The Effect of Three Different Crown Heights and Two Different Bone Types on Implants Placed in the Posterior Maxilla: Three-Dimensional Finite Element Analysis

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Purpose: The purpose of this study was to determine the amount and localization of functional stresses in implants placed in two different bone types (type 3 and type 4) with three different crown heights in the atrophic posterior maxilla using finite element analysis. Materials and Methods: A three-dimensional finite element model of the posterior maxilla was created from a computerized tomography image by using the Marc 2005 (MSC Software) program. Three different crown/implant ratios (1/1, 1.5/1, 2/1) in the first molar tooth zone were modeled. Type 3 and type 4 bone quality according to the classification system of Lekholm and Zarb was created. The total oblique force of 300 N with a 30-degree angle was applied from the locations of the mesiobuccal cusp (150 N) and the distobuccal cusp (150 N) of first molar teeth. Results: For the implants, the highest stresses were observed around the implant neck at the crown/implant ratio of 2/1 (430.57 MPa). As the crown/implant ratio increased two times, the von Mises stresses increased at a rate of 47%. The highest tensile values exceeded the ultimate tensile strength of the cortical bone for all the designs. Also, the highest compressive values exceeded the ultimate compressive strength of the cortical bone in the 2/1 design for type 3 bone, and in the 1.5/1 and 2/1 designs for type 4 bone. As the crown/implant ratio increased from 1/1 to 2/1, the highest tensile value and the highest compressive value increased 13%. For the spongious bone, as the crown/implant ratio increased, the highest tensile value increased 42% and 85%, respectively. Tensile stresses increased at a rate of 26% in the 1/1 ratio, 30% in the 1.5/1 ratio, and 32% in the 2/1 ratio when the density of spongious bone decreased. Conclusion: Compressive and tensile stresses formed mostly at the alveolar bone around the implant neck that was cortical bone. Thus, it had to be preserved during the surgical procedures. Deformation due to the stresses had great importance for the type IV spongious bone due to the increase caused by the higher crown height levels. INT J ORAL MAXILLOFAC IMPLANTS 2016;31:e1–e10. doi: 10.11607/jomi.4048

Keywords: single-tooth implants, crown-implant ratio, crown length

The first molars are the first permanent teeth to erupt in the mouth and often the first teeth lost as a result of decay, failed endodontic therapy, or fracture.¹ Implant rehabilitation has been a well-accepted treatment modality for partially edentulous patients, and several studies have demonstrated the validity of dental implants for the rehabilitation of missing teeth in the posterior region.²⁻⁵ Available bone has been an important factor in implant dentistry, and it describes external architecture or volume of the edentulous area.⁶ The density of available bone in an edentulous site has been a determining factor in the treatment planning, implant design, surgical approach, healing time, and initial progressive bone loading during prosthetic reconstruction.⁷,⁸ Different bone qualities for an implant-supported crown have affected the stress distribution and the stress values.⁹ Generally, bone types 3 and 4 have been observed in the maxilla. Mainly, type 4 bone has been seen in the molar region, and the greatest clinical failures have been reported for this region.⁹⁻¹³ According to Lekholm and Zarb, the density of maxillary bone deficiency in comparison with that of the mandible is responsible for the difficulty of implant anchorage and loading conditions in this area.¹⁴

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Changes in the crown height related to bone resorption would affect the crown/implant ratio. The crown height affects the appearance of the final prosthesis and the amount of moment force on the implant and surrounding crestal bone during occlusal loading. The crown height also affects the load distribution in the implant-denture system. As the crown neck has a vertical lever effect, the moment effect under the lateral load increases as the height of the crown increases. A 1-mm increase in crown height has been reported to increase the force by 20%. The ideal crown/root ratio for teeth has been reported to be 2/3, and the minimum ratio has been reported to be 1/1. The supracrestal part of the implant bone reconstruction is often long in relation to the clinical crowns of the remaining dentition and to the supporting implant due to the vertical loss of the alveolar bone after tooth extraction.

Mechanical analysis using numerical methods has commonly been performed to evaluate the biomechanical behavior around dental implants with reliability and accuracy, without the risk of implantation. Finite element analysis (FEA) is a numerical method that can predict stress distributions in the contact area of the implants with the cortical bone and around the apex of the implants in the spongious bone.

