Zygomatic Implants: The Impact of Zygoma Bone Support on Biomechanics

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Maxillectomy and severely resorbed maxilla are challenging to restore with provision of removable prostheses. Dental implants are essential to restore esthetics and function and subsequently quality of life in such group of patients. Zygomatic implants reduce the complications associated with bone grafting procedures and simplify the rehabilitation of atrophic maxilla and maxillectomy. The purpose of this study was to compare, by means of 3-dimensional finite element analysis, the impact of different zygomatic bone support (10, 15, and 20 mm) on the biomechanics of zygomatic implants. Results indicated that maximum stresses within the fixture were increased by 3 times when bone support decreased from 20 to 10 mm and were concentrated at the fixture/bone interface. However, stresses within the abutment screw and the abutment itself were not significantly different regardless of the bone support level. Supporting bone at 10 mm sustained double the stresses of 15 and 20 mm. Fixture's deflection was decreased by 2 to 3 times when bone support level increased to 15 mm and 20 mm, respectively. It was concluded that zygomatic bone support should not be less than 15 mm, and abutment screw is not at risk of fracture regardless of the zygomatic bone support.

Key Words: zygomatic implants, biomechanics, stress analysis

INTRODUCTION

Dental implants have been used clinically since 1965 to restore edentulous spaces. Their success is based on osseointegration, which is limited by the amount of bone available to support and anchor the titanium fixture.[1] Thus, one of the challenges in implant dentistry is the restoration of severely resorbed or atrophic bone ridges.

Early tooth loss, periodontal disease, trauma, tumor resection, and pneumatization of the sinus are causative factors for atrophy of the maxillary bone leading to insufficient volume, height, and width, thereby preventing successful osseointegration of implants without prior bone augmentation/graft procedures.[2,3]

Bone augmentation is commonly used to increase bone volume prior to implant placement. However, these procedures are not without complications; they require invasive surgical intervention leading to patient morbidity, prolonged treatment time, and increased costs. To provide an alternative to such procedures, an extended length screw-shaped implant was developed and became known as the zygomatic implant.[2] A zygomatic implant rather than being fixed into the alveolar bone is inserted through the palatal aspect of the residual alveolar bone in the posterior maxilla region, through the maxillary sinus and into the body of the zygomatic bone without the need for bone augmentation.[3] This has many advantages, such as shortened treatment time and less patient morbidity, allowing the rehabilitation of the patient to improve mastication, speech and esthetics and overall improving the quality of life. There are a few different sizes for the zygomatic implant, varying

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between 35 and 50 mm (Nobel Biocare, Göteborg, Sweden).[3,4] They are self-tapping and have a 45° angulated head to allow for the angulation between the zygoma and maxilla.[4]

The zygomatic bone is pyramidal in shape[5] and on average is 14.1 mm in length,[6] consisting of both trabecular and cortical bone.[7,8] Its density has been shown to be 98%, thus allowing it to be used for implant placement.[9] When occlusal forces are applied to the implant fixture, the load is transferred to the trabecular and cortical bone.[10] Kato et al[3] examined the structure of the zygomatic bone using micro-computerized tomography (CT) analysis; they found that the greatest thickness/density of trabecular bone was found in the "jugale" region, which is the most concave point between the lateral margin of the upper zygomatic bone and the upper margin of the zygomatic arch. It was revealed that bone density in this region does not decrease as it does in other regions following loss of teeth because of the insertion of masseter muscles, which provide adequate stress to continue successful osteoblastic activation and bone turnover. Thus, adequate thickness of zygomatic bone is sufficient to provide anchorage and then load bearing for a zygomatic implant.

Two well-known methods for placing zygomatic implants have been described in the literature: the original technique by Branemark where the implant passes through the maxillary sinus,[11] and more recently, the exteriorized technique where the implant passes outside of the sinus.[12] The exteriorized technique requires less surgical time, is less invasive, and allows an increased length of osteotomy in the zygomatic bone, which in turn results in greater mechanical stability for the implant.[13] Most surgeons have their own preferred technique; however, the clinical situation can dictate the technique that should be utilized. The Branemark technique is indicated when the concavity formed between the maxillary sinus, ridge crest, and region of implant insertion is small, but when the concavity is big, the exteriorized technique should be adopted.[13]

