Three-Dimensional Finite Element Analysis of Different Implant Configurations in Enlarged First Molar Areas

Gokce Soganci Unsal, DDS, PhD

Purpose: The purpose of this in silico study was to determine appropriate implant treatment planning using three implant diameters and four different superstructures in enlarged mandibular first molar areas. Materials and Methods: A mandibular bone block was constructed, and four configurations using three implants (2.9 × 10 mm, 4.1 × 10 mm, and 4.8 × 10 mm) were created for the first molar area. The four superstructures were designed as one large crown for a wide-diameter implant, a crown with a cantilever for a wide-diameter implant, two splinted crowns of one standard-diameter and one narrow-diameter implant, and two separate crowns of one standard-diameter and one narrow-diameter implant. Vertical loads of 200 N and oblique loads of 100 N were applied to various predetermined spots on the occlusal surfaces of these superstructures. Principal and von Mises stresses were analyzed on both the cortical bone and implant structures. Results: Stresses were intensified in the cortical bone around the implant neck and implant-abutment interface. The highest compressive (36.97 MPa) and von Mises (265.71 MPa) stress values were noted in the model with standard-diameter implants supporting two separate crowns. The lowest compressive (15.86 MPa) and von Mises (16.36 MPa) stress values were observed in the model with a distally positioned wide-diameter implant supporting the crown with a cantilever. Conclusion: In an enlarged first molar area, a configuration with a wide-diameter implant near the second molar and a cantilevered crown might distribute stresses more favorably than other configurations. Int J Oral Maxillofac Implants 2020;35:675–683. doi: 10.11607/jomi.8143

Keywords: crown, dental implant, finite element analysis, mandible, molar

First molars erupt at an early age and are exposed to many factors that may result in their loss. Loss of first molars due to caries, periodontal diseases, or other injuries has several treatment alternatives, such as fixed partial dentures or implant placement. Implant treatment is an effective and predictable solution for tooth loss. Implants are an excellent alternative to fixed partial dentures for posterior tooth loss because they have a more natural appearance and can help preserve the other teeth in both the maxilla and mandible. When the mesiodistal width of an interdental space in the molar region is ≥ 14 mm, it is recommended that two regular 4-mm implants be placed. However, in such cases, the molar area can be too large for one implant and too narrow for two implants. In this situation, the clinician should consider the implant configuration along with the implant diameter, location, number, and prosthetic superstructure design to determine the most favorable treatment. Replacing molars with a single implant can cause mechanical problems because the molars have multiple roots and naturally bear intense forces and stress. Implant-supported restorations, especially in the first molar area, have risks involved with stress distribution, including mechanical failure, crown or abutment fracture, or screw loosening, because they are subjected to high occlusal forces and bending moments created by lateral forces and have a large occlusal table. Crown width is also essential for stress distribution to prosthetic implant components. Modifying the prosthetic superstructures, such as narrowing the occlusal table, minimizing the offset or cantilever length, or changing the implant configuration if there is enough space, can prevent complications. Stress around the implant and bone may be reduced by using two implant-supported, splinted restorations instead of one implant-supported restoration with a cantilever. However, mesial and distal cantilevers are still alternative treatment options for both the single crowns and fixed partial dentures that are used in some studies. Narrow-diameter implants might be a predictable solution for restricted spaces or an alternative to standard-diameter implants if the molar area is compromised. Studies have shown that the durability of narrow-diameter implants is comparable to that of standard-diameter implants, and narrow-diameter implants may be used in the posterior region of the mandible.

1Department of Prosthodontics, Ankara Yildirim Beyazit University, School of Dentistry, Ankara, Turkey.

Correspondence to: Dr Gokce Soganci Unsal, Department of Prosthodontics, Ankara Yildirim Beyazit University, School of Dentistry, Ayvali Mah. 150. Sk. Etlik, Kecioren, 06010, Ankara, Turkey.
Fax: +90 312 906 2983. Email: dt.gokce@hotmail.com

Submitted October 29, 2019; accepted February 12, 2020. ©2020 by Quintessence Publishing Co Inc.
Biomechanical stability is essential for implant-supported prostheses, for both the implant and prosthetic system and the alveolar bone.6,9 Finite element analysis is a kind of biomechanical analysis widely used in the field of dentistry to understand the behavior of stresses in structures such as bone and other components.9,16 Although finite element analyses have some limitations,17,18 studies on nonlinear contact analysis have become more common.9 Contact between prosthetic structures can be defined with frictional coefficients, and screw preloading should be done before performing the occlusal loadings.9 Treating bone as an anisotropic material, rather than an isotropic one, may ensure more realistic results due to the measuring of mechanical properties in three dimensions.19–21

The aim of this study was to compare different combinations of implant configurations and superstructure designs in terms of biomechanical stress when the molar area is too wide for one and too narrow for two standard-diameter implants.

