

Impact of Dental and Zygomatic Implants on Stress Distribution in Maxillary Defects: A 3-Dimensional Finite Element Analysis Study

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The aim of this study was to evaluate the stress distribution in the bone around dental and zygomatic implants for 4 different implant-supported obturator prostheses designs in a unilaterally maxillary defect using a 3-dimensional finite element stress analysis. A 3-dimensional finite element model of the human unilateral maxillary defect was constructed. Four different implant-supported obturator prostheses were modeled; model 1 with 2 zygomatic implants and 1 dental implant, model 2 with 2 zygomatic implants and 2 dental implants, model 3 with 2 zygomatic implants and 3 dental implants, and model 4 with 1 zygomatic implant and 3 dental implants. Bar attachments were used as superstructure. A 150-N vertical load was applied in 3 different ways, and von Mises stresses in the cortical bone around implants were evaluated. When the models (model 1–3) were compared in terms of number of implants, all of the models showed similar highest stress values under the first loading condition, and these values were less than under model 4 conditions. The highest stress values of models 1–4 under the first loading condition were 8.56, 8.59, 8.32, and 11.55 Mpa, respectively. The same trend was also observed under the other loading conditions. It may be concluded that the use of a zygomatic implant on the nondefective side decreased the highest stress values, and increasing the number of dental implants between the most distal and most mesial implants on the nondefective side did not decrease the highest stress values.

Key Words: dental implant, zygomatic implant, obturator, prosthesis, finite element analysis

INTRODUCTION

In dentate maxillary defects, achievement of retention and optimum stability of obturator prosthesis by conventional techniques is very difficult.^{1–7} The advent of osseointegration and the combination of implants and prosthetic obturators has provided significant benefit, especially in the rehabilitation of edentulous maxillectomy

patients.⁵ Endosteal implants can enhance patients' use of the prostheses and can markedly improve the quality of life of edentulous patients after maxillectomy.² Because a limited amount of maxillary bone remains following maxillectomy, implant placement for anchoring a prosthesis usually involves more remote sites, such as the zygomatic bone.^{2,4,5} The zygomatic implants were first introduced to dentistry for reconstruction of the atrophic edentulous maxilla^{1–3,7} and are now being used for establishing retention and support for a maxillary prosthesis after maxillectomy.^{1,2} Schmidt et al¹ found that the combination of zygomatic and standard endosseous implants can be used for retaining and support of maxillary obturator prostheses after extensive resec-

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tion of the maxilla. With the advent of predictable implant support and retention, the implant-supported obturator prosthesis procedures and designs have become an effective treatment modality.^{1,2,5} But it is known that the design of the dental superstructures has significant influences on the loading of dental implants and the deformation of the bone.⁸ This deformation may cause excessive stress concentration in the bone around the implants and may lead to bone resorption and, ultimately, failure of the implant.⁸⁻¹¹

In the past 2 decades, finite element analysis (FEA) has been used extensively for the quantitative evaluation of stresses on the implant and its surrounding bone.^{8,12,13} As the available evidence and information on the basic theory, methodology, application, and limitations of FEA in implant dentistry are accumulating, clinicians are in a better position to use FEA study results and extrapolate these results to clinical situations in advance.^{8,12,13}

However, biomechanical stresses in supporting bone around dental and zygomatic implants under obturator prosthesis in maxillary defects have not been thoroughly investigated, and the literature in this area is scant. Recent studies focused either on zygomatic implants or on obturator prosthesis separately.^{7,14,15} Using the 3-dimensional (3D) finite element method, Ujigawa et al⁷ have compared the zygomatic implants with or without connected implants supporting the superstructures. Ying et al¹⁵ established a modularized finite element model of a normal human skull for biomechanical evaluation of unilateral maxillary defect restoration. In addition, Jian et al¹⁴ described a 3D finite element model for human unilateral maxillary defect along with the remaining teeth from the central incisor to the second premolar on one side and compared the stress distribution of the traditional obturator and resin-bonded extracoronary obturator attachment. There are also other studies analyzing the stress distribution of implant-supported overdentures.^{9,16-22}

Universally, in implant treatment, economical factors often play a critical role. It is important to be able to justify how many implants should be used for retention or support of an overdenture in each individual case. In recent years, despite implant-supported overdenture prostheses being preferred for the treatment of total edentulous patients,^{17-21,23,24} there is a lack of consensus on the optimum number of implants that can provide

adequate support. The aim of this study was to evaluate, by using 3D finite element stress analysis, the effect of number of implants and zygomatic implant usage on stress distribution in the bone around implants in dentate unilaterally maxillectomy patients. We used a digital biomechanical model of a unilaterally maxillary defected patient skull, which was constructed using computerized tomography (CT) data. Typical occlusal loads were simulated, and stresses in the bone around implants were examined.