Implants are subjected to both vertical and lateral loadings, and in order to be successful they must be able to deal with the forces that develop. Stress arises in both the bone and implant structure. It has been shown that when the implant is loaded, stresses concentrate within the zygomatic bone rather than the remaining alveolar crest and that the zygomatic bone is well adapted to withstand these stresses.[14]

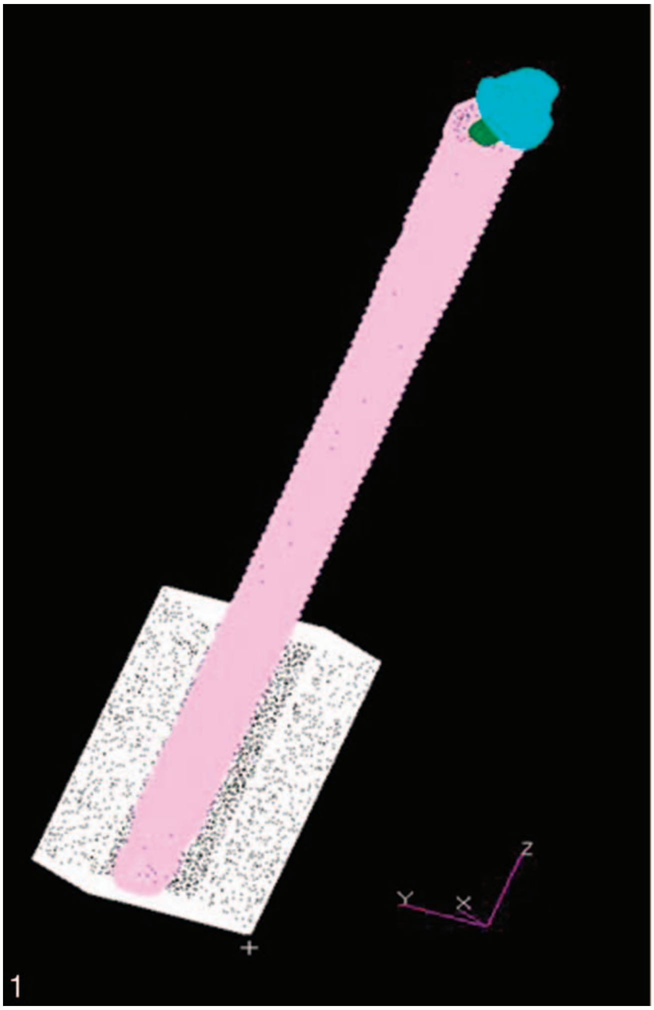
Theoretically, implants should be able to withstand stresses up to 900 $N/mm^{2(15)}$; however, failures are known to occur, and this could be due to the amount of bone available for anchorage, which may in turn affect the degree of stress concentration within the fixture.

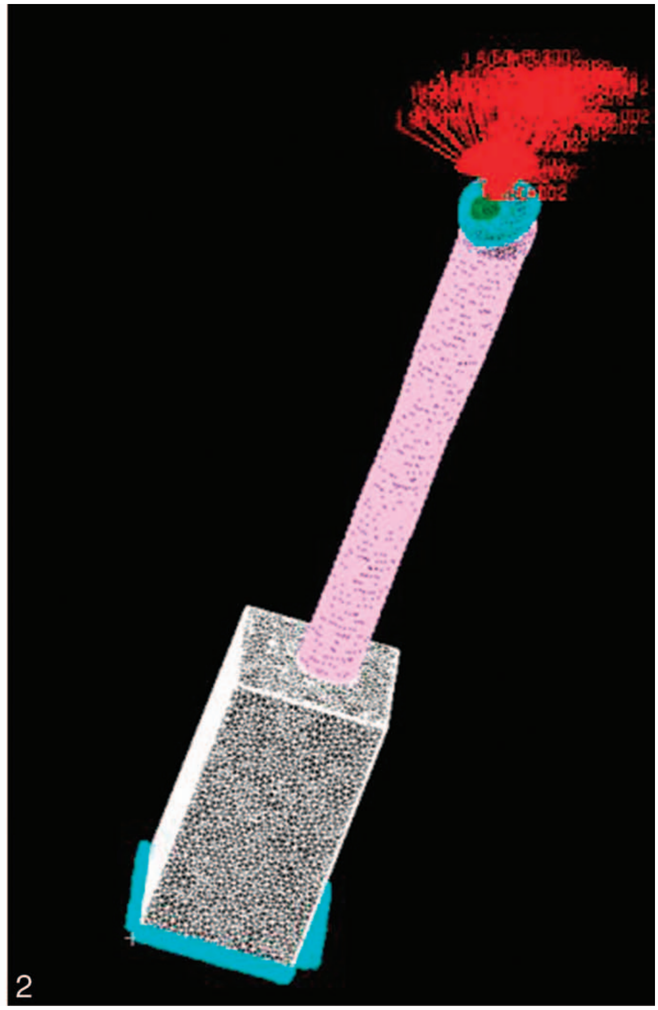
The aim of this study was to compare different zygomatic bone support levels (10, 15, and 20 mm) on the biomechanics of zygomatic implants under occlusal loading.