In this study, the effect of crown height on implant failure was evaluated using the finite element stress analysis for implants embedded in the first molar site in the posterior region of the maxilla.
mm with a porcelain thickness of 0.35 mm. The cement thickness layer was not modeled. The geometry of the tooth model has been described by Wheeler28 (Fig 1).

Six three-dimensional (3D) FEA models were created. The models represented three different crown heights of 10, 15, and 20 mm. For each group, internal-hexagon implant (4.1 × 10 mm) geometries were used. The crown/implant ratio (1/1, 5/2) was calculated by dividing the crown height by the implant length.

All materials were presumed to be linearly elastic, homogenous, and isotropic.9,10,29–32 The corresponding elastic properties such as Young's modulus [E] and Poisson's ratio [μ] were determined from the literature and are summarized in Table 1.33–44 Elements and node numbers for the models are summarized in Table 2. Spongious bone was modeled as a solid structure in cortical bone. A fixed bond between the bone and the implant along the interface was presumed.24–26

There were no gaps in the implant-abutment and abutment-cylinder connections, or frictional coefficient, with a perfect fit situation assumed among the implants, the bone, and the prosthetic structure.

The total oblique force of 300 N was applied from the inner inclines of the mesiobuccal (150 N) and the distobuccal (150 N) cusp to simulate the mean off-axis interval in the clinical situation (Fig 2). The applied forces were static.

The boundary conditions, loading, and mathematical models were prepared with finite element software. The outputs were transferred to the Marc 2005 (MSC Software) program to display the stress values and the distributions. The data for stresses were produced numerically and were color-coded.

The principal stress (tensile stress and compressive stress) values were important for brittle materials such as bone, because failure occurred when tensile stress was greater than or equal to the ultimate tensile strength of the bone, or compressive stress was greater than or equal to the ultimate compressive strength of the bone. The maximum (tensile) and minimum (compressive) principal stresses have been reported to be an adequate criterion to evaluate the occurrence of bone resorption in full osseointegration conditions, and the threshold ranges are 100 to 130 and 170 to 190 MPa, respectively.45–47 In this study, the critical values of the maximum and minimum principal stresses adopted were 130 and 190 MPa, respectively.

Von Mises stress values were defined as the beginning of deformation for ductile materials such as implants; thus, these values were important in interpreting the stresses occurring within the implants. Failure occurred when the von Mises stress values exceeded the yield strength of the implant material. The peak von Mises stress values were compared with the yield strength of the implant (550 MPa).

Elastic strain values were evaluated, as these values revealed the amount of deformation resulting from tensile and compressive stresses. The peak elastic deformations due to the tensile and compressive stress values were recorded and compared related to the deformation amounts.

**RESULTS**

Since the numerical values maintained from the stress analysis were mathematical calculations without variance, statistical analyses were not required. However, in order to benefit from the results of these stress analyses for clinical applications, sufficient and satisfactory explanations were given.

The distribution of the von Mises stresses for the implants was similar for all designs. All values were far from the yield strength of the implant material. Von Mises stresses were concentrated on both the buccal and lingual aspects of the bone-implant interface. Von Mises stress values were compared with the yield strength of the implant (550 MPa). The stress distribution within the implant and the abutment were evaluated (Fig 3).
The peak stresses were observed around the implant neck at the crown height of 20 mm (430.57 MPa). As the crown height increased by 10 to 15 mm or 15 to 20 mm, the stress zone spread and the degree of deformation extended, and the von Mises stress values increased by 14% and 28%, respectively. When the crown height increased twofold, the von Mises stresses increased at a rate of 47%. The peak von Mises stress values recorded for the implant material are shown in Fig 4.

For the implant, the peak strains resulting from tensile stresses were observed at the crown height of 20 mm. As the crown height increased from 10 to 15 mm or 10 to 20 mm, strain values increased by 16% and 72%, respectively. The peak strain values resulting from compressive stresses were increased by 15% and 41%, respectively (Fig 5).

The stresses in the bone were generally accumulated in the cortical bone that is adjacent to the implant neck (Fig 6). The peak tensile and compressive values for cortical bone are shown in Fig 7. The peak tensile values for both type 3 and type 4 bone formed due to the tensile stresses increased by 10% and 19%, respectively, as the crown height increased from 10 to 15 mm or 10 to 20 mm. The peak compressive values for type 3 bone increased by 7% and 13%. The peak compressive values for type 4 bone increased by 5% and 11% (Fig 8).

