Comparative Finite Element Analysis of Short Implants with Different Treatment Approaches in the Atrophic Mandible

Ozge Doganay, DDS1/Erdem Kilic, DDS, PhD1

Purpose: This three-dimensional finite element analysis study aimed to compare the stresses transmitted to short, tilted, and vertical implants used in different configurations and to the surrounding peri-implant bone in the atrophic mandible.

Materials and Methods: A three-dimensional model of an atrophic mandible was made using customized computer software. Four models including short, tilted, and vertical implants were constructed with and without cantilever extension. Four or six implants in different configurations were placed into the models and mounted with the same fixed prosthesis. An oblique force of 200 N was bilaterally applied to the most distal part of the fixed denture. Von Mises stress values on implants and minimum and maximum principal stress values transmitted to peri-implant bone were analyzed.

Results: The highest stress values recorded in the tilted implants (von Mises: 129 MPa), in the peri-implant bone around the tilted implants (minimum principal stress: –40 MPa), and overall stress values were found to be higher in the model including tilted implants with cantilever extensions. Distally placed short implants, with consequent elimination of the cantilevers, resulted in decreased stress values for all of the treatment variabilities of an atrophic mandible. Von Mises stress values were found as 129 MPa in tilted (model I), 48 MPa in short (model II), 47 MPa in short (model III), and 57 MPa in vertical (model IV) at the most distal implant location. Lower compressive stress values were noted in the bone around straight and short implants compared with the tilted implants in all models (model I, tilted: –40 MPa; model II, short: –34 MPa; model III, short: –33 MPa; model IV, vertical: –25 MPa).

Conclusion: Distally placed short implants contributed to the reduction of stress values of the implants and the surrounding bone. The combination of two short and four straight implants without cantilevers may be a beneficial design in the rehabilitation of posteriorly atrophic mandibles.

Keywords: atrophic mandible, bone, finite element analysis, short implant, stress, tilted implant

Rehabilitation with implants in the severely atrophic mandible has been considered to be a prosthetic and surgical challenge due to insufficient vertical alveolar ridge and anatomical restrictions, such as the presence of the inferior alveolar and mental nerve.1 The close proximity of the mandibular canal to the alveolar crest precludes the insertion of regular dental implants in the posteriorly atrophic mandible.1 In order to overcome this restraint, advanced surgical techniques such as autogenous bone grafting, guided bone regeneration, and distraction osteogenesis were developed to insert an implant of standard length.1 However, all of these procedures can be challenging, technically sensitive, and time consuming, and require an additional financial burden. Moreover, extremely high postoperative graft complication rates up to 95% were reported.2

Rehabilitation of the posteriorly atrophic mandible using tilted implants between the interforaminal region has been successfully performed for years.3,4 Tilting implants enables distribution of occlusal forces, and aims to reduce long cantilever extensions in the posteriorly atrophic mandible by engaging available bone for the fixed prosthetic rehabilitation.5,6 However, some authors have concerns regarding the prognosis of distally tilted implants placed in the mandible. Although the inclination of the distally tilted implants increases the bony contact between the bone and implant surface, and hence seems to be an advantage for the load transfer along the implant, tilted implants are extremely subjected to lateral direction of occlusal forces and a greater possibility of bending moment.7,8 Certain anatomical conditions, such as an anteriorly positioned mental foramina leading to a long distal cantilever, may restrict the beneficial biomechanical properties of using tilted implants.9,10 In fact, a distal cantilever can be considered to be a contributing factor leading to higher stresses around the implants and the peri-implant bone in the tilted implant concept.11

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Another concern is that flexural movement of the mandible during opening and protrusion of the jaw causes an alteration of the mandible's shape and subsequently micromovement of the implant after prosthetic rehabilitation, and thus, it may compromise different stages of osseointegration.12–14 The most posterior implants would be highly prone to microdamage, most specifically in cantilever situations due to the mandibular flexure. In other words, anteriorly positioned implants in the intermaxillary foramen, which are supported fixed prostheses with posterior cantilevers, would lead to leverage effects around the midline of the jaw. Therefore, considerable stress around distal implants would arise eventually.12–15