Materials and Methods

A 50-mm zygomatic implant (Nobel Biocare) was scanned by micro-CT scanner (GE, Delran, NY) in 3 parts: fixture, abutment screw, and abutment. These 3 parts were segmented and reconstructed using scanIP (Simpleware, Exeter, UK) according to their pixel density into 3-dimensional stereolithographic models (STL 3D-model). These 3 STL models were exported to scanCAD (Simpleware, Exeter, UK) to assemble them in an arrangement similar to the clinical implant setup. A block of alveolar bone was created to support the apical part of the zygomatic implant in 3 dimensions $10 \times 10 \times 10$ mm, $10 \times 10 \times 15$ mm, and $10 \times 10 \times 20$ mm. Thereafter, 3 STL models with different bone support levels (10, 15, 20 mm) were imported by scanIP for optimization and finite element (FE) meshing. Each model was divided into 4 groups (fixture, abutment, abutment screw, and bone) of different mask colors (Figure 1)

These 3 models were subsequently imported by Patran (MSCSoftware, Newport Beach, Calif) for preprocessing and postprocessing. All materials included in the FE models were considered to be isotropic, homogeneous, and linearly elastic; details of the material properties are in Table 1. The boundary conditions were applied to the model by constraining the models at the base of the alveolar bone from all directions ($X = 0$, $Y = 0$, $Z = 0$, $XY = 0$, $ZY = 0$, $ZY = 0$). A load of 150 N was applied 45° to the long axis of the zygomatic implant as a uniform pressure on the occlusal surface of the abutment (Figure 2). The FE solutions were all linearly elastic and carried out by Nastran (MSCSoftware). The FE results were all plotted and analyzed by Patran. Comparative FE stress analyses were carried out to





Figures 1 and 2. Figure 1. Three-dimensional finite element model which includes an abutment (blue), abutment screw (green), fixture (pink), and supporting bone (white). **Figure 2.** A load of 150 N was applied at 45° to the long axis of the implant and bone constrained at the base of supporting bone at all directions.

identify maximum von Mises stress (the equivalent stress of principal stresses in X, Y, and Z directions) and their distribution.

$$\text{von Mises stress} = 1/2[(\sigma 1 - \sigma 2) \wedge 2 + (\sigma 2 - \sigma 3) \wedge 2 + (\sigma 3 - \sigma 1) \wedge 2]$$

Where $\sigma 1, \sigma 2, \sigma 3$ are principal stresses and $\sigma 1 > \sigma 2 > \sigma 3$. [14]

Results

Applying a 150 N load 45° to the long axis of the zygomatic implant resulted in von Mises stresses 3 times higher when bone support was reduced from 20 to 10 mm. Bone support of 15 mm caused von Mises stresses of 991 MPa (Table 2), which was slightly higher than the stresses at the 20 mm bone support. Abutment screw sustained stresses 2 times higher when bone support was reduced from 15 to 10 mm and the lowest stresses when bone support was 20 mm (79 MPa). There was not much difference in abutment stresses when bone support was increased to 20 mm. The supporting bone sustained the highest level of stresses (922 MPa), which was concentrated at the fixture/bone interface at 10 mm bone support (Figure 3). However, increasing bone support to 15 or 20 mm resulted in 50% reduction in von Mises stresses (Table 2). The

Table 1

Properties of materials included in FE models[25]

Material	Young's Modulus, MPa	Poisson Ratio
Titanium	110000	0.32
Bone	18500	0.30

Table 2

von Mises stresses (MPa) under occlusal loading

Bone Support level	Bone	Fixture	Screw	Abutment
10 mm	922	2650	184	334
15 mm	634	991	95	295
20 mm	488	862	79	285

fixture displacement in 10 mm bone support was (5.5 mm) almost 2 and 3 times higher compared with 15 and 20 mm bone support, respectively (Table 3). Abutment and abutment screw sustained similar displacement values to the fixture (Table 3), which were at their highest level when bone support was reduced to 10 mm. However, increasing bone support to 15 or 20 mm resulted in significantly lower displacement in all implant parts, including supporting bone (Figure 4).