For the spongious bone, the peak strain values for type 3 and type 4 bone formed due to the tensile stresses increased by 17% and 35%, respectively, as the crown height increased from 10 to 15 mm or 10 to 20 mm. The peak compressive values for the type 3 bone increased by 11% and 23%. The peak strain values due to the compressive stresses for type 3 bone increased by 12% and 25% (Fig 9).

The peak tensile values exceeded the ultimate tensile strength of the cortical bone for the 20-mm crown height. As the crown height increased from 10 to 15 mm or 10 to 20 mm, the peak tensile values increased by 6% and 13%, respectively, and the peak compressive values increased by 7% and 13%, respectively. The peak compressive values did not exceed the ultimate compressive strength of cortical bone for any of the designs. As the compact bone thickness was the same for the bone types, the change in the density of spongious bone did not affect the stresses at the cortical bone.

For the spongious bone, the tensile stresses were observed at the buccal and the palatal sides of the crest of the bone (Fig 8). The peak tensile values were observed in the 20-mm crown height in type 4 bone (11.59 MPa). As the crown height increased from 10 to 15 mm or 10 to 20 mm, the peak tensile values increased by 42% and 85%, respectively. The compressive stresses for the spongious bone were observed at the buccal of the crest and the apical parts of the bone (Fig 8). The peak compressive values were observed in the 20-mm crown height in type 4 bone (12.53 MPa). As the crown height increased from 10 to 15 mm or 10 to 20 mm, the peak compressive values increased by 7% and 14%, respectively. The peak tensile and compressive values for spongious bone are shown in Fig 9.

For the cortical bone, the peak strain values for both type 3 and type 4 bone formed due to the tensile stresses increased by 10% and 19%, respectively, as the crown height increased from 10 to 15 mm or 10 to 20 mm. The peak strain values that resulted from the compressive stresses for type 3 bone increased by 7% and 13%. The peak strain values due to the compressive stresses for type 4 bone increased by 5% and 11% (Fig 10).

For the spongious bone, the peak strain values for type 3 bone formed due to the tensile stresses increased by 17% and 35%, respectively, as the crown height increased from 10 to 15 mm or 10 to 20 mm. The peak strain values for the type 4 bone increased by 21% and 41%. The peak strain values that resulted from the compressive stresses for type 3 bone increased by 11% and 23%. The peak strain values due to the compressive stresses for type 4 bone increased by 12% and 25% (Fig 11).
Fig 6 (above) Stress distribution around cortical bone. (a) Tensile stresses for 20-mm crown height. (b) Tensile stresses for 15-mm crown height. (c) Tensile stresses for 10-mm crown height. (d) Compressive stresses for 20-mm crown height. (e) Compressive stresses for 25-mm crown height. (f) Compressive stresses for 10-mm crown height.

Fig 7 (right) P Max and P Min stress values for cortical bone.

Fig 8 (below) Stress distribution around spongious bone. (a) Tensile stress distribution for type 4 bone, 20-mm crown height. (b) Tensile stress distribution for type 4 bone, 15-mm crown height. (c) Tensile stress distribution for type 4 bone, 10-mm crown height. (d) Compressive stress distribution for type 4 bone, 20-mm crown height. (e) Compressive stress distribution for type 4 bone, 15-mm crown height. (f) Compressive stress distribution for type 4 bone, 10-mm crown height.
DISCUSSION

Stress and strain distributions around osseointegrated dental implants were affected by a number of biomechanical factors, including the type of loading, material properties of the implant and the prosthesis, implant geometry, surface structure, quality and quantity of the surrounding bone, and the nature of the bone–implant interface.23

Utilization of finite element analysis to analyze the effect of stress on the implant and neighboring bone has been common in the past 20 years9,38,42,49,50. Finite element stress analysis has enabled the analysis of different parameters, such as the implant diameter, implant shape, and the direction of the load used for assessment of the mechanical structure of dental implants.39

Finite element analysis has been used extensively to predict the biomechanical performance of implant designs and the effect of clinical factors on the success of an implant.23 The major reason for short-term implant failure has been insufficient primary stability, whereas long-term implant failure has been due to clinical factors such as overloading on incomplete osseointegration. Thus, reports evaluated bone overloading with variable implants using principle stresses to predict the risk of alveolar bone resorption.34

In the present study, 300 N of overloading oblique force was chosen to model the worst clinical cases of patients having parafunctional habits such as bruxism, tooth grinding, and clenching.48

In this study, the peak stress values occurred in the implant because of the high elasticity module of titanium and the tightness of the contacts in the implant system. Assuming a tight contact between the components of the implant system, most of the recorded forces were transferred to the implant. The von Mises stress values increased with an increase in the crown height. A twofold increase in the crown height caused a severe increase of stress in the implant system, and this stress caused much more deformation on the implant system. As the crown height increased from 10 to 20 mm, strain values increased by 72% for tensile stresses and 41% for compressive stresses. This could cause biomechanical complications on the implant system.