MATERIALS AND METHODS

Design
The study consisted of three-dimensional (3D) models of four configurations of the mandibular bone block, including the second premolar, first molar, and second molar areas. Three types of implant diameter were used. The placement of implants and crown superstructures was varied: one centrally located implant supporting one large crown with mesial and distal offsets, one distally located implant with a mesial cantilever, and two implants next to each other supporting either two splinted crowns or two separate crowns. Analyses were performed under vertical and oblique loadings.

3D Finite Element Modeling
The 3D finite element (FE) models were constructed using a computer. Titanium bone-level implants (Straumann, Institut Straumann) of three different diameters were selected (4.1 \( \times \) 10 mm, 4.8 \( \times \) 10 mm, and 2.9 \( \times \) 10 mm). Implants and straight titanium abutments were scanned with a 3D scanner (Activity 880 3D scanner, Smart Optics Sensor-technik). Images in Standard Tessellation Language (.stl) data were transferred and modeled using Rhinoceros 4.0 software (Robert McNeel & Associates). The mandibular cross-sectional bone block was created according to type II bone properties. Dimensions of the bone segment were 23 mm in height, 25 mm in width, and 8 mm in thickness around the edentulous area. The distance between the second premolar and second molar was 13 mm. The cortical bone thickness was defined as 2 mm with trabecular bone in the center, and the mucosa was not modeled.

Implants were placed 1.5 mm away from each tooth in the edentulous mandibular bone area according to Misch.5 The distance was arranged 3 mm between implants. Cement-retained porcelain-fused-to-metal crowns were simulated with feldspathic porcelain on a chromium-cobalt framework. Coping thicknesses were 0.8 mm, and the porcelain margin was 1.5 mm of occlusal clearance. Zinc phosphate cement was selected based on previous studies,18,22 and cement thickness was assumed to be 25 mm.23

Implants were assumed to be 100% osseointegrated, similar to other studies.19,21 All the components were gathered in the software (Rhinoceros 4.0, Robert McNeel & Associates), and the intersections between components were subtracted using Boolean operations.

Configurations were as follows (Fig 1):

- Configuration 1 (C1): A wide-diameter implant (4.8 \( \times \) 10 mm) was placed in the middle of the interdental space, and one large crown with mesial and distal offsets was created.
- Configuration 2 (C2): A wide-diameter implant (4.8 \( \times \) 10 mm) was placed on the distal side of the interdental space, and a crown with a mesial cantilever was created.
- Configuration 3 (C3): A standard-diameter implant (4.1 \( \times \) 10 mm) was placed on the distal side, and a narrow-diameter implant (2.9 \( \times \) 10 mm) was placed on the mesial side of the interdental space, and two splinted crowns were created.
- Configuration 4 (C4): A standard-diameter implant (4.1 \( \times \) 10 mm) was placed on the distal side, and a narrow-diameter implant (2.9 \( \times \) 10 mm) was placed on the mesial side of the interdental space, and two separate crowns were created.

Mesh Generation and Material Properties
Ten-node quadratic tetrahedral elements were used, which can be automated more easily and ensure more adequate results and geometry of surfaces when refining meshes (VRMesh Studio, VirtualGrid). The convergence test was used to refine meshes until the change was less than 5%, and the number of elements was increased to obtain accurate results in this study. The mesh size was 0.2 mm near bone-to-implant contact and differed in other areas. For the four configurations, the number of elements was 345,117; 358,669; 519,811; and 496,318, and the number of nodes was 69,001; 74,342; 111,150; and 96,965, respectively.

Data from the meshed models were transferred to a finite element analysis program (Algor Fempro, ALGOR) for preprocessing procedures. Anisotropic bone properties were defined for both trabecular and cortical bone. Other materials, including the implant system,
superstructures, and cement, were assumed to be isotropic and linearly elastic. Young’s modulus (E) and Poisson’s ratio (ν) of anisotropic bone properties are displayed in Table 1,20,24 and other components are listed in Table 2.9,17,23,25,26

The friction coefficients between all-titanium surfaces such as the implant, abutment, and screw were assumed to be 0.30,9,27,28 and the friction coefficient between the abutment and crown was assumed to be 0.20.16

**Boundary Conditions and Loading**

All nodes at the bottom of the artificial mandible bone block were completely restrained. Before occlusal loading, 35 Ncm of clockwise rotational torque was applied to the abutment screw according to the manufacturer’s instructions.

Vertical loads of 200 N and oblique loads of 100 N (45 degrees to the longitudinal axis of the implant) were used as previously described.17,29,30 Vertical loadings were applied to predetermined spots according to the contact points (four contact points for molars and two contact points for premolars) of the cusp-fossa relationship. The buccal cusp contact of the premolar cantilever was excluded. Oblique loadings were also applied to predetermined areas (two loading spots for molars and one loading spot for premolars) from each buccal cusp tip of the molar and premolar superstructures.