MATERIALS AND METHODS

Construction of 3D finite element model

A CT image with 0- to 3-mm serial axial sections on a unilateral maxillary defected dentate patient were used to obtain an accurate geometry of the prosthesis, maxilla, and zygomatic bone. Three-dimensional data of the maxilla and zygomatic bone were obtained from CT (ILUMA CBCT, Imtec Imaging, Ardmore, Okla), which were transferred into 3D-Doctor software (Able Software Corporation, Lexington, Mass) and Rhinoceros software (McNeel, Seattle, Wash) to generate a 3D finite element model of the maxilla and zygomatic bone.

The 3D finite element model of dental and zygomatic implants, superstructures, and obturator prosthesis was constructed from digitized surface data using NextEngine (Santa Monica, Calif). The data were then transferred into the 2 software packages, namely, 3D-Doctor and Rhinoceros.

The 3D model that was created from 3D-Doctor and Rhinoceros was then transferred to Fempro software (Algor, Pittsburgh, Pa) with a scene export format .stl file to allow the necessary refinements and to constitute the final finite element mesh model. The finite element models considered in this study are constituted of mucosa, compact bone, trabecular bone, zygomatic implant, and multi-unit abutments (Branemark System, Nobel Biocare AB, Goteborg, Sweden), standard dental implant and multi-unit abutments (Institute Straumann, Waldenberg, Switzerland), bar attachment system (Institute Straumann, Waldenberg, Switzerland), and obturator prosthesis. Cortical bone with 1.5-mm thickness was uniformly defined around the trabecular core body. Mucosa was assumed to be 1.5-mm thickness. Standard dental implants with a diameter of 4.1 mm and a length of 10 mm, zygomatic implants with a

diameter of 4 mm and length of 35 mm, titanium U-shaped dolder bar with a height of 3 mm, and titanium dolder bar matrix with a height of 4.5 mm were modeled in all models generated.

The zygomatic and dental implants were oriented to the defective maxilla in 4 different configurations. The 3D finite element model of 4 different types of obturator prostheses was established according to these designs. Four different configuration models were as follows.

Model 1

This design included placement of 2 zygomatic implants—1 on each side of the maxilla—in combination with 1 anteriorly placed dental implant and completion of the restoration with the fabrication of a rigid bar connecting the 2 zygomatic implants to the anterior implant (2 ZI and 1 DI; Figure 1).

Model 2

This design included placement of 2 zygomatic implants—1 on each side of the maxilla—in combination with 2 dental implants and completion of the restoration with the fabrication of a rigid bar connecting the 2 zygomatic implants to the 2 dental implants (2 ZI and 2 DI; Figure 2).

Model 3

This design included placement of 2 zygomatic implants—1 on each side of the maxilla—in combination with 3 dental implants and completion of the restoration with the fabrication of a rigid bar connecting the 2 zygomatic implants to the 3 dental implants (2 ZI and 3 DI; Figure 3).

Model 4

This design included placement of 1 zygomatic implant on the defective side of the maxilla in combination with 3 dental implants that were placed on the nondefective side and completion of the restoration with the fabrication of a rigid bar connecting the zygomatic implants to the 3 dental implants (1 ZI and 3 DI; Figure 4). Bone-implant interfaces were assumed as perfect bonding surfaces for all models (ie, osseointegrated implants). The geometry was later meshed using the Fempro software package. After meshing, the first model consisted of 43.331 nodes and 156.979 elements, the second model consisted of 45.033 nodes and