All those mentioned factors might have unfavorable effects on the prognosis of the implant and implant-related fixed prosthesis. Therefore, a larger number of implants would be warranted to reduce the extrinsic forces leading to the implant and surrounding bone failure apart from occlusal loads.6,9 At sites where the bone availability and implant length are compromised, using short implants in the posterior mandible can be considered in order to eliminate the cantilever effect, to relieve stress of anteriorly positioned implants, and to improve the survival of both implants and prosthetic structures, if a residual ridge height is at least 6 mm for the insertion.16,17

Three-dimensional finite element analysis (FEA) is a valuable method to mimic biomechanical behavior of the implant and surrounding bone that would not be clinically possible to observe. It has been well-established, and the effects of different connection types, implant designs, surface morphologies, and prosthetic components on the stress distribution around short or tilted implants and their surrounding structures have been studied extensively.5,18–20

In the recent past, it was believed that the amount of bone is one of the major determinants of the success of implant surgery.2 Yet, current approaches such as tilted and short implants and developments in surface technology and designs enable clinicians to do optimum treatment planning in accordance with the available amount of bone.21 Nevertheless, the ideal treatment modalities of the posteriorly atrophic mandible for better longevity and outcomes of implants and implant-related prostheses still cannot be drawn due to the diversity of the clinical scenarios.16,18,22,23

Given the lack of general consensus in the literature regarding the best approach to rehabilitate the posteriorly atrophic mandible, the present study aimed to build up the models including posteriorly placed short implants. The stress transmission of short implants was compared with tilted and vertical implants in the four different treatment combinations supported with fixed prostheses via three-dimensional finite element analysis. This study was conducted to use as a guide in clinical trials.

**MATERIALS AND METHODS**

The three-dimensional (3D) model of the atrophic mandible was produced from the clinical computed tomography data of a patient meeting the appropriate properties. Mesh generation of the 3D simulated model was performed with 10 noded elements to maximize the sensitivity of the analysis.

**Material Properties**

Four models with different implant positions and numbers were analyzed. The diameters of all implants used in the simulations were 4.1 mm; 10-mm length, bone-level tapered (BLT) implants and 4-mm length, standard plus short implants (titanium-zirconium alloy, Roxolid, Institut Straumann) were simulated. The framework and superstructure of the restoration comprised cobalt-chromium alloys (Wirebond C, BEGO Medical) and feldspathic porcelain (Dentsply Ceramco), respectively.

All structures were considered linearly elastic, isotropic, and homogenous.24 Young's modulus and Poisson's ratio of the variable elements in the designs were set in accordance with data available in the literature.22,25 All values related to the materials of this study are given in Table 1.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Young's modulus (MPa)</th>
<th>Poisson ratio</th>
<th>Tensile strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compact bone</td>
<td>13,700</td>
<td>0.3</td>
<td>–</td>
</tr>
<tr>
<td>Cancellous bone</td>
<td>1,370</td>
<td>0.3</td>
<td>–</td>
</tr>
<tr>
<td>Ti-Zr implant (Roxolid)</td>
<td>100,000</td>
<td>0.3</td>
<td>953</td>
</tr>
<tr>
<td>Framework (Co-Cr)</td>
<td>218,000</td>
<td>0.33</td>
<td>–</td>
</tr>
<tr>
<td>Feldspathic porcelain</td>
<td>82,800</td>
<td>0.35</td>
<td>–</td>
</tr>
</tbody>
</table>

**Modeling**

All structures provided in the study had been previously scanned with a digital scanner (Smart Optics Sensortechnik). The measured data were transferred to the Rhinoceros 4.0 program (McNeel) to construct the solid models. The same superstructure was applied to each model in order to keep the load transfer constant. Type II bone structure was simulated based on Lekholm and Zarb classification.26 Compact bone thickness was considered to be 2 mm in all regions.
The mesiodistal length of the mandibular arch was determined to be 40 mm, whereas the height of the mandible in all regions was approximately 16 mm. After completion of the procedure, all models were transferred to Algor Fempro (ALGOR) software in stl format to analyze.

