechanical stability and strong bone-to-implant contact.2

Implant design refers to the three-dimensional structure of the implant, with all the elements and characteristics that compose it. Endosseous dental implants exist in a wide variety of designs, with the main objective, in every instance, being the long-term success of the osseointegrated interface and uncomplicated function of the prosthetic replacement.7

Implant design can be categorized into two modalities: macrodesigns and microdesigns. Macrodesign refers to the shape of the thread, implant body, prosthetic connection, and collar design. Microdesign refers to the implant material, surface morphology, and surface treatments.6 Researchers have targeted implant macrodesign in attempts to understand the biomechanical factors that most affect long-term implant success.

Commercial implant bodies, which are used frequently today, have three main design concepts. These are screwed, threaded, and tapered implant bodies. These designs are recommended to support the biomechanical and clinical behavior of the implants. A threaded implant design reduces the mobility after implant placement by increasing the contact at the implant-bone interface. In the same way, the stepped body design simulates the form of a natural tooth and provides appropriate stress relief. Another concept is the tapered concept, which is advantageous for directing force. This type of implant design shows good success rates that are due to the removal of stress from the cortical bone to the trabecular bone.5 The cortical bone is stronger than the trabecular bone, but repair is slower in the case of damage. Trabecular bone is more resilient and can absorb functional stresses. Damage to the trabecular bone heals faster.8 Consequently, the delivery of stresses to the trabecular bone leads to successful implant treatment. Each of the three designs has unique advantages. However, there is no consensus on which implant body design is better.5

The implants can be conical, parallel, stepped, or solid.3 However, although the diameter and length of the outlet profiles are different, the shape of the conical implants to the bone is similar. In fact, the use of traditional implants, which are completely different from the conical implants, has been reduced by the spread of conical implants, but not by enough to show that these alternatives reflect an advantage.

The triple cylindrical implant (Bepa Dental Medical Goods and Trade Industry), a new implant design, is produced for indications that would cause problems in the application of conical implants. This design can reduce the stress in both cortical and trabecular bone and establish an implant with a longer duration and success. The aim of this study was to evaluate the effect of different implant designs on the stress distribution in abutments, implants, and cortical and trabecular bone via three-dimensional finite element analysis.

**MATERIALS AND METHODS**

In this study, two different implant designs were compared to each other by creating a model with different lengths and diameters. The first implant design was created for standard cylindrical implants (Fig 1a), and the second design was created for triple cylindrical implants (Fig 1b); under the two groups, four different models with different lengths and diameters were designed for a total of eight models. The study models are shown in Table 1.

The edentulous mandible was modeled using VRMESH and Rhinoceros software programs with a 2-mm cortical bone layer covering the trabecular bone. The implants and the prosthetic components were scanned in the optical scanner (Activity 880, Smart Optics Sensortechnick), and data were reconstructed with VRMESH software. All structures were
modeled using the Rhinoceros 4.0 program. Models were developed for the triple cylindrical and cylindrical implant designs by including mandibular trabecular bone, cortical bone, implant designs, abutments, screws, cobalt-chrome metal infrastructure, and porcelain superstructure (Figs 2 and 3).

The generated geometric models were exported to Algor Fempro (Algor) in a .stl format. All models were converted into solid models in the form of bricks and tetrahedral elements and, to the extent possible, eight-node elements were used; seven-, six-, five-, and four-node elements were used in cases where eight-node elements could not reach. The number of elements and nodes in the final models are presented in Table 1. The models were fixed at the bottom and sides of the bone so that they had zero movement in the degree of freedom (DOF). All models were accepted as linearly elastic, homogenous, and isotropic. Mechanical properties (Elastic modulus and Poisson’s ratios) of the materials were obtained from the most frequently used values of researchers in previous studies and are presented in Table 2.

Considering the average load on the first molar tooth, a 200-N load was applied at a 45-degree angle to the long axis of the implant on the buccal cusp as the loading condition. Analysis results were measured numerically, and visual results were obtained with color codes. The highest maximum principal stress

<table>
<thead>
<tr>
<th>Model</th>
<th>Implant design</th>
<th>Implant diameter (mm)</th>
<th>Implant length (mm)</th>
<th>Elements</th>
<th>Nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cylindrical</td>
<td>3.5</td>
<td>6</td>
<td>330,714</td>
<td>63,814</td>
</tr>
<tr>
<td>2</td>
<td>Cylindrical</td>
<td>3.5</td>
<td>10.5</td>
<td>361,564</td>
<td>68,962</td>
</tr>
<tr>
<td>3</td>
<td>Cylindrical</td>
<td>4.5</td>
<td>6</td>
<td>326,174</td>
<td>63,069</td>
</tr>
<tr>
<td>4</td>
<td>Cylindrical</td>
<td>4.5</td>
<td>10.5</td>
<td>359,401</td>
<td>68,543</td>
</tr>
<tr>
<td>5</td>
<td>Triple cylindrical</td>
<td>3.5</td>
<td>6</td>
<td>620,608</td>
<td>116,303</td>
</tr>
<tr>
<td>6</td>
<td>Triple cylindrical</td>
<td>3.5</td>
<td>10.5</td>
<td>632,530</td>
<td>123,803</td>
</tr>
<tr>
<td>7</td>
<td>Triple cylindrical</td>
<td>4.5</td>
<td>6</td>
<td>635,642</td>
<td>118,959</td>
</tr>
<tr>
<td>8</td>
<td>Triple cylindrical</td>
<td>4.5</td>
<td>10.5</td>
<td>749,581</td>
<td>139,732</td>
</tr>
</tbody>
</table>