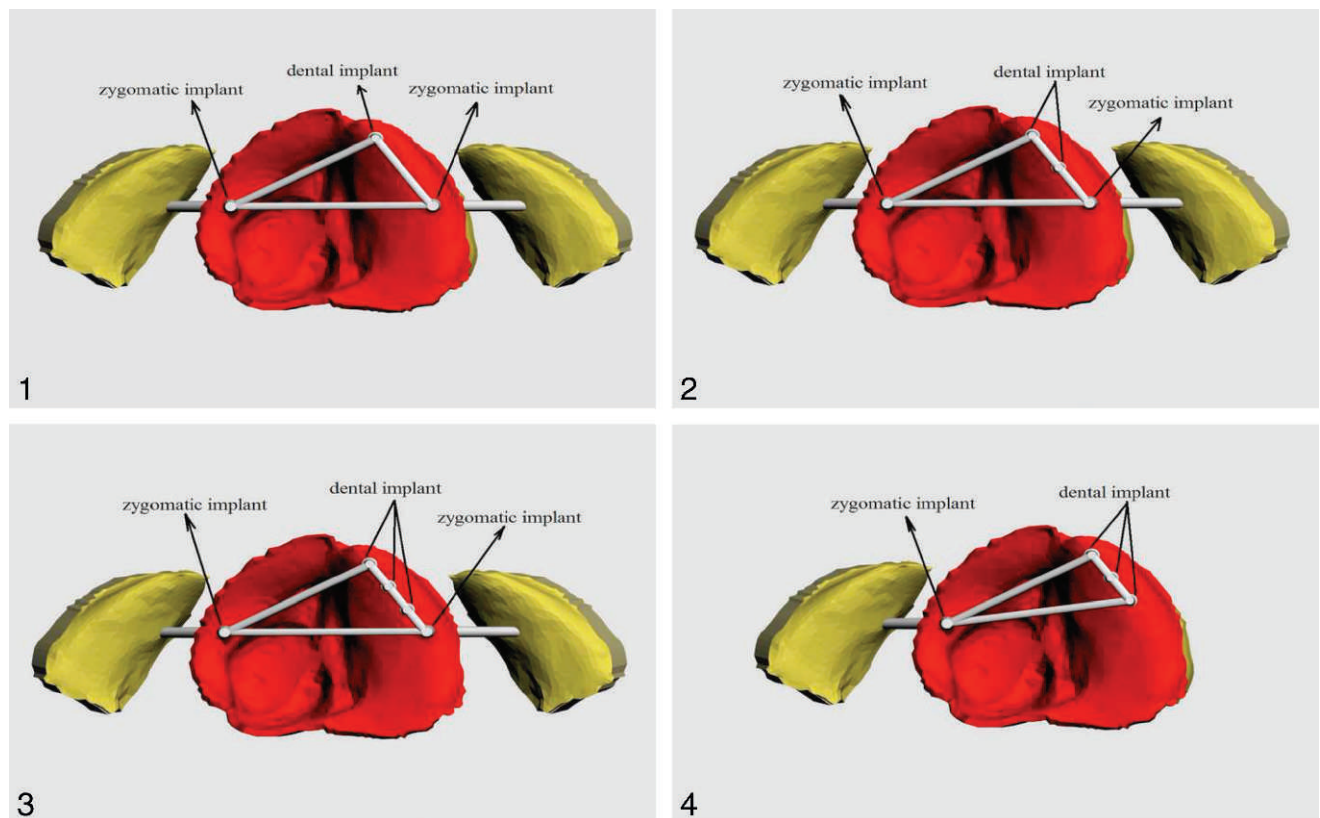
Material	Elastic Modulus (ϵ) (Gpa)	Poisson's Ratio (ν)
Cortical bone	13.7	0.3
Trabecular bone	1.37	0.3
Mucosa	0.001	0.04
Pure titanium	117	0.3
Ti6Al4V	110	0.33
Resin	2.7	0.35

164.431 elements, the third model consisted of 47.056 nodes and 172.233 elements, and the fourth model consisted of 39.951 nodes and 142.899 elements.

Because of an absence of information about the precise organic properties of the mucosa, cortical, and trabecular bone, they were assumed to be isotropic, homogeneous, and linearly elastic. The implants used in this study were modeled as a titanium alloy (Ti6Al4V). Multiunit abutments and bar attachments were assumed to be made of pure titanium, and the obturator prosthesis was modeled with a resin. The mechanical properties of the components of the models were taken from previous studies.^{7,8,11-13} The elastic modulus and Poisson's ratios of the materials used in the analysis are listed in Table 1.

Loading

The nondefective side of the maxilla and zygomatic bone on that side and zygomatic bone of the nondefective side of the maxilla were designed as fixed in all directions to skull with zero displacement. It was assumed that the prosthesis and maxilla would have perfect bonding. To simulate a clinical situation, loading consisted of a simulating bite force of 150 N applied as a distributed vertical load to the occlusal surfaces of the artificial teeth of the prosthesis. The whole vertical load on all of the artificial teeth was 150 N. This load was distributed to 15 points, with each point consisting of 10-N forces. Four points vertical load were applied to premolars, and 7 points vertical load were applied to first molar. The load was distributed as 40 N on every premolar tooth and 70 N on the first molar. No load was applied to the second molar tooth. A 150-N vertical force was applied in 3 different ways: first, loading was applied to the defective side; second, to the nondefective side; and third, loading



FIGURES 1–4. **FIGURE 1.** Finite element model of the configuration 1 (model 1): 2 zygomatic implants connected to one dental implant by a rigid bar. **FIGURE 2.** Finite element model of the configuration 2 (model 2): 2 zygomatic implants connected to the 2 dental implants by a rigid bar. **FIGURE 3.** Finite element model of the configuration 3 (model 3): 2 zygomatic implants connected to the 3 dental implants by a rigid bar. **FIGURE 4.** Finite element model of the configuration 4 (model 4): 1 zygomatic implant in the defective side connected to the 3 dental implants by a rigid bar.

was applied simultaneously to both sides (Figure 5). Both loading and boundary conditions of the finite element models are shown in Figure 5. Von Mises stresses in the cortical bone around implants were then evaluated. The analysis process was performed using Fempro Technologies.