The crown/implant ratio could be considered as a risk factor for some mechanical complications of implant-supported rehabilitations such as screw loosening, porcelain fractures, loosening of maxillary anterior crowns, and fractures of 2-mm-wide implant abutments supporting single crowns in the posterior region.51,52 It was interesting to underline that most of the prosthetic failures were reported by the studies with higher crown/implant ratio values.51,52 Based on these data, clinicians should be very cautious with the implant-abutment connection when restoring dental implants with unfavorable crown/implant ratios. The crown/implant ratio was an important factor in single-unit restorations for avoiding screw loosening and eventual prosthetic failure.53

Stresses in the bone occurred mainly in the cortical bone next to the cervical region of the implant. Many
studies support this result. Hoshaw et al reported that bone resorption around the implant neck increased and mineralized bone decreased when the forces on the implants increased. In this study, increase in the crown height also increased the compressive and tensile stresses in the cortical bone. There was little difference between type 3 and type 4 bone. The peak tensile stress was observed in type 4 bone at the crown height of 20 mm. Sütpideler et al reported that stress in the neighboring bone increased as the denture height increased. Meyer et al reported that a decrease in bone height increased the amount of strain.

Lee and Lim found that the average stresses at the cortical bone were approximately eight to nine times the values for the spongious bone. When the length of the implant was increased from 8.5 to 15 mm, the maximum and average values at the cortical bone were decreased. Meanwhile, in the spongious bone, there was a tendency toward stress reduction, but it showed almost constant value regardless of implant length.

The elasticity module of cortical bone was higher than that of spongious bone. Hence, it was more durable and more resistant to deformation. Absence of cortical bone would directly lead the stress to intensify on spongious bone. A decrease in cortical bone thickness significantly increased the tensile stresses in the alveolar crest. In the in vivo studies of Miyata et al and Isidor, which were carried out with monkeys, extreme occlusal loads caused losses in cortical bone. A lateral force on a natural tooth dissipated rapidly away from the crest of bone toward the apex of the tooth. The healthy, natural tooth moved almost immediately 56 to 108 μm and pivoted two-thirds down toward the tapered apex with a lateral load. This action minimized crestal loads to the bone. An implant did not exhibit a primary immediate movement with a lateral load. Instead, a more delayed movement of 10 to 50 μm occurred, which was related to the viscoelastic bone movement. In addition, this action did not pivot toward the apex but instead concentrated greater forces at the crest of the surrounding bone. Therefore, if an initial lateral or angled load of equal magnitude and direction was placed on an implant crown and a natural tooth, the implant system sustained a higher proportion of the load that was not dissipated to the surrounding structures. As the crown/implant ratio increased, the amount of moment force on the implant and surrounding crestal bone during occlusal loading would increase.

An increase in the crown height also increased the principle stress values in spongious bone. Stress distribution was similar in type 3 and type 4 bone; however, a higher extent of tensile-related deformations in spongious bone were seen in type 4 bone. Tensile stress increased at a rate of 26% at the 10-mm crown height, 30% at the 15-mm crown height, and 32% at the 20-mm crown height when the density of spongious bone decreased. Compression-related values also increased by decreased bone density. Minimum principal stresses increased 34% at the 10-mm crown height, 35% at the 15-mm crown height, and 36% at the 20-mm crown height when the density of the spongious bone decreased. The degree of deformation in the spongious bone increased as the bone density decreased. Holmes and Loftus stated that the only difference between type 4 and type 3 bone was the decrease in the density of spongious bone by half, and that stress displayed the same distribution as type 3 bone; however, the resistance of spongious bone was lower since it is thinner. Tepper et al observed the end of the implant move threefold more when cortical bone was absent. Cortical bone loss decreased the hardness of the bone-implant system, and this change increased the amount of tensile stress on the top of the crest. Spongious bone was affected by crown height changes higher and earlier than the cortical bone. The stretch resistance of cortical bone was higher than that of spongious bone. Thus, cortical bone was stronger than spongious bone, it was more resistant to deformation, and it might have resisted more force compared with spongious bone. In the present study, tensile stresses were increased 14% for cortical bone and 85% for spongious bone as the crown height increased 10 to 20 mm. Thus, more stresses developed in the bone when cortical bone that was significant for the posterior region of the maxilla was absent. Bone in that region was weaker than bone in the other regions of the mouth. Preservation of cortical bone was significant for stresses not to be destructive.

