Finite Element Analysis of the Influence of Implant Inclination on Stress Distribution in Mandibular Overdentures

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The purpose of this finite element study was to evaluate the influence of implant inclination on the stress pattern in the bone surrounding the implants that support mandibular overdentures. The models used in this study were 3-implant-supported mandibular overdentures with a bar-and-clip attachment system. Each model was modified according to the distal implant inclination (0 and 20°). A unilateral vertical load was applied unilaterally to the first molar and first premolar of the overdenture, and the stress distribution in the bone was analyzed. Implant inclination decreased the stress distribution pattern in bone surrounding the implants when the load was applied on the molar site, but when applied at the premolar site, similar stress value changes were not found. Within the limitation of this study, it seems that the inclination of splinted implants in mandibular overdentures does not have any adverse effect on stress distribution pattern values around the implant.

Key Words: inclined implant, cantilever, overdenture, stress, finite element analysis

INTRODUCTION

Various treatment modalities have been used for retaining and stabilizing dentures on edentulous mandibular ridges.[1,2] The mandibular implant-supported overdenture is one of the most effective treatments for edentulous patients.[3–6] Mandibular overdentures are usually supported by 2 to 5 implants between the mental foramina with soft tissue support in the posterior areas.[7,8] It has been concluded that the stress distribution pattern is more uniform when the load is inserted over an increasing number of implants.[9–11] In the presence of implants with less than 8 mm length, narrow implant diameter (3.3 mm), opposing dentate maxilla, superficial mental foramina, sensitive mucosa, V-shaped anterior ridges, sharp mylohyoid ridges, or high muscle attachments.[12–15]

Using 2 or 3 implants can be useful for retaining and stabilizing dentures and has economic benefits to the patient.[8,16] Placement of more than 2 implants in the interforaminal area may create a greater implant-to-bone contact area that allows for better stress distribution and minimizes crestal bone loss.[7] Also, inserting more than 2 implants in this region can create an angular relationship between the implants instead of a straight-line relationship.[8] Inserting 3 implants and splinting them with a connecting bar is more congruent with the ridge shape. Three anterior implants that are splinted with a bar permit the center implant to act as an indirect retainer of the prosthesis.[8,12,17] Additionally, the risk of abutment screw loosening and the implant reaction force is reduced.

Due to the effects of long-term edentulism, implant placement may be limited by alveolar process resorption. Different methodologies have been described to manage deficient mandibular bone anatomy. The use of inclined implants to avoid the mandibular nerve has been proposed.[1,18] Watanabe et al.[19] observed in a 2-dimensional finite element (FE) study using a single implant that, regardless of the location and direction of loading, compressive stress at the bone-implant interface increases with increasing implant inclination. Comparable results were found in similar studies investigating nonsplinted implants.[20,21] However, it has been observed clinically that for splinted implants, inclination does not have a negative effect on stress distribution in bone. Interestingly, it has been concluded that tilting of implants allows for better prosthetic support due to larger interimplant distances.[1,19,22,23] Finite element analysis (FEA) has been widely used to investigate the stress and strain distribution at the peri-implant bone interface in edentulous jaws.[4,24,25] Despite limitations of this theoretical method, FEA is acceptable in stress distribution analysis in complicated structures such as human alveolar bone.

However, there is no detailed, definitive study comparing stress distribution around inclined versus straight implants in

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overdentures with 3 supporting implants. The aim of this finite element study was to evaluate the influence of implant inclination on stress distribution in the bone surrounding the implants supporting mandibular overdentures.

Materials and Methods

In this in vitro study, the experimental design of a simulated 3-implant-retained overdenture model was fabricated. For this purpose, an acrylic model of an edentulous mandible was fabricated with clear acrylic resin (Meliodent Multicryl, Heraeus-kulzer GmbH, Wehrheim, Germany). The configuration of the bone was duplicated from an edentulous mandibular skeleton. Three screw types (Biohorizons Internal, BioHorizons Implant Systems Inc, Birmingham, Ala), 4 × 10.5 mm with 4.5-mm-diameter abutment platform were embedded in the interforaminal region of the acrylic model using a surveyor (Ney Surveyor, Dentsply Intl, York, Pa). In this model, the implants were vertically oriented, perpendicular to the occlusal plane and parallel to each other. The crestal bone position of the implants was on the top of the ridge. The interimplant distance among 3 implants was 12 mm. One implant was placed in the midline of the arch, and the others were placed approximately in the canine regions. Custom cast abutments (4.5, PGCAH, BioHorizons Implant Systems Inc) were placed on each implant. A connecting bar (Egg-shaped Dolder bar-Micro, Straumann, Basel, Switzerland) was fabricated from a base metal alloy (Biosil-F; Degudent GmbH, Hanau, Germany), and passive fit was confirmed by tightening one screw and observing complete seating at the other two implant-abutment interfaces. The connecting bar was parallel to the plane of occlusion and aligned perpendicularly to the line bisecting the angle between the posterior edentulous ridges to allow rotation of the prosthesis.[26] The connecting bar was attached to the abutments using a torque wrench (TW20, Zimmer Dental, Carlsbad, Calif) and a hex tool (TW1.25, Zimmer Dental), applying 20 Ncm torque.