RESULTS

The highest von Mises stress values in the cortical bone for all models for all loading conditions are shown in Table 2.

Outcome of model 1

Von Mises stress values model 1 (2 ZI and 1 DI) are shown in Figure 6 for the defective side (a), nondefective side (b), and both side (c) loading conditions, respectively. In the case of model 1, the highest von Mises stresses value (8.56 Mpa) was determined in the first loading condition. This

highest stress was recorded at the mesial surface of the cortical bone around the zygomatic implant on the defective side and was higher than caused by the second and third loading conditions. The highest stress values resulted from the second and the third loading conditions and were 4.38 and 7.79 Mpa, respectively (Table 2).

Outcome of model 2

von Mises stress values in model 2 (2 ZI and 1 DI) are shown in Figure 7 for the defective side (a), nondefective side (b), and both side (c) loading conditions, respectively. In the case of model 2, the highest von Mises stress value (8.59 Mpa) was determined in the first loading condition. This highest stress was recorded at the mesial surface of the cortical bone around the zygomatic implant on the defective side and was higher than that caused by the second and third loading conditions. The highest stress values that were caused by the

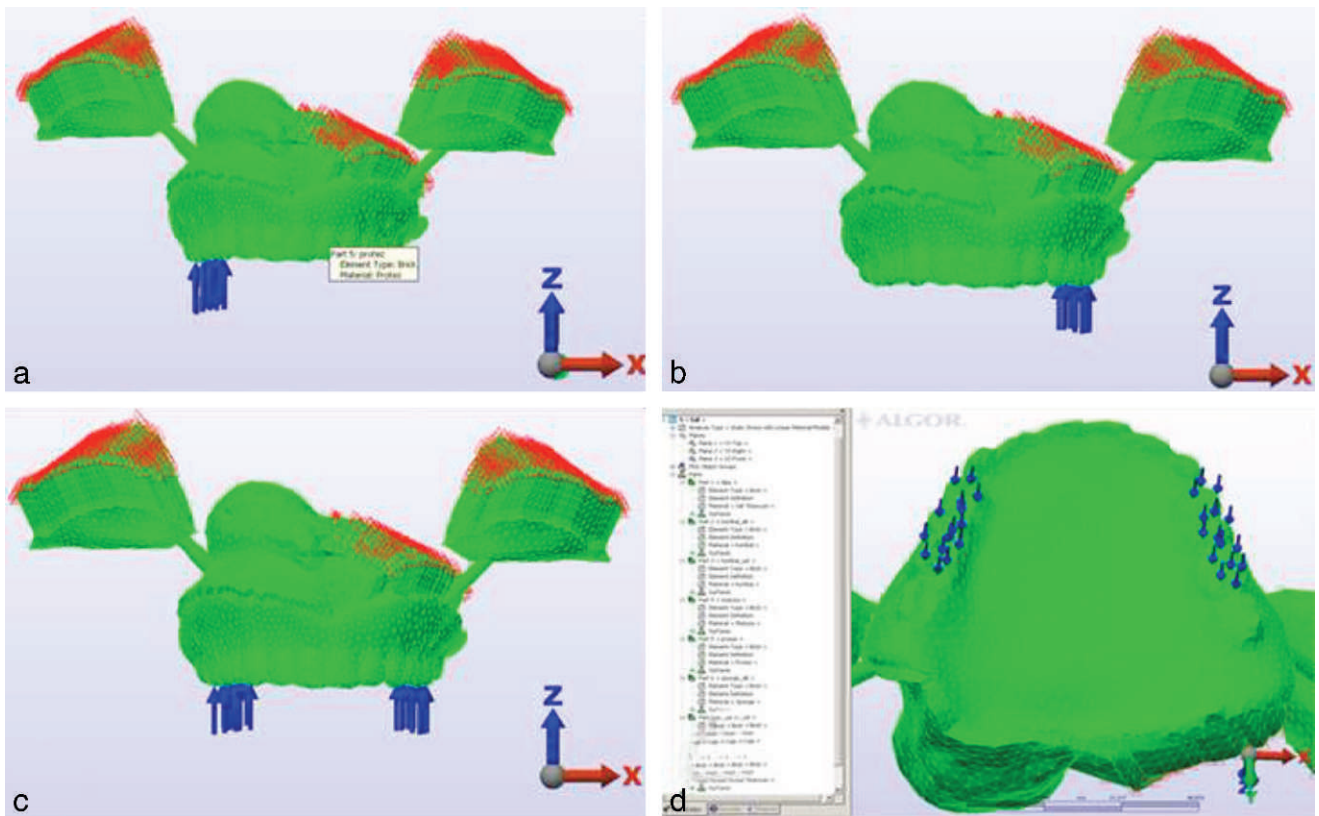


FIGURE 5. Appearance of the loading and boundary conditions. (a) Frontal view of the first loading, (b) frontal view of the second loading, (c) frontal view of the third loading, and (d) occlusal view of the third loading.

second and third loading conditions were 3.61 and 8.33 Mpa, respectively (Table 2).