Discussion

The aim of this study was to investigate the mechanical behavior of zygomatic implants at 3 different bone support levels using 3-dimensional finite element analysis (FEA). Three-dimensional FEA has been validated by various experimental studies, and it was proven that micro-CT–based FEA is a valid research method, despite its limitation in accurately simulating all clinical variables at 1 research model.[16–18] In this study, 3-dimensional FEA was carried out on a 3-dimensional model reconstructed from segmented micro-CT data, which is a sophisticated model representing a zygomatic implant with different zygomatic bone support. The investigated variables of stress distribution, fixture displacement, and abutment screw susceptibility to fracture were assessed within 95% accuracy of the convergence analyses.

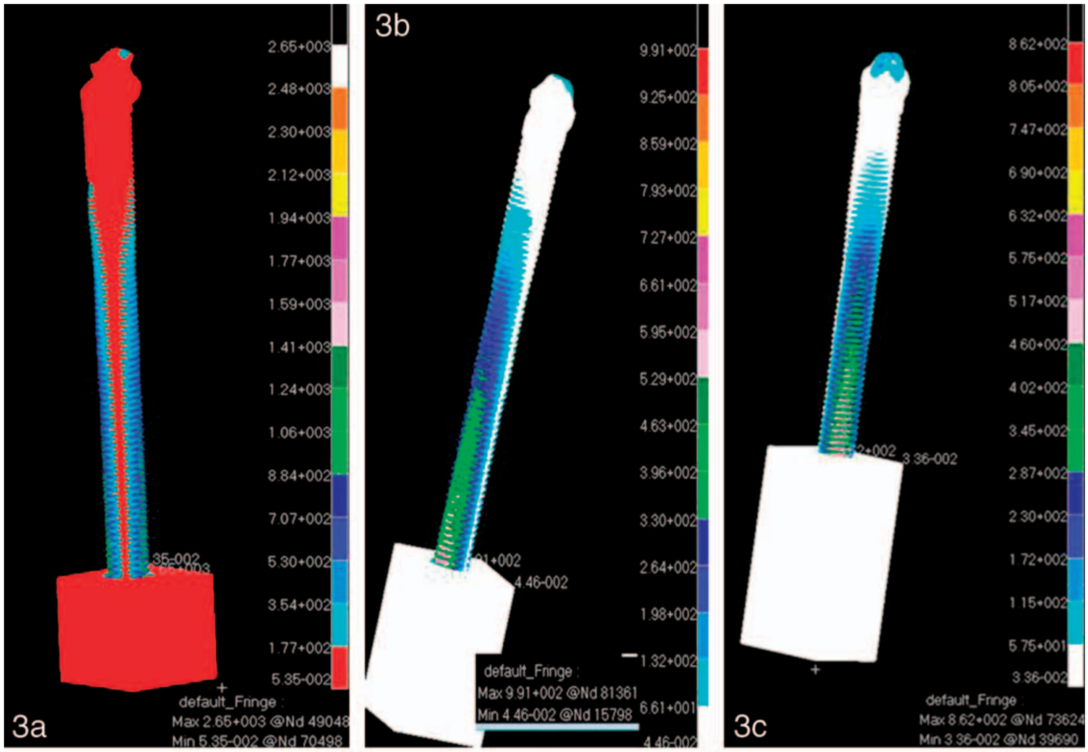
The mechanical advantage of including zygomatic implants in the rehabilitation of defects caused by maxillectomy surgeries or severely resorbed maxillary ridges has been found to be an effective treatment modality.[19–21] However, the role of dental implants in combination with zygomatic implants is unclear, though all mechanical analyses using 3-dimensional FEA have indicated that dental implants are paramount in reducing stress levels around zygomatic implants and their supporting bone.[14–22]