**Boundary and Loading Conditions**

Boundary conditions were modeled for fixing the lower border of the mandible, the mesial and distal region of the mandibular sections, the compact and the cancellous bone, the insertion of the masseter and medial pterygoid muscles, implants, and prosthetic structures in all directions. The movements of nodes in all areas were completely constrained, and the implants and the prosthetic restoration were assumed to behave as a monolith. The connection between the superstructure and the implant was considered to be tightly bonded, and the complete osseointegration between the bone-implant interface was assumed. Standardized application of a static 45-degree oblique load of 200 N in the buccal-lingual direction was placed on the buccal cusp of the most distal part of the prosthesis for each model.

**Models**

In this study, four different treatment modalities were constructed. Implants 10 mm in length were placed in the interforaminal regions, while short implants were placed behind mental foramens in accordance with the simulated model. All simulations are shown in Fig 1:

- **Model I**: Emergence profiles of two straight implants were designated to the lateral incisor regions, while two tilted implants angled at 30 degrees and the cantilever with 11-mm length were bilaterally inserted into the second premolars.
- **Model II**: Two straight implants in the lateral incisor regions, and two tilted implants angled at 30 degrees and the cantilever with 11-mm length in the second premolars were bilaterally inserted. In addition, this model had two distally short implants at the first molar areas. There was no cantilever in the superstructure.
- **Model III**: The implants were placed into the lateral incisor, first premolar, and first molar areas. This model included four straight implants between mental foramen and two short implants. There was no cantilever in the superstructure.
Table 2  Von Mises Stress, Minimum, and Maximum Principal Stress Values of Each Implant (in MPa)

<table>
<thead>
<tr>
<th>Implant model</th>
<th>von Mises</th>
<th>Maximum principal stress</th>
<th>Minimum principal stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model I</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tilted</td>
<td>129</td>
<td>9</td>
<td>–40</td>
</tr>
<tr>
<td>Vertical</td>
<td>74</td>
<td>6</td>
<td>–3</td>
</tr>
<tr>
<td>Model II</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Short</td>
<td>48</td>
<td>12</td>
<td>–34</td>
</tr>
<tr>
<td>Tilted</td>
<td>57</td>
<td>6</td>
<td>–8</td>
</tr>
<tr>
<td>Vertical</td>
<td>34</td>
<td>2</td>
<td>–3</td>
</tr>
<tr>
<td>Model III</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Short</td>
<td>47</td>
<td>12</td>
<td>–33</td>
</tr>
<tr>
<td>Vertical middle</td>
<td>48</td>
<td>6</td>
<td>–7</td>
</tr>
<tr>
<td>Vertical mesial</td>
<td>33</td>
<td>2</td>
<td>–3</td>
</tr>
<tr>
<td>Model IV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical distal</td>
<td>57</td>
<td>14</td>
<td>–25</td>
</tr>
<tr>
<td>Vertical middle</td>
<td>49</td>
<td>6</td>
<td>–6</td>
</tr>
<tr>
<td>Vertical mesial</td>
<td>31</td>
<td>2</td>
<td>–3</td>
</tr>
</tbody>
</table>

- Model IV: The implants were placed into the lateral incisor, first premolar, and first molar areas. There was no cantilever in the superstructure. This model including six vertical implants with standard length and diameter is generally used in the rehabilitation of jaws without the need for grafting and served as control in this study.

The von Mises stress analysis was performed to determine the stress values of the implants and restorations. Minimum and maximum principal stress values used for the identification of local risk factors leading to bone resorption were applied to the models. All data were determined with the range scales and produced quantitatively and color-coded on any identified location and then compared among all models.27

RESULTS

The von Mises and maximum and minimum principal stress values corresponding to the different implant configurations of four models are listed in Table 2.

Von Mises Stress

In the models, the highest stress areas were located at the top threads of the implants. The amount of stress intensified when the tilted implants were used at the most distal implant location to support fixed prostheses in model I. Stress values of the tilted implants decreased due to the posteriorly placed short implants in model II (model I: 129 MPa, model II: 57 MPa). The lowest stress levels among posteriorly atrophic treatment modalities (models I, II, and III) were achieved in model III, including two short and four vertical implants (short: 47 MPa, vertical middle: 48 MPa, vertical mesial: 33 MPa). Additionally, lower stress concentrations were obtained with the short implants compared with the vertical or the tilted implants, which functioned at the most distal implant location (model I, tilted: 129 MPa; model II, short: 48 MPa; model III, short: 47 MPa; model IV, vertical: 57 MPa). All stress concentration areas and values were demonstrated in Fig 2.