Outcome of model 3

von Mises stress values in model 3 (2 ZI and 3 DI) are shown in Figure 8 for the defective side (a), nondefective side (b), and both side (c) loading conditions, respectively. In the first loading condition, the highest von Mises stress value (8.32 Mpa) was the same as that was caused by the third loading condition. In both the first and third loading condition, the highest stress value was recorded at the mesial surface of the cortical bone around the zygomatic implant on the defective side, and this was higher than that caused by the second loading condition. The highest stress value caused by the second loading condition was 4.91 Mpa (Table 2).

Outcome of model 4

von Mises stress values in model 4 (1 ZI and 3 DI) are shown in Figure 9 for the defective side (a), nondefective side (b), and both side (c) loading conditions, respectively. In the case of model 4, the

highest von Mises stresses value (18.79 Mpa) was determined at the third loading condition. This highest stress value was recorded at the distal surface of the cortical bone around the most distal dental implant on the nondefective side, and this was higher than that resulting from the first and second loading conditions. The highest von Mises stress values resulting from the first and second loading conditions were nearly the same, 11.55 and 11.57 Mpa, respectively (Table 2).

Comparison of models with regard to the von Mises stress values

For the first loading condition, while the highest von Mises stress values were nearly the same in model 1 (2 ZI and 1 DI) and model 2 (2 ZI and 2 DI), the highest stress value in model 3 (2 ZI and 3 DI) was relatively less than in model 1 and model 2. A higher stress value under the first loading condition was determined in model 4 (1 ZI and 3 DI) when compared with models 1–3 (Table 2).

For the second loading condition, similar highest stress values were recorded in model 1 and model

TABLE 2

Highest von Mises stress values recorded in the models under different loading conditions

Loading Condition	von Mises Stress (Mpa)			
	Model 1 (2 ZI and 1 DI)	Model 2 (2 ZI and 2 DI)	Model 3 (2 ZI and 3 DI)	Model 4 (1 ZI and 3 DI)
First loading	8.56	8.59	8.32	11.55
Second loading	4.38	3.61	4.91	11.57
Third loading	7.79	8.33	8.32	18.79

3, and the highest stress value of model 2 was relatively less than model 1 and 3. A higher stress value under the second loading condition was determined in model 4 when compared with models 1–3 (Table 2).

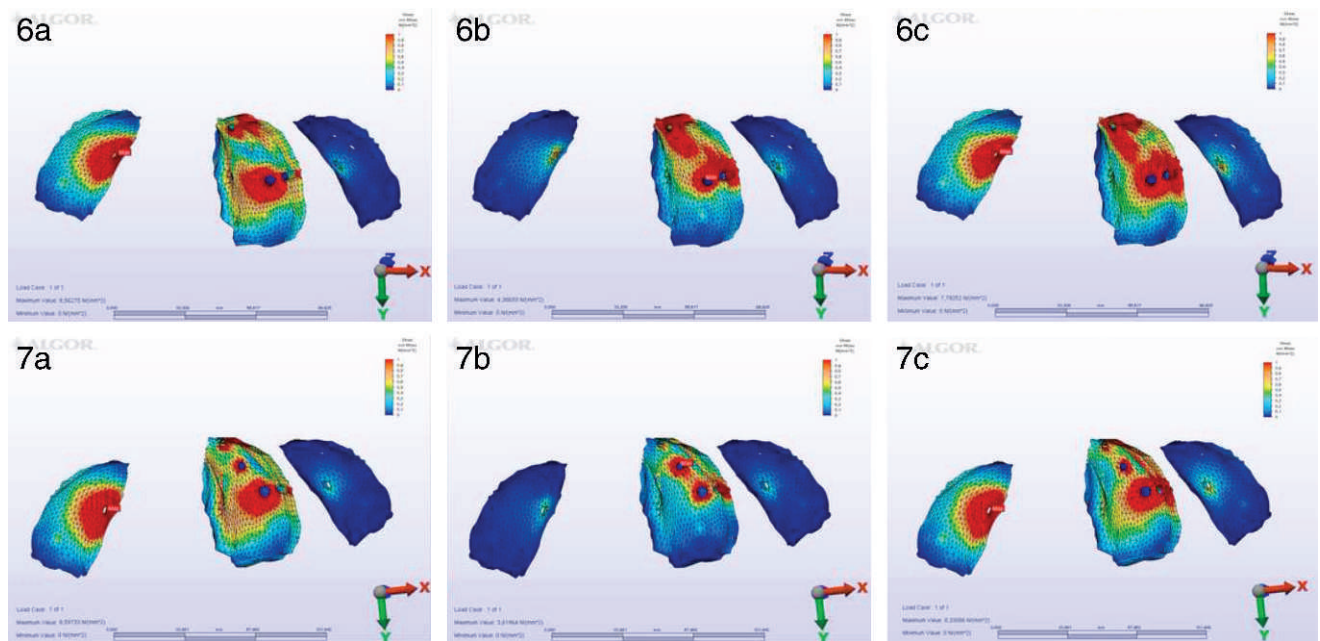
For the third loading condition, the highest stress values observed for model 2 were close to the highest stress values of model 3. Compared with model 2 and model 3, model 1 had relatively lower stress values. The highest von Mises stress values of model 4 under the third loading condition were much higher than the values of models 1–3.