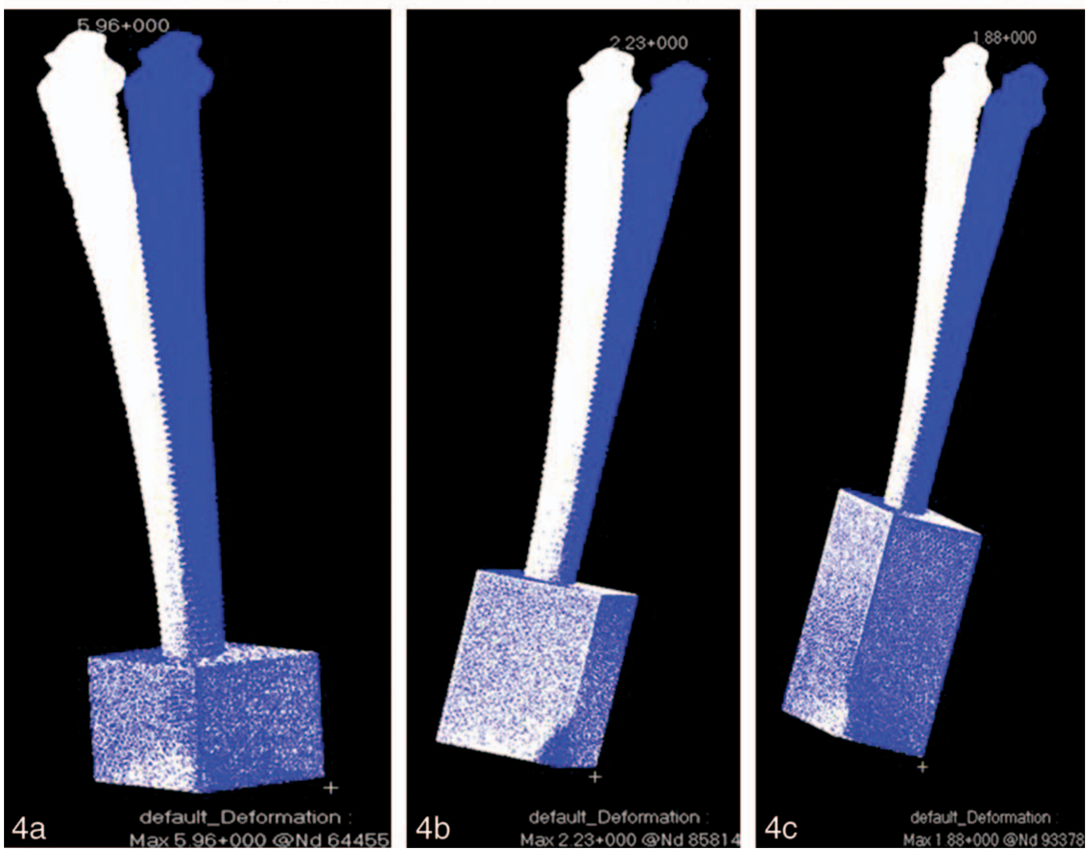
The placement protocol of zygomatic implants is either intrasinus, which will make the implant head encroached in the palatal vault, or extrasinus, to get better positioning for the zygomatic implants, particularly when the buccal concavity is large. On either placement protocol, the most important factor is to reduce postoperative complications and accomplish long-term predictable outcomes.[12,13,23,24]

The thickness of the zygoma bone is variably different among women and men. However, the average length of the zygomatic bone is 14 mm, which seems to be, through the finding of this FEA study, sufficient to reduce the level of von Mises stresses less than the yield strength of fixture, abutment screw, and abutment.[7,8,15]

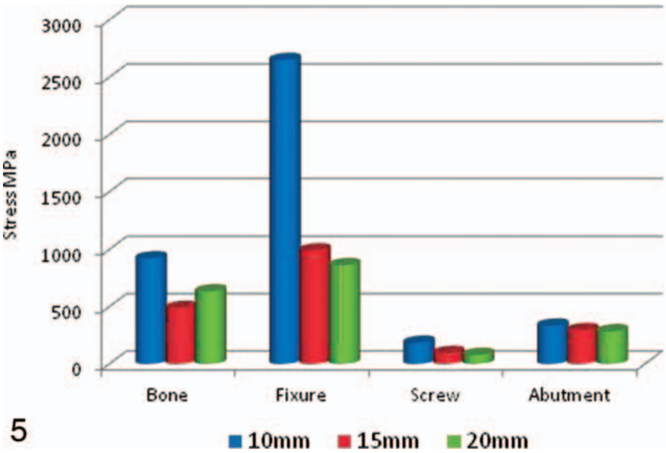
The thickness of the zygoma determines the position and angulation of the zygomatic implant to get maximum bone support and avoid the maxillary sinus involvement. As indicated in previous research, the extrasinus approach ensures longer fixture with better angulation.[23] Subsequently, this will not interfere with maintaining good oral hygiene around the abutment and will achieve satisfactory esthetic outcome for the patient.[23] The length and the configuration of the head of the zygomatic implant, which makes a 45° angle to the long axis of the fixture, has shifted the stress concentration toward the implant/bone interface, avoiding high stress concentration at the screw abutment or the alveolar bone surrounding the neck of the implant.