Principal Stresses

In all models, the highest equivalent stress of the compact bone was found around the neck of the implants. Mean equivalent stress values of the compact bone were greater than that of the cancellous bone. The highest compressive stress values of the bone were observed at the lingual site near the neck of the implant, whereas the highest tensile stresses of the bone occurred on the buccal side. The highest minimum principal stress (compressive) values were obtained in the bone surrounding the tilted implant (–40 MPa) in model I. Lower compressive stress values were noted in the bone around vertical and short implants compared with the tilted implants in all models (model I, tilted: –40 MPa; model II, short: –34 MPa; model III, short: –33 MPa; model IV, vertical: –25 MPa) (Fig 3).

DISCUSSION

The present study aimed to investigate whether using short implants would have an additional benefit in reducing the stress values of all components in the posteriorly atrophic mandible. Distally placed short implants used in models II and III were found to function successfully in reducing the overall stress.

Understanding the stress distribution of the biomaterials used in implant dentistry is a key factor to predict the success or failure rates of the methods. Therefore, FEA is frequently used to investigate the effect of biomechanical properties of the dental implants, prosthetic structures, and the surrounding bone in which visualization of stress distribution is clinically impossible.28

On the other hand, FEA study models represent a simplification of the investigated structures. Data obtained from an FEA study are not reproducible, and thus, unfavorable to perform statistical analysis. Indeed, a 3D FEA only allows approximation of statistical analysis. Indeed, a 3D FEA only allows approximation of material behaviors through 3D modeling in a virtual environment. It is assumed that there is a complete osseointegration between the bone and the implant interface as well as fixed boundary and loading conditions, which may not fully represent clinical scenarios.5,11
Fig 2 (left) Von Mises stress values and stress distribution of the implants under oblique loading (MPa). (a) Stress values of model I including two tilted and two vertical implants. (b) Stress values of model II including two tilted, two vertical, and two short implants. (c) Stress values of model III including four vertical and two short implants. (d) Stress values of model IV including six vertical implants (X = distal side; Z = occlusal side).

Fig 3 (below) Minimum principal stress values (MPa) and stress distribution of mandibular compact bone under oblique load. (a) Stress values of model I including two tilted and two vertical implants. (b) Stress values of model II including two tilted, two vertical, and two short implants. (c) Stress values of model III including four vertical and two short implants. (d) Stress values of model IV including six vertical implants (X = distal side; Y = buccal side).
In this experimental design, it was aimed to demonstrate the maximum stress values in different regions of the models. It should be emphasized that the theme of the present study was not reporting the precise values of the stress, but rather comparing the stress distribution among different treatment modalities.

The tilted implant concept is one of the most commonly used protocols, which enables fixed prosthetic rehabilitation of an atrophic edentulous mandible and eliminates the need for bone grafting and/or nerve transposition techniques. Moreover, the concept offers some biomechanical advantages by using longer implants, achieving a larger bone-implant interface, and providing better load distribution on the occlusal plane. This technique also avoids the presence of a long distal cantilever, which causes higher stress levels in the surrounding bone, implants, and prosthetic components.

On the other side, anatomical limitations, such as short distance in the interforaminal region and anteriorly positioned mental foramen, which constitutes long distal cantilevers, may imperil the stable environment around the tilted implants. Moreover, the assumption that reducing the cantilever length by using tilted posterior implants improves stress transmission is debatable. Mandibular flexure as well as occlusal forces on distal cantilevers cause excessive bending moments over the implants, resulting in higher peri-implant bone stress. This hinging effect caused by load application on the cantilever may increase stress on the closest implant. Although tilting the posterior implant reduces the posterior cantilever length, and thereby seems to decrease stress transmission in the atrophic jaw, it may cause higher stresses in the peri-implant bone due to the direction of the chewing forces as well as the aforementioned drawbacks.