In models 1 and 2, the highest stress values were determined under the first loading condition. For both models, the third loading generated higher stress values than the second loading condition did. For model 3 design, the first and third loadings

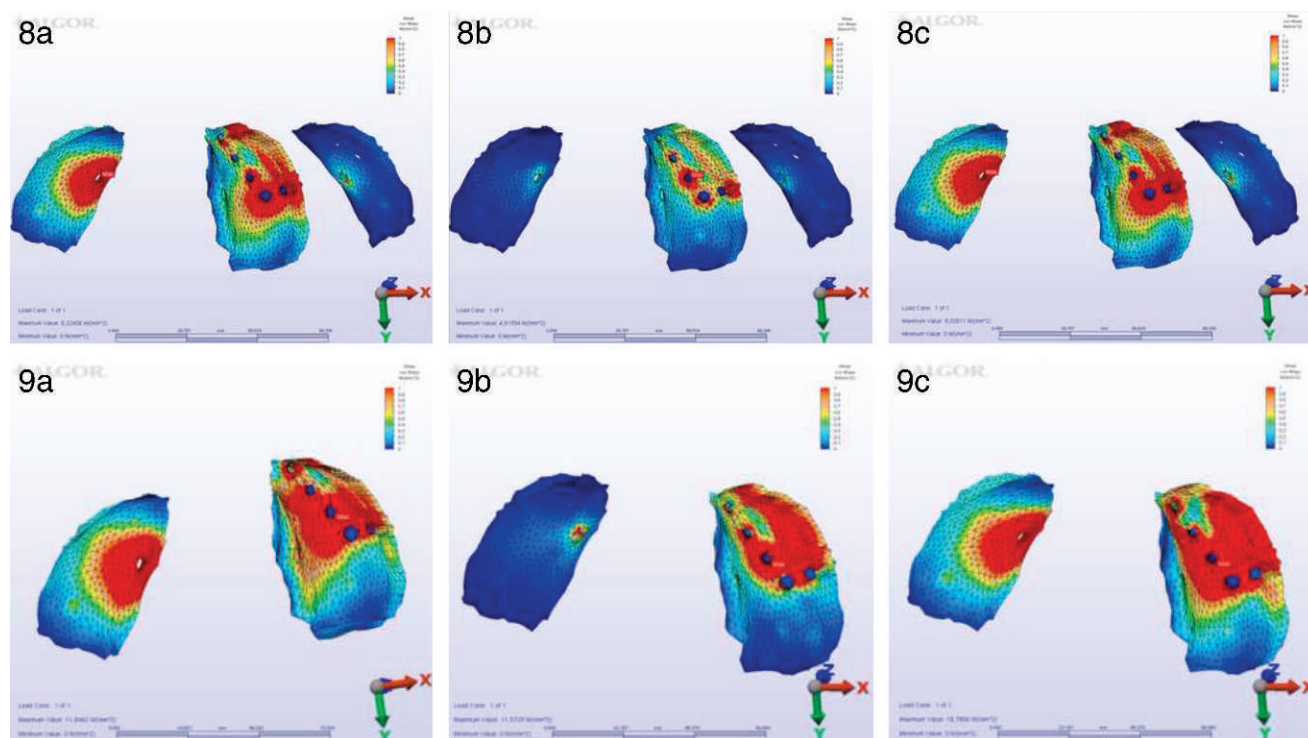
generated the same stress levels, and the highest stress value, which was determined under the second loading condition, was lower than the first and the third loading. In model 4, the highest stress values under the first loading condition were closer to the values resulting from the second loading, and both loading conditions generated lower stress levels than the third loading condition did.

DISCUSSION

Excessive stress at the implant-bone interface is among the potential causes of peri-implant bone loss and failure of osseointegration; hence, the estimation of the peak level of stress is of importance for the success of rehabilitation of



FIGURES 6 AND 7. FIGURE 6. The von Mises stress distributions in the cortical bone around implants under (a) first loading, (b) second loading, and (c) third loading conditions for model 1 (unit: MPa). Colors indicate level of stress from dark blue (lowest) to red (highest). FIGURE 7. The von Mises stress distributions in the cortical bone around implants under (a) first loading, (b) second loading, and (c) third loading conditions for model 2 (unit: MPa). Colors indicate level of stress from dark blue (lowest) to red (highest).