Table 2 Mechanical Properties of the Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Elastic modulus (MPa)</th>
<th>Poisson’s ratio</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cortical</td>
<td>13,700</td>
<td>0.30</td>
<td>9</td>
</tr>
<tr>
<td>Trabecular bone</td>
<td>1,370</td>
<td>0.30</td>
<td>9</td>
</tr>
<tr>
<td>Titanium</td>
<td>110,000</td>
<td>0.30</td>
<td>10</td>
</tr>
<tr>
<td>Cobalt-chromium</td>
<td>218,000</td>
<td>0.30</td>
<td>11</td>
</tr>
<tr>
<td>Ceramics</td>
<td>70,000</td>
<td>0.22</td>
<td>11</td>
</tr>
</tbody>
</table>
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(Pmax) and minimum principal stress (Pmin) values were used for cortical and trabecular bone; the highest von Mises (mvM) stress values were used for implants and abutments.

RESULTS

In this study, the stress distribution of different implant designs and the structure of the surrounding tissues were examined on the edentulous mandible, and the stress values of two different implant designs of different lengths and diameters in the abutments, implants, cortical bone, and trabecular bone are shown in Table 3.

The mvM stress values of the abutments did not differ according to implant length and implant diameter; however, the mvM stress values seen in triple cylindrical implant abutments were significantly lower than the stress values in cylindrical implant abutments. The mvM values measured in abutments are in the middle of the implant-abutment junction area for both designs (Figs 4a and 4b).

Although the mvM stress values of the implants were similar for both triple cylindrical and cylindrical implant designs with different lengths and diameters, in the cylindrical implant design, very high stress values were observed compared with the triple cylindrical implant design. In both implant designs, the mvM values were measured from the neck region of the implant (Figs 5a and 5b).

Pmax and Pmin stress values of cortical bone for the triple cylindrical design on implants of 3.5-mm
diameter were lower than the stress values of cylindrical implants. In the 4.5-mm-diameter implants, they produced similar stress values in the two designs. The 4.5-mm-diameter implants had lower values than the 3.5-mm-diameter implants. Stress values in the cortical bone were considerably below the end strength of the cortical bone (end strength values: Pmin: 170 to 190 MPa; Pmax: 100 to 130 MPa), and maximum Pmin and Pmax values were measured from the bone around the implant neck (Figs 6a to 6d).

In the two implant designs, the Pmax values of the 6-mm-long implants, formed on the trabecular bone, were similar to each other and were over 5 MPa of the capacity of the bone (Figs 7a and 7c). The 10.5-mm-long implants had lower stress values than the 6-mm-long implants, but these values were below 5 MPa.

In the triple cylindrical implant design, the Pmin values in the trabecular bone were lower than the cylindrical implants, and all of its Pmin values were below –5 MPa (Figs 7b to 7d).
DISCUSSION

In this study, a new implant design with different diameters and lengths was compared with a cylindrical implant design on the edentulous mandible, using mathematical biomechanical analysis.

Implant geometry is one of the factors affecting biomechanical behavior. Cylindrical implants may not be the best choice for all clinical conditions. Various implant designs have been introduced in order to obtain successful results in different anatomical and bone conditions. According to the results of the triple cylindrical implant stress distribution, which is a new implant design, it has better stress values than cylindrical implants. The triple cylindrical implant design is thought to be more effective in distributing the force, especially due to the wide triple cylindrical structure in the mesiodistal direction.

Only short implants can be used in cases with severe alveolar bone loss. However, short implants are not capable of carrying occlusal loads. When wide and short implants are used, reduced remaining bone around the implant, and also increased crown-implant ratio, and longer leverage of superstructure can play a role in causing implant failure. One solution to this problem is bone augmentation to accommodate standard implants. However, surgical procedures for augmentation include some risks, such as infection and loss of graft material. In the present study, the triple cylindrical implant design showed less favorable stress distribution compared to cylindrical implants with small diameters and short lengths. In particular, a 3.5-mm-diameter and 6-mm-long implant may be an alternative to the standard treatment protocols in cases with insufficient bone support.