A complete overdenture containing 3 clip attachments was fabricated on this bar attachment model by conventional dental laboratory techniques. The plastic model, acrylic denture, implants, and the bar-and-clip attachments were used for computerized reproduction. To decrease analytical problems, the implants were considered as flat cylinders. The 3-dimensional (3D) geometry of the whole system was scanned and digitized using ATOS II (Triple Scan) scanning technology (GOM mbH, Braunschweig, Germany) and ATOS Viewer (Version v6.3.0) software (GOM). The resultant dense point cloud was transferred to CATIA modeling software (BM, Kingstone, NY). The mucosa and cortical bone were reproduced as 2 mm and 2.5 mm layers, respectively (Figure 1). The implant-bone interface was assumed to be completely bonded (fully osseointegrated condition) without any craterlike defects. In the first computerized situation (Model 1), the implants were placed similarly to the plastic model. In the second model (Model 2), the middle implant was vertical but the two other implants were 20° divergent from the midline, maintaining 12 mm interimplant distance. The crestal bone position of the implants was on the top of the ridge. All materials were assumed linear, elastic, and isotropic; their properties were taken from the literature (Table 1).[22,27–30]

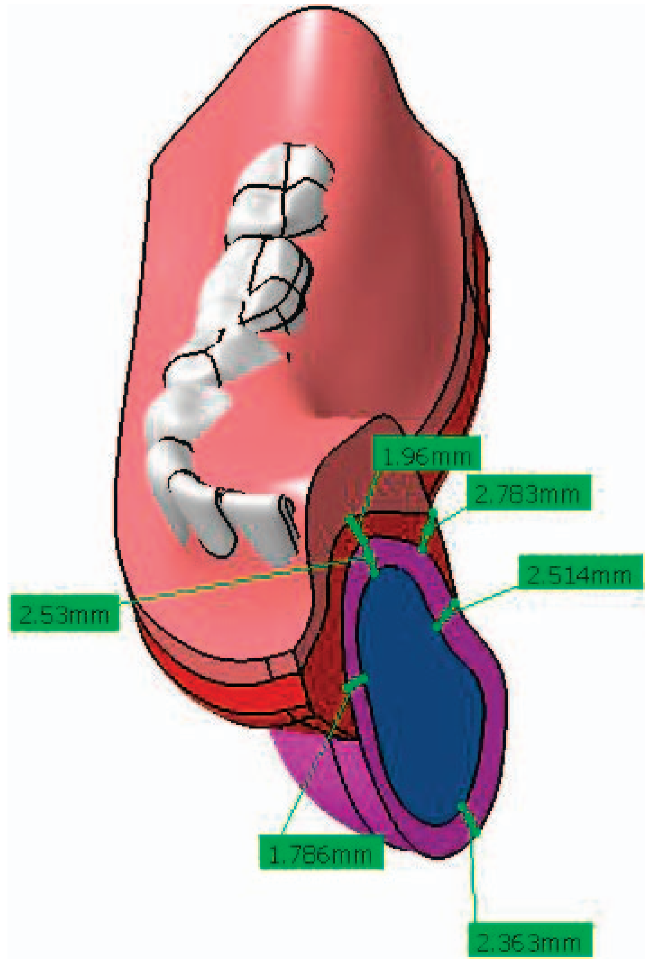


Figure 1. Three-dimensional model of mandible plus overdenture.

Stress analysis was performed using the FE software ABAQUS v6.9 (ABAQUS Inc, Providence, RI). In all situations (Model 1 and Model 2), an arbitrary 15-pound vertical and unilateral load representing the masticatory force was applied to the distal occlusal fossa of the first premolar of the prosthesis. Furthermore, vertical loads of 15 and 30 pounds were applied unilaterally to the central fossa of the first molar. Stress distribution was assessed around the implants and the edentulous ridge according to implant inclinations.