Previous studies have analyzed von Mises stress for ductile materials and principal stress for friable materials like bone.17,31 The von Mises stress on the implants, abutments, and retaining screws were evaluated. The principal stress on the crestal bone and around the implant neck was noted. Qualitative analyses of stress patterns were also evaluated for all models.
RESULTS

Von Mises Stress on Implant, Abutment, and Screw
The von Mises stress (maximum equivalent stress) values and patterns were evaluated under vertical and oblique loadings. Implants, abutments, and retaining screws were compared between configurations in terms of biomechanical aspects. Stresses were observed at the implant and prosthetic component contacts as both vertical and oblique loadings. Oblique loadings caused higher stress values than vertical loadings in all configurations. The highest von Mises stress value (265.71 MPa) was isolated to the abutment of the narrow-diameter implant of C4 under oblique loading. The lowest von Mises stress value (16.36 MPa) was found around the neck of the standard-diameter implant of C3 under vertical loading. Stresses were intensified on the abutments in C1 and C2 under all loading conditions. However, stresses were concentrated on the screws in C3 and C4 under all loading conditions. The stress on implants for all configurations was similar under vertical loading; however, the stress on implants after oblique loading was higher in configurations with two implants, especially on the narrow-diameter implants (Fig 2). Crowns were also evaluated in terms of stress patterns, and the best stress distribution was on the cantilevered crown in C2, whereas the worst stress distribution was seen on the large crown in C1. Stress values from all configurations are illustrated in Fig 3, and stress patterns can be observed in Fig 4 for both loading conditions.

Principal Stresses (Cortical Bone)
Maximum and minimum principal stresses on cortical bone were investigated. Maximum principal stress refers to tensile stress, and minimum principal stress is attributed to compressive point stresses. Maximum and minimum principal stress values under oblique
loading were higher than those of vertical loading. Moreover, compressive stresses were higher than tensile stresses in all configurations. The lowest tensile stress value (1.46 MPa) was obtained from the cortical bone around the wide-diameter implant neck in C1 under vertical loading. The highest tensile stress value (5.21 MPa) was observed around the narrow-diameter implant neck in C4 under oblique loading. The lowest compressive stress (15.86 MPa) was determined around the standard-diameter implant neck under vertical loading in C3, and the highest compressive stress value (36.97 MPa) was seen around the narrow-diameter implant under oblique loading in C4. When all minimum and maximum principal stresses were compared, the values were similar among configurations under both loading conditions, except for the minimum principal stresses in C4 under oblique loading (Fig 5). Stress values for both loading conditions in all configurations are shown (Fig 6).

DISCUSSION

A challenge is presented when the first molar area is too large for one implant. In this study, different implant configurations were planned for an enlarged mandibular first molar area supporting alternative superstructures. In this situation, the diameter, number, and location of the implant(s) should be considered in terms of their clinical and biomechanical aspects for effective implant treatment.

The stress values and patterns on the implants and components in this study revealed that one wide-diameter implant supporting a cantilevered crown had the most favorable stress distribution. However, in terms of bone stress, two implants supporting two splinted crowns had the best stress distribution on the cortical bone around the implants. When considering the von Mises and principal stress values for all configurations, the results were lower than the ultimate yield.
strengths of both titanium\textsuperscript{24,32,33} and bone\textsuperscript{15,27,33} and did not reach the failure limits of either material.

Similar to previous studies\textsuperscript{9,16,18,30,34} the stresses on the implant structures were intensified at both the implant-abutment interface and the crestal bone around the implant neck. In contrast to studies focused on stress around the interface between the cortical bone and implant, clinical situations have shown that abutment and screw fractures are a significant factor in implant failure\textsuperscript{21}. In the present study, fixation screws experienced the highest stress among the titanium components in configurations with two implants.
under both loading conditions. This result is consistent with the study of de Souza Batista et al., in which two standard-diameter implants with a cantilevered pontic design were used. The high stress values on the screws may also be attributed to the applied torque before the occlusal loadings, as reported by Cho et al. and Peixoto et al. However, stresses were distributed more evenly in wide screws than in standard or narrow screws in this study. This was attributed to the width of the screw in wide-diameter implants. The von Mises stress on the abutments was higher than on the screws in configurations with one wide-diameter implant. This may be due to the forces being distributed to the wide abutment body so that the stress is transferred less to the screws. However, standard and narrow abutments may transfer the forces directly to the screws. Moon et al. used wide-diameter implants in their finite element analysis study, and consistent with the results herein, they concluded that von Mises stress values were higher in abutments than in screws. Furthermore, abutments were affected more than screws under oblique forces compared with vertical forces in this study. This was corroborated by Mao et al., which evaluated the stresses on different sizes of abutment and fixation screws in implant systems.