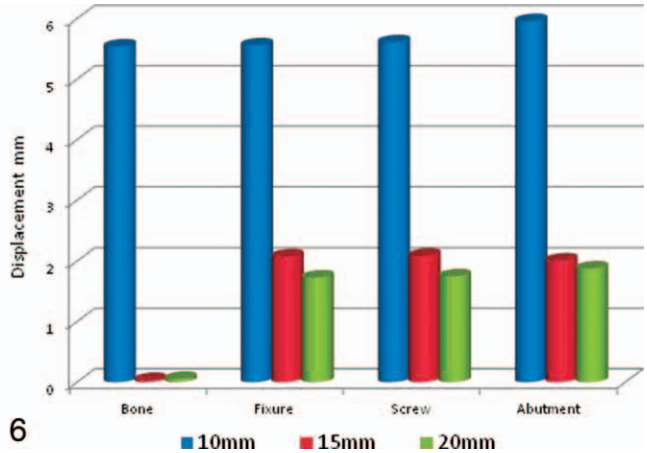
This configuration of zygomatic implant head, which is different from the conventional dental implants, has resulted in redirecting lateral occlusal loading along the long axis of the fixture head. Therefore, the abutment screw was protected from getting overloaded during function. It is highly unlikely that the zygomatic implant will be subjected to occlusal loading in different directions as a single unit, unless it is part of a group of implants supporting a fixed or removable prosthesis.





FIGURES 3 AND 4. FIGURE 3. von Mises stresses within the zygomatic implant and its supporting bone at different bone levels. (a) 10 mm bone level support. (b) 15 mm bone level support. (c) 20 mm bone level support. **FIGURE 4.** Displacement of zygomatic implant and its supporting bone at different bone levels; (a) 10 mm bone level support. (b) 15 mm bone level support. (c) 20 mm bone level support.





Figures 5 and 6. Figure 5. von Mises stresses (MPa) within the zygomatic implant and its supporting bone at different bone level support. **Figure 6.** Displacement (mm) within the zygomatic implant and its supporting bone at different bone level support.

Looking at the findings of this 3-dimensional FEA study, the maximum von Mises stress distribution and fixture displacement did not seem to be significantly different when bone support level was 15 or 20 mm. However, decreased bone support level to 10 mm had caused significant increase in maximum von Mises stresses (Figure 5). This could be explained by the increased flexibility of the fixture, which showed high level of displacement particularly at reduced bone support (Figure 6). The maximum von Mises stresses were concentrated at the implant/bone interface, which if exceeding the yield strength of bone, might induce the bone remodeling process, causing progressive marginal bone loss and subsequent loss of the implant.

The finding of this study and previous literature clearly demonstrate that the zygomatic implant supported by more than 15 mm bone level along with some alveolar bone support is not at risk of mechanical failure or fixture or abutment screw fracture. However, an investigation into this placement protocol (extrasinus) in the rehabilitation of the maxillary arch with an implant-retained bridge under different loading conditions is recommended.

Conclusions

Within the limitations of this study, the following conclusions might be drawn:

(1) Maximum von Mises stresses around zygomatic implants were concentrated at the implant/bone interface regardless of the bone support level.
(2) Zygoma bone support at 10 mm level sustained the highest level of stresses, which were double the maximum stresses at 20 mm bone level.
(3) Zygoma implant fixture displacement was 2 and 3 times lower when bone level increased to 15 and 20 mm, respectively.
(4) The abutment and the abutment screw sustained the lowest level of stresses and displacement.
(5) Increasing zygoma bone support from 10 mm to 20 mm reduced von Mises stresses by almost 3 times at the fixture/bone interface.

Abbreviations

CT: computerized tomography

Table 3

Displacement (mm) under occlusal loading

Bone Support level	Bone	Fixture	Screw	Abutment
10 mm	5.54	5.56	5.61	5.96
15 mm	0.0557	2.08	2.09	2.01
20 mm	0.0359	1.73	1.75	1.88

FE: finite element
FEA: finite element analysis

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