A feature of the FEA is that the reference plane for

Table 1

Table of material properties

Materials	Elastic Modulus (Pascal)	Poisson's Ratio
Cortical bone[22]	1.37×10^{10}	.30
Cancellous bone[22,27]	1.37×10^{9}	.30
Mucosa[28]	1.0×10^{7}	.40
Acrylic resin[27,29]	2.7×10^{9}	.35
Titanium[22,29]	1.17×10^{11}	.33
Gold[30]	1.0×10^{11}	.3

TABLE 2

The numbers of elements and nodes in two study models

Modeling Situations	Study Model	
	Elements	Nodes
Vertically implants (Model 1)	232 918	63 132
Inclined distal implants (Model 2)	293 604	72 669

deformation must be defined to remove possible rigid body motion; therefore, a loading boundary condition was considered at the distal end of the bone (beneath the model) in the range of 30 mm (near joining area of masseter and internal pterygoid muscles).[31–33] Table 2 represents numbers of elements and nodes in two study models. The analysis was performed on a computer with Windows XP; AMD-Athlone 64 Processor 3200+; CPU: 2.00 GHz; RAM: 2GB.

Results

Stress distribution for 15-pound force in premolar region (Figures 2 and 3)

Stress analysis revealed that in Model 1, the stress distribution pattern around the middle implant was different from those in other regions. Stress distribution patterns in other regions were similar, and the highest value was seen in the distal bone adjacent to the ipsilateral implant. However, the widths of higher stress areas in Model 2 were smaller than in Model 1. The highest stress in the posterior edentulous ridge was observed in the premolar area, and by moving to more distal regions, the resultant stress was decreased. The stress values are shown in Table 3.

Stress distribution for 15-pound force in molar region (Figures 4 and 5)

The stress distribution pattern in the molar region was different from that in the premolar region. The highest stress was seen in the bone surrounding the contralateral implant. In Model 1, the stress distribution pattern at the contralateral implant was clearly different from those in other regions, where the stress distribution patterns were nearly similar to each other. In Model 2, the stress distribution pattern in the bone surrounding the contralateral implant became more uniform, but it was still higher than in other regions. The highest stress in the posterior edentulous ridge was observed in the molar area. Stress values are shown in Table 3.

Stress distribution for 30-pound force in molar region (Figures 6 and 7)

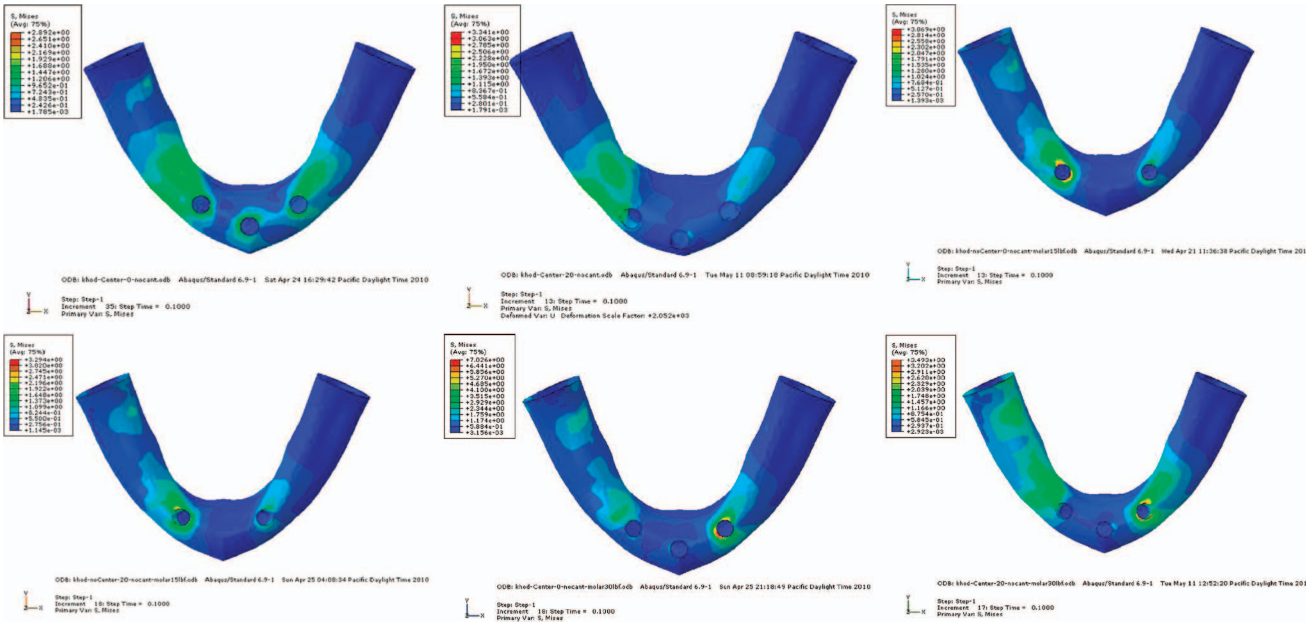
This stress distribution pattern was similar to the one observed when the 15-pound force was used in the molar region. The highest stress value was observed in the bone surrounding the contralateral implant. In Model 1, the stress distribution pattern in the bone surrounding the contralateral implant was clearly higher than in other regions, where the patterns were nearly similar to each other. In Model 2, stress distribution pattern in the bone surrounding the contralateral implant became more uniform, but it was still higher than in other regions. In the posterior edentulous ridge, the highest stress was observed in the distal side of the ipsilateral implant and the force application site. Stress values are shown in Table 3.