The use of long implants may be considered to reduce the crown/implant ratio. However, long implants were reported not to decrease the stress concentration in the bones around the implants. The effect of length on stress distribution was less, and the stress of 12-mm implants was reported to be lower than that of 10-mm implants. However, it was reported that using 12-mm implants did not counteract the developing stresses when the cantilever was 9 mm or longer. According to the results of these studies, it was concluded that decreasing the crown/implant ratio by increasing the implant length did not reduce stress. In the study of Huang et al, stresses in cortical and spongious bone were reduced by at least 50% for implant lengths greater than or equal to 8.5 mm with bicortical anchorage. The use of a wide implant decreased the stress by 24% to 42% in cortical bone and 17% to 36% in spongious bone. The effects of implant diameters on reducing bone stress were primarily a result of the increased contact area between implant and bone.

It was concluded that embedding two small-diameter implants or one wide implant depending on the distance to the molar region, embedding a long implant by taking future bone loss into consideration, or performing additional surgeries prior to implant...
surgery to shorten crown height would increase the chances of success.

Nissan et al showed a statistically significant increase of microstrain values as the crown/implant ratio increased from 1/1 to 1.5/1. They also found that force application at 30 degrees in the cases with crown/implant ratios of 1.75/1 and 2/1 resulted in fracture of the abutment screw followed by dislodgement of the crowns.65

With reference to the previous studies,10,46 in the biomechanical point of view, implant diameter was considered to be a more effective design parameter than implant length. For this reason, implant length was not considered as a significant factor contributing to osseointegration, because the applied stress was distributed mainly on cortical bone rather than on the rest of the bone-implant interface.66 According to Misch et al,57 increased crown height, high bite forces, and bone density were the factors that affect the implant-bone interface, not the implant length. Blanes et al11 found a positive correlation between increasing the crown/implant ratio and increasing the first bone-to-implant contact over 1 year. Nissan et al65 showed that nonaxial loading of 30 degrees generated a proportional increase in stress distribution when the crown/implant ratio and crown height space increased. Prosthetic failure occurred at a crown/implant ratio of 1.75/1 or greater and crown height space of 15 mm or greater. They also found that crown splitting increased cervical stresses and could not prevent prosthetic failure. According to the findings of Urdaneta et al,51 an increased crown/implant ratio did not lead to an increased risk of crestal bone loss or to an increase in implant failures or crown failures after the insertion of single-tooth locking-taper implant restorations. Locking-taper implants were successfully restored as single-tooth replacements when limited bone was available and when the crown height was up to 4.95 times the length of the implant within the bone.

In the present study, it was seen that the 10-mm crown height yielded better results than the other ratios in implant treatment that would be performed in the presence of one missing tooth in the posterior region of the maxilla. Marginal bone loss that could develop over a long time period would clinically interfere with this 1/1 ratio and cause more stresses in the bone by increasing the crown/implant ratio. Thus, a crown/implant ratio of less than 1/1 in the course of implant placement would yield better clinical outcomes. For this purpose, placing implants that are as long as possible and decreasing the crown height with additional surgeries was important. According to the results of this study, it was concluded that cortical bone should be preserved to avoid formation of detrimental stresses.

CONCLUSIONS
An increase in the crown/implant ratio increased the stresses in the implant and the bone and increased the area in which the stresses were distributed. Changing the bone type while preserving cortical bone did not affect the stresses on the implant. Compressive and tensile stresses formed mostly at the alveolar bone around the implant neck that was cortical bone. Thus, it had to be preserved during the surgical procedures. Deformation due to the stresses had great importance for the type IV spongious bone due to the increase caused by the higher crown height levels.

ACKNOWLEDGMENTS
The authors would like to acknowledge Dr Ahmet Utku Ozden for his support in the mechanical tests of the study. The authors reported no conflicts of interest related to this study.

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