FIGURES 8 AND 9. FIGURE 8. The von Mises stress distributions in the cortical bone around implants under (a) first loading, (b) second loading, and (c) third loading conditions for model 3 (unit: MPa). Colors indicate level of stress from dark blue (lowest) to red (highest). **FIGURE 9.** The von Mises stress distributions in the cortical bone around implants under (a) first loading, (b) second loading, and (c) third loading conditions for model 4 (unit: MPa). Colors indicate level of stress from dark blue (lowest) to red (highest). Note that the lower hole on the nondefective side that was formed during the modeling has not been considered in the analysis.

implant-supported prostheses.^{8,10,25–28} A number of different methods, including photoelastic stress analysis, strain-gage analysis, and finite element stress analysis, have been widely used for stress analysis.²⁹ We designed 4 different implant-supported bar-retained obturator prosthesis models for unilaterally maxillary defects, and by using finite element stress analysis, we found that use of zygomatic implant on the nondefective surface provided decreased stress values, while increasing the number of dental implants between the most distal and most mesial implant on the nondefective side did not yield any additional advantage with respect to highest stress value.

The finite element stress analysis method has been applied in the dental implant field for prediction of stress distribution patterns in the implant-bone interface.^{8,12,13} This allows not only comparison of various root form, length, and diameter implant designs but also modeling of various clinical scenarios and prosthesis designs, offering many advantages over the other methods.^{29–31}

For implant-supported prostheses, the number of supporting implants is among the factors affecting the bone-implant stress distribution and ultimately the success of the prosthesis.⁸ Although multi-implants provide better stability and retention, considering the costs, patient comfort, and the associated risks of the surgery, the number of implants used and their necessity require a rational decision. When we tested the impact of the number of implants in our 3 different models (model 1, model 2, and model 3, which differ only with respect to implant number on the defective side; Figures 1–3), we found similar highest stress values. This result is in agreement with the study by Chao et al,¹⁶ which demonstrated that the number of implants under a prosthetic construction seems to have less influence on stress distribution than the design of the superstructure. Another study by Meijer et al²¹ conducted an FEA of 2 vs 4 implants placed in the interforaminal region of the mandible and concluded that the extreme principal stress was not reduced when the load was distributed over an increasing number of implants providing that the

load was uniformly distributed, corroborating the present study. By measuring photoelastically the biologic behavior of 2 or 3 implants retaining different designs of cantilevered bar mandibular overdentures and comparing the load characteristics, Sadowsky and Caputo¹⁷ found that the plunger-retained prosthesis retained with 2 implants provided a more uniform stress transfer to the ipsilateral terminal abutment than the clip retained with 3 implants. Overall, in agreement with the cited literature, the results of the present study indicated that increasing the number of dental implants did not always decrease the maximum stress affecting the bone around the implants under the implant-supported bar-retained obturator prosthesis. The design differences of the superstructures (fixed or removable) should be considered when comparing the results of the summarized literature with our findings.

Furthermore, a prospective 12-month study by Batenburg et al,²² a prospective 10-year study by Meijer et al,³² and a 5-year study by Visser et al³³ evaluated mandibular overdenture patients with respect to clinical outcomes, radiographical state, and patient satisfaction. They found no difference in clinical outcomes and radiographical state of patients treated with an overdenture on 2 or 4 implants during these evaluation periods, and patients of both groups were as satisfied with their overdentures.^{22,32,33} On the other hand, there are also studies indicating an advantage of use of an increased number of implants. The study by Koriath et al²⁷ examined the effect of implant number on transverse bending moments during simulated unilateral loading of mandibular fixed detachable prostheses and suggested that a higher number of mandibular implants may decrease the bending moments affecting mandibular fixed-detachable prostheses during unilateral biting tasks. The possible explanation of difference between our study and the latter study could be the use of fixed prostheses as superstructure, which results in different stress transferring in their study. Again, in contrast to our results, Duyck and coworkers¹⁰ determined higher forces on implants when the number of implants was reduced from 5–6 to 3–4, obtaining higher bending forces with 3 implants. The discrepancy between that study and ours could be due to the difference in fixed prostheses and implant-supported obturator prostheses and use of

different analysis methods (FEA in our study vs strain gauge analysis in their study). Although our results also differ from other FEA studies,^{7,9,15,18,20,29} they involve direct application of loads over abutments and implants without simulating the prosthesis device.