Discussion

The predisposing stress pattern around implants supporting overdentures is considered to be more complicated than in fixed prostheses. Furthermore, with the increasing resiliency of mucosa and movement of the prosthesis, this problem becomes more sophisticated. In the present study, the load levels (15 and 30 pounds) were selected because they were within the range of normal occlusal mastication force and near the maximum load measured in implant overdenture patients.[8,11,14] The first molar was chosen because maximum bite forces are often exerted in the region where there is maximum contraction of all elevator muscles. Additionally, the first premolar was chosen for a more anterior load application because food is predominantly masticated between the premolars and molars.[14,34] These forces were applied unilaterally because in some studies, there was no difference in the stress pattern produced by loading on either the right or left side of the arch.[8,21] Furthermore, it has been shown that in unilateral loading, little or no discernible stress was transferred to the nonloaded side of the arch,[8,14,21,34] This explains the reason for not choosing the contralateral posterior edentulous ridge as a location for stress measurement. Furthermore, a spacer was used and, thus, prosthesis movement was considered as a type-3 prosthesis movement with an apical and hinge motion.[7] With the application of a 15-pound load at the premolar distal fossa of the model with inclined implants (Model 2), the induced stresses in the bone around the ipsilateral and the middle implants were increased, and the stresses in the bone around the contralateral implant and the edentulous ridge were decreased.

With 15- and 30-pound loading at the central fossa of the first molar in the Model 2, the resultant stresses were decreased in the bone around all 3 implants and in the residual edentulous ridges.

In most studies, the amount of stress was increased with the increasing degree of inclination of implants; however, the implants were not splinted, and therefore were subject to a more pronounced rotating momentum.[19,21,35] However, if an implant is a part of a multiple implant-supported superstructure, the spread of the implants and stiffness of the superstructure will reduce the resultant stress.[1,19,22–24,35–37] Zampelis et al[22] concluded that this is due to the fact that stress distribution in the bone follows the same pattern, regardless of the inclination angle. Even in a study by Jofre et al[36] splinted mini-implants supporting a mandibular overdenture showed less marginal bone loss compared with non-splinted mini-implants. Celik et al[8] compared load transfer characteristics of four different attachment systems for a 3-implant retained mandibular overdenture involving vertically oriented and inclined implants (0 and 20°). In Celik's study for the inclined implant scenario, moderate stresses were noted for nonsplinted designs, and low stresses were observed for splinted designs on the loaded side implant. In this current study, loading in the



FIGURES 2–7. FIGURE 2. Pattern of stress distribution in vertical implants by loading 15 pounds force in premolar region. **FIGURE 3.** Pattern of stress distribution in inclined implants by loading 15 pounds force in premolar region. **FIGURE 4.** Pattern of stress distribution in vertical implants by loading 15 pounds force in molar region. **FIGURE 5.** Pattern of stress distribution in inclined implants by loading 15 pounds force in molar region. **FIGURE 6.** Pattern of stress distribution in vertical implants by loading 30 pounds force in molar region. **FIGURE 7.** Pattern of stress distribution in inclined implants by loading 30 pounds force in molar region.

molar region decreased the resultant stress in the bone around implants, but loading in the premolar region did not alter the stress distribution pattern in the surrounding bone. According to these findings, it can be concluded that posterior loading, even in the presence of inclined implants, does not increase the resultant stress in the bone surrounding implants. In some studies, it is stated that more posteriorly applied loads resulted in increased stress transfer to the edentulous ridge by the denture base while simultaneously reducing the load to the ipsilateral implant.[8,21] Although by loading the vertically oriented implants in the premolar region, the resultant stresses in the contralateral and the middle implants were unusually increased in comparison to the Model 2.