Renouard and Nisand investigated the effect of implant length and width on implant success, and they reported that short implants used in the posterior region have low success rates. Similarly, another study reported that large-diameter implants yielded more successful results than small-sized implants, especially in the posterior region. In the present study, the results are similar, with the stresses that the cylindrical implants have on their body and abutments being significantly higher than the same stresses on the new triple cylindrical implant design. When looking at the stresses of abutments and implants, the cylindrical type of implant is close to, or above, the final endurance capacity of titanium. The larger surface area of the triple cylindrical implant design in the mesiodistal direction is thought to play a role in low stress distribution within the body by spreading the occlusal loads to a larger area.

Implant design and implant diameter and length affect the stress distribution in the surrounding bone. In a study examining the effect of implant diameter on stress distribution with finite element analysis, it was said that the increased implant diameter reduces the stresses around the implant neck. Similarly, the present study found that the increased diameter of the implant decreased the amount of stress in the cortical bone. However, for the two implant designs with different diameters and lengths, the stress values were similar.

The highest stresses of the cortical bone, located at the crestal region around the implant, are relevant to the clinical findings of crestal bone loss. The highest stress values for both implant designs were measured from the cortical bone of the mandible around the implant neck. This is similar to other implant studies. The two implant designs in cortical bone exhibited similar values and are well below the last limit of cortical bone for resorption (Pmin: 170 to 190 MPa; Pmax: 100 to 130 MPa).

Implant design may give a different stress distribution in jawbone. The stress values of the 3.5-mm-diameter triple cylindrical implant in the cortical bone are lower than the stress values of the cylindrical implants. For lower-diameter implants, the triple cylindrical implant design provides a more convenient stress distribution.

In their study, El-Anwar and El-Zawahry emphasized that implant length is biomechanically important, especially for increasing the contact area of low-diameter implants. Similarly, in the present study, the low-diameter triple cylindrical implant design produced lower stress values of the cortical bone.

The lowest stress values in the trabecular bone were observed in the triple cylindrical implant design with a 10.5-mm-long implant. Increased implant length in the triple cylindrical implant design increases surface area much more compared with cylindrical implants. This condition was thought to be effective in obtaining lower values with the triple cylindrical implant. In a study conducted by Baggi et al in 2008, it was emphasized that the increased length of the implant decreases the stress on the trabecular bone. This result is similar to the results of the present study. Stresses in the trabecular bone decreased with increasing implant length.

In terms of clinical relevance, the triple cylindrical implant design has some advantages when used at the posterior mandible compared with conventional cylindrical implants. Wide implants achieve a larger surface area to contact the bone, and as a result, this triple cylindrical design shows more osseointegrated surfaces compared with conventional cylindrical implants. This design improved biomechanical behavior by reducing stress magnitudes in implants and trabecular and cortical bone due to the wide implant surface area. Additionally, the triple cylindrical design
of the abutment and its bigger mesiodistal diameter, compared with the conventional cylindrical abutment, can be more ideal for the molar region to manufacture wider crowns. Thus, food impaction can occur less in the interpapillary area through a wider emergence profile that was created by not only the crown but also the abutment.

In their study, Chun et al\textsuperscript{25} stated that similar stresses were observed in different models when vertical loads were applied, and at the oblique loadings, they stated that the different models create distinct differences. Other researchers have reported that oblique loads reflect more realistic forces in finite element analysis, and for this reason, they stated that there was no need to apply the vertical forces\textsuperscript{18,26} in the present study, vertical loads were not performed in accordance with other studies, and oblique loading was applied in all plans. The unilateral measurement of the maximum occlusal force in the molar region is between 300 and 600 N in healthy natural-toothed individuals.\textsuperscript{27} To evaluate the maximum effects of stresses, 200-N forces were applied to the implants to simulate average masticatory force on natural molar teeth.

The present study tried to imitate clinical situations as much as possible. However, it is impossible to reflect all factors in the mouth with a computer simulation.\textsuperscript{5,28} The limitations of this study included the following: the level of osseointegration for the implants used in this study was accepted as 100\%, and the materials used in the models were accepted to be isotropic and homogenous. However, the purpose of this study was not to calculate exact stress values, but to compare the stress of two different designs with each other in terms of stress formation and distribution.

To achieve clinical success of different implant designs, it is necessary to understand biomechanical behavior.\textsuperscript{6} In this study, finite element analysis was used to see the biomechanical behavior of a new implant design. Although the results obtained by finite element analysis on the edentulous mandible have helped in better understanding the stress and distribution of the implant with the new implant design and the cylindrical design, long-term clinical studies are needed to evaluate this design.

CONCLUSIONS

Within the limitations of this study, the triple cylindrical implants with a new implant design showed appropriate results in terms of abutment, implant, and bone tissue stress. In particular, in cases with excessive bone loss and anatomical limitations, these new implants with an alternative design may exhibit a better outlet profile than conventional cylindrical implants placed in a molar tooth area, and may play an important role in clinically successful results.

ACKNOWLEDGMENTS

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REFERENCES