The implant neck has a close relation to the implant-abutment and abutment-framework connections. Therefore, higher stresses are possibly observed around the neck of the implant, even though the connections are designed to be rigid in most FEA studies. In corroboration with previous reports, the images of this study revealed that maximum stress values were concentrated at the neck area of the implants and at the cortical bone of the tilted implants in all models. The cantilever extension, which was reported to have deleterious effects on both the implant and the surrounding structures, may be responsible for the higher peri-implant bone stresses around the tilted implants in this study. Accordingly, elimination of the cantilever extension in models III and IV involving short implants may be considered to have a primary role in decreasing the overall stress. With regard to this, using short implants may contribute to the long-term success of both the prosthesis and implants in the posteriorly atrophic mandible if rehabilitation with the long distal cantilever prosthesis is inevitable.

Several biomechanical factors, such as bone quality at the insertion area, implant type, occlusal conditions, and length and diameter of the implants, are known to have an influence on stress transmission from the implant to the bone. It is well-known that increasing the length and/or the diameter of the implants is essential in reducing the stress transmission. Shortening the length of the implants exhibits higher stress values in the bone as well as implant components due to the limited distance for the load distribution and increased crown height resulting from the excessive interocclusal distance. On the other hand, it was reported that splitting the implants located in the arch reduces the stresses of the bone and implants. This method enables better load distribution on the components and helps avoid loss of bone, and thus, may positively affect the prognosis of the rehabilitation. Many reports showed higher stresses around short implants when used in nonsplinted models. The results of the present study show that stress reduction in the models with short implants may support the favorable effects of splinting on load distribution.

In the present study, short implants exhibited lower stress values compared with the vertical or tilted implants in models II and III despite functioning at the most affected site during simulations. Furthermore, short implants demonstrated greater stress reduction at the level of the most distal implant, compared to model IV, including six vertical implants 10 mm in length. Previous studies showed that the diameter, length, tapers, fillet ends, and design of implants could essentially affect equivalent stress. Also, implant design can modify the applied forces acting on the bone. Despite short implants seeming to have biomechanical disadvantages, it may be implied that the extended contact area of the occlusal part of the short implants used in this study contributed to the reduction of stress values.

Considering the ultimate bone strength as a physiologic limit, as the minimum compressive principal stress exceeds 170 to 190 MPa in compression, and the maximum tensile principal stress exceeds 100 to 130 MPa in tension, local overloading occurs at the level of compact bone. In the models, all stress values were found under the limits of ultimate bone strength, and there were no major differences in terms of the magnitude and distribution of the stress transmitted to the bone-implant interface. This is in approximate agreement with the findings of reported studies. It might be inferred that all models can be applied to clinical practice.

It is commonly known that accumulated microdamage may lead to bone resorption, even if the stress...
values are below the estimated limits. FEA studies have reported that a tilted implant generated higher compressive stress in the surrounding bone compared with the stress transmission of bone around a single vertical implant. Although splinting the tilted implants provides better stress distribution, microdamage in the bone and the materials due to the bending forces may cause detrimental effects on the surrounding bone as well as other components in the long-term follow-up. On the basis of this 3D FEA study and prior knowledge, it may be suggested that the combination of short and vertical implants provides favorable results by avoiding cantilever extension in the posteriorly atrophic mandible.

Data from this study may contribute to a valuable basis for the rehabilitation of the posteriorly atrophic mandible. It may also provide a better understanding of the biomechanical behavior of implant designs and treatment modalities. Configurations of the implants, variabilities in the macrostructure, and designs would play a decisive role in the long-term success. The results obtained from this study can also be influenced by other clinical demands, material properties used for the rehabilitation of atrophic arches, and treatment planning, which were not entirely investigated in the present study. Even so, it seems that the use of short implants in the tilted implant concept as a posterior support may offer promising results in the future.

Further in vivo experiments and clinical studies are needed to demonstrate the prognosis of the implant configurations and designs in certain clinical conditions.

CONCLUSIONS

Based on the results from this study, posteriorly placed short implants may contribute to the stress reduction on both implants and surrounding bone by avoiding cantilever extension. Furthermore, the use of short implants in the posteriorly atrophic mandible combined with vertical and/or tilted implants may be beneficial to reduce cortical bone resorption, if adequate bone height is present for the placement of a short implant.

ACKNOWLEDGMENTS

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REFERENCES