It is well known that the length, diameter, and positioning of implants also have significant influence on both force transfer and subsequent stress distribution around implants.^{8,11,13,30,34} Available evidence indicates that increasing the diameter and length of the implant leads to reduced stress and strain on the alveolar crest and provides more favorable stress distribution, especially on bending moments.^{8,11,13,30,34} In our study, despite the number of implants being the same, the stress level on model 2 was lower than the stress level on model 4 in all loading conditions. On the non-defective side, the most distal implant was the zygomatic implant on model 2, while it was a dental implant on model 4. This may be because the length and the width of the zygomatic implant were higher than that of the dental implant. The more distal position of the zygomatic implant on the nondefective side in model 2 compared with the dental implant on the healthy side in model 4 could be another reason for the observed difference. This may have caused decreased lever arm and lower bending moment.

Another result of this study is that placement of the zygomatic implant on the nondefective side decreased the maximum von Mises stress value in the cortical bone around the implants. There was no zygomatic implant in model 4. In the current study, model 4 resulted in the highest stress values compared with the other models under all loading conditions. This result is in agreement with the study by Ujigawa et al.⁷ Ujigawa et al⁷ compared the stress distribution of zygomatic implants with or without connected implants supporting the superstructure and found that stress due to occlusal force was mainly supported by the zygomatic bone and was dispersed in different directions. A higher stress under vertical load was generated in the implant model without connected standard implants supporting the superstructure compared with the craniofacial model. These findings corroborate the results of model 4 in the current study as model 4 does not involve a zygomatic implant in the defective side generating higher stress values than

the other 3 models. In model 4, the highest stress value was determined in the third loading condition. The stress values of the first and second loading conditions were quite close. The simultaneous application of load to both sides in the third loading condition might have generated the high tipped force. The reason for the observed stress difference may be due to the lack of zygomatic implant in model 4.

In addition, first loading to the defective side generated higher maximum stress values than that of the second loading condition to the nondefective side in model 1, model 2, and model 3. This may be explained by the fact that the zygomatic implant on the defective side acts as a long lever arm, creating high bending moments. In these 3 models (model 1, model 2, model 3), stress levels determined under the first loading condition were closer to stress levels resulted from the third loading condition, possibly because of the uniform distribution of the force under each loading condition.

In FEA studies, the accuracy of the tests is critically affected by the assumptions regarding the mechanical properties of the materials, geometry, interface definitions, loads, and constraints applied to the models.^{13,18} One of the advantages of our study is the character of modeling, which was based on the data obtained from an actual maxilla and zygoma CT compared with previous studies in which only schematic models were used. Another advantage of the present study is the actual modeling of obturator prostheses, which previous FEA implant-supported overdentures studies lack.^{9,18,20,29} In those studies, loads were applied directly to overabutments and implants without simulating the prosthesis device, whereas in the present study, an obturator prosthesis was modeled, loads were applied over the prostheses, and the stress in the cortical bone around the implants was calculated. Modeling the prostheses better simulates the actual condition and therefore provides more realistic results.

As in every FEA study, there are some limitations in our study. One limitation of the current study is that only vertical loads were considered. When applying FEA to dental implants, it is important to consider not only axial loads and horizontal forces (moment-causing loads) but also a combined load (oblique occlusal force), because the combined load mimics the masticatory pattern more realistically

and generates considerable localized stress in bone.^{24,35}

For most individuals, occlusal forces frequently decrease because of age-related deterioration of the dentition or loss of teeth.³⁶ Maximal biting force was measured at 144.4 N for patients who had been treated with implants.³⁷ In the present study, a maximum load of 150 N was applied on the prosthesis and distributed to premolars and first molar teeth. The reason for selection of this load was to simulate the actual maximum biting force. In 3D models, stress is generally represented by a stress tensor, which has 6 components. The von Mises equivalent stresses are most commonly used in FEA studies to summarize the overall stress state at a point.¹² Accordingly, a von Mises stress criterion has been used in this study.

Because finite element models are not necessarily identical to actual ones,^{20,32} when interpreting the results of modeling studies involving FEA, the inherent limitations of this study have to be taken into consideration. However, the findings of our study may provide a general insight into the biomechanical aspects of the implant-supported obturator prosthesis and zygomatic implants under average conditions. Long-term clinical studies or 3D FEAs are necessary for determination of influence of observed stress levels on functionality of the tissue and prosthesis.

CONCLUSIONS

Within the limitations of this study, the following conclusions were drawn: (1) placing a zygomatic implant instead of dental implant on the nondefective side markedly decreased the maximum stresses affecting the cortical bone, (2) increasing the number of dental implants on the nondefective area did not decrease the maximum stress affecting the bone around the implant, and (3) loading to the nondefective side generated less stress levels when compared with other loading conditions (except all loading conditions in model 4).

Clinical implications

Zygomatic implants should be used for maxillary defects in the nondefective side when possible. The use of an increased number of dental implants on the nondefective side may not always be rational.

But there is a need for more comprehensive studies for a conclusive statement on this.

ABBREVIATIONS

3D: 3-dimensional

CT: computerized tomography

FEA: finite element analysis

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