The present study is in disagreement with some other studies about the location of the highest resultant stress in the case of molar region loading. In those studies, simulated occlusal force in the molar region generated the highest stresses to the contralateral implant with decreased load transfer to the adjacent implant regardless of the anchorage design.[8,11,14,20,34] It should be noted that the present study is different from other investigations in terms of implant numbers, connector design, and the presence of a resilient mucosa beneath the overdenture. One of the other possible explanations for this finding is the different rotational movement in the 3-implant-retained mandibular overdenture design in this study as compared with other investigations. This may be due to premature contact between the acrylic denture base with the contralateral implant. This demonstrated that the precise relief of the acrylic denture base around the overdenture abutments can be an important issue, especially when more resilient clips are used for the bar attachment.

Surprisingly, little or no noticeable stress was noted on the

TABLE 3

Stress values (MPa) in this study

Force	Modeling Situations	Bone Around Ipsilateral Implant	Bone Around Middle Implant	Bone Around Contralateral Implant	Posterior Edentulous Ridge in Ipsilateral Side
15 pounds premolar	Model 1*	1.816	1.864	1.869	8.669×10^{-1}
	Model 2†	2.246	8.541×10^{-1}	8.933×10^{-1}	3.836×10^{-1}
15 pounds molar	Model 1	1.232	5.956×10^{-1}	4.223	1.353
	Model 2	7.703×10^{-1}	2.662×10^{-1}	1.117	7.579×10^{-1}
30 pounds molar	Model 1	2.497	1.399	7.026	2.322
	Model 2	1.563	9.439×10^{-1}	3.493	1.508

*Model 1: Model with the vertical implant arrangement.
†Model 2: Model with distal inclined implants.

middle implant in our study. This implant received lower stress than the residual ridge. It can be concluded that in terms of stress distribution, it is not necessary to use more than 2 implants for supporting mandibular overdentures. This is in agreement with some other studies that concluded there seems to be no need to insert more than 2 endosteal implants to support an overdenture.[9,10] However, it has been said that with inserting 3 implants and splinting them with a connecting bar, the anterior implant acts as an indirect retainer for the prosthesis.[8,12,17] Additionally, the risk of screw loosening is reduced with a third implant, and the resultant greater surface area of implant to bone allows better distribution of forces and, therefore, minimizes the loss of crestal bone.[7]

In the present study, by posterior shifting of the loading point, the resultant stresses at the ipsilateral and the middle implants were decreased, but the generated stress in the contralateral implant and the residual ridge were increased. These findings are in agreement with Federick et al[21] only in the matter of exerting stress on the residual ridge.

In the present study, with increasing load value in the molar region (15 to 30 pounds), the resultant stress was increased but with the same pattern. In the reports by Tashkandi et al[38] and Kennedy et al,[39] the pattern of strain did not change when the load was increased. It can be assumed, therefore, that as load is increased, the strains transferred to the implant and bone will increase.

The finite element studies are theoretical in nature and have some limitations when predicting the response of the biological tissues to applied loads;[22,40] therefore, we cannot make reliable clinical conclusions based on these studies. It is important to know that peri-implant tissues are complex and their simulation in FEA is approximate.[22] However, the aim of such studies is not to report absolute values of stress but to compare stress concentration areas.

In the current study, it was assumed that the bone-implant interface was completely adhered. This assumption may not reflect the actual clinical situation[26] because of possible osseo-integration defects at the per-implant region.[25,41]

Another limitation of this study was modeling the implants as flat cylinders and assuming the threads as a negligible factor in the stress analysis. It has been noted in previous studies that this assumption results in an underestimation of stress patterns in bone.[1,42] Additionally, the connecting screws at the implant-abutment interface were not modeled, although some authors have shown that modeling the screw is not necessary.[22]

Conclusions

Within the limitations of this in vitro study, the following conclusions can be drawn:

1. When applying force on the molar region, using inclined implants for 3-implant-supported overdentures leads to decreased stress in the bone surrounding the implants and the edentulous ridge.
2. When applying force to the premolar region, the highest stress was observed in the ipsilateral inclined implant, but in Model 1, there was no difference between stress values in the ipsilateral and the contralateral implants. However, by applying force to the molar region, the highest stress was seen in the contralateral implant.
3. When applying force (especially to the molar region), little or no noticeable stress was observed around the middle implant.
4. With increasing load value in the molar region (15 to 30 pounds), the resultant stress was increased, but with the same pattern.

Abbreviations

3D: three dimensional
FE: finite element
FEA: finite element analysis

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