Occlusal forces were applied to the superstructures as 200-N vertical and 100-N oblique (45 degrees to the longitudinal axis of the implant) forces buccolingually as previously described. These loads were applied at four points on the molars and two points on the premolars to simulate the occlusal relationship. Oblique loading generated a bending moment that caused higher stress values on both the titanium structures and cortical bone, consistent with other finite element analyses.

The dimensions of the occlusal table, along with the superstructure design, was an important factor for the effects of occlusal forces. Due to the small occlusal table width, stress distribution in C2 was better than in C1 in this study. De Souza Batista et al. reported that a narrow occlusal table ensures favorable stress distribution to the supporting structures, which is corroborated by the present study.

Some studies have pointed out that splinted crowns have better stress distribution than separate crowns in regard to biomechanical aspects. Accordingly, the two splinted crowns in C3 distributed stresses more evenly than the separate crowns in C4 in this study. Therefore, if two implants are chosen for treatment, splinted crowns could be preferable to separate crowns due to this uniform stress distribution. However, if one implant is preferred, a wide-diameter implant with a cantilevered crown had lower stress values than standard- and narrow-diameter implants with splinted crowns in this study. This may be because of different occlusal contact points in the cantilevered crown and splinted crowns. The mesial marginal contacts were eliminated on the cantilever. Similar to the present study, Sato et al. reported that the elimination of occlusal contacts was advantageous for biomechanical aspects. Aglietta et al. and Hågl et al. both reported that cantilever extensions did not result in implant failure or marginal bone loss around implants. On the contrary, studies on implant placement in molar sites have concluded that two implants, rather than one wide-diameter implant with a cantilevered crown, ensure better stress distribution and are a better choice when a large, single molar space is present.

A distal cantilever was not planned for this study because of the increased occlusal contacts toward the second molar and the occlusal table width. Furthermore, it has been shown that mesial cantilevers distributed stress more evenly compared with distal cantilevers. This is attributed to the forces that act more in the molar region than the premolar region, due to the occlusal table width. In addition, the occlusal forces on the second molar were 10% higher than on the first molar.

It has been suggested that two standard-diameter implants (3.75 mm in diameter) should be used in a molar site in regard to both biomechanical and clinical aspects for preserving the bone and emergence profile. However, when the buccolingual and mesiodistal width of the bone is not sufficient for two standard-diameter implants, narrow-diameter implants may be a good alternative for replacing single roots of the first molar. Narrow-diameter implants could also be used in posterior areas in appropriate indications; however, these implants experience more failure than conventional implants. The most common failures in narrow-diameter implants are fatigue fractures seen around the implant neck due to bending moments. Nevertheless, studies have shown that narrow-diameter implants can be used in posterior regions for prosthetic purposes. The results of this study demonstrate that narrow-diameter implants might be used in first molar sites along with standard-diameter implants. However, a configuration with splinted crowns might ensure more even stress distribution than separated crowns.

Cortical bone was assumed to be anisotropic, which allowed better simulation of the mechanical bone properties in three dimensions compared with isotropic bone properties. The friction coefficients defined between structures were also more suitable for finite element analysis. However, one limitation of this study is that other structures in the models were assumed to be homogenous, isotropic, and linearly elastic, and the implant-bone interface was assumed to be completely osseointegrated. Although 100% bone-to-implant contact is contradictory to the clinical situation, studies on the effects of the degree of osseointegration (25%, 50%, 75%, and 100%) on stress distribution showed...
that these differences had minimal effects (0.5% to 8%) that can be ignored in finite element analysis.\textsuperscript{3,19} Another limitation to this study was the loadings, which were assumed to be static, and the horizontal forces present in clinical situations were ignored.\textsuperscript{10,15} Further in vitro and in vivo investigations should be conducted regarding fatigue behavior and clinical situations.

CONCLUSIONS

Based on the findings of this study, it is concluded that oblique loadings generated higher stress levels than vertical loadings on both the cortical bone and the implant components. Furthermore, wide-diameter implants might be preferred on the distal side of an enlarged first molar area restored by a cantilevered crown instead of a centrally located wide-diameter implant with one large crown. Alternatively, configurations with combined narrow- and standard-diameter implants with splinted crowns may be used instead of a centrally located wide-diameter implant with one large crown for better stress distribution. However, narrow- and standard-diameter implants with two separate crowns should not be preferred because this configuration may lead to mechanical failures in time. The occlusal table width and the forces placed on crown superstructures can also be adjusted to prevent possible bending moments and uneven forces placed on the superstructures.

ACKNOWLEDGMENTS

The author thanks Ay-Tasarım Ltd. (Ayberk Yagiz, Gözde Uluçay, and Gizem Kasaci) for contributions to finite element models and analysis. The author has declared that no conflicts of interest exist.

REFERENCES