Extramus Zygomatic Implant Placement in the Rehabilitation of the Atrophic Maxilla: Three-Dimensional Finite Element Stress Analysis

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Placement of zygomatic implants lateral to the maxillary sinus, according to the extrasinus protocol, is one of the treatment options in the rehabilitation of severely atrophic maxilla or following maxillectomy surgery in patients with head and neck cancer. The aim of this study was to investigate the mechanical behavior of a full-arch fixed prosthesis supported by 4 zygomatic implants in the atrophic maxilla under occlusal loading. Results indicated that maximum von Mises stresses were significantly higher under lateral loading compared with vertical loading within the prosthesis and its supporting implants. Peak stresses were concentrated at the prosthesis-abutments interface under vertical loading and the internal line angles of the prosthesis under lateral loading. The zygomatic supporting bone suffered significantly lower stresses. However, the alveolar bone suffered a comparatively higher level of stresses, particularly under lateral loading. Prosthesis displacement under vertical loading was higher than under lateral loading. The zygomatic bone suffered lower stresses than the alveolar bone and prosthesis-implant complex under both vertical and lateral loading. Lateral loading caused a higher level of stresses than vertical loading.

Key Words: finite element analysis, zygomatic implants, stress analysis

INTRODUCTION

Successful osseointegration of implants is limited by the amount of bone volume available for their anchorage. For years, bone augmentation and grafting procedures have been conducted to ensure sufficient bone volume is available to support the implant fixture. Such procedures lead to increased patient morbidity, surgical time, and cost. Atrophy of the maxillary bone is common as a result of early tooth loss, periodontal disease, trauma, tumor resection, and pneumatization of the sinus; therefore, bone augmentation procedures are frequently required in the atrophic edentulous maxilla if implants are to be successfully osseointegrated. To alleviate the need for bone-grafting procedures in the edentulous maxilla, Brånemark developed implants known as zygomatic implants. These are extended-length implants varying between 35 and 50 mm. Rather than being fixed in to the alveolar bone, the implant is placed through the palatal aspect of the remaining alveolar bone in the posterior maxilla (second premolar) region, through the maxillary sinus, and into the body of the zygomatic bone without the need for bone augmentation.

Several studies have reported considerable success with the use of zygomatic implants. Brånemark treated 81 patients with 132 zygomatic implants; the success rate was 97%. Ferrara and Stella carried out a study in which they placed 25 zygomatic implants in 16 patients; a similar success rate (96%) was reported. In a retrospective review of the survival of 101 zygomatic implants placed between 1998 and 2004, the success rate (96.04%) was similar to most published data.

Two methods for placing zygomatic implants have been described in the literature: the original technique by Brånemark, which is called the intrasinus technique, and, more recently, the exteriorized or extrasinus technique. In the Brånemark technique, the implant passes through the maxillary sinus with a classic sinus window technique, whereas the implant passes outside the sinus in the extrasinus technique. Most surgeons have their own preferred techniques; however, the clinical situation may dictate the technique that might be used. The Brånemark technique is indicated when the concavity formed between the maxillary sinus, ridge crest, and region of implant insertion is small, but when the cavity is big, the extrasinus technique might be adopted.

The extrasinus technique has various advantages; it requires shorter surgical time, has a lower risk of sinus complications such as sinusitis, has simpler restorability and clensability, and allows an increased hole length for a longer zygomatic implant, which in turn results in greater mechanical stability for the implant and probably better stress distribution. As most of the implant is external to the maxillary bone,
the technique relies on the soft-tissue adhesion to aid in stability. Studies have shown that an oxidized implant surface aids with this soft-tissue adhesion.\textsuperscript{12} Malo et al.\textsuperscript{11} demonstrated a 98.5% survival rate of implants placed via the extrasinus technique after 1 year.

Placing a single zygomatic implant results in a biomechanically unfavorable situation because the implant has to be angulated and the loading point of the implant is some distance from the anchorage point. Overloading would occur in such a case, leading to increased stress concentration, bone resorption, and subsequently implant failure. It was common as a result to supplement the zygomatic implants with at least 2 anterior conventional implants to help distribute axial and lateral loads. However, to place these conventional implants, bone-grafting procedures are still often required, thereby ultimately questioning the main advantage of zygomatic implants. To overcome this problem, it has been suggested that 2 to 4 implants should be placed in the zygomatic region connected by a rigid bar without use of conventional implants and therefore no bone-grafting procedure.\textsuperscript{13} Such a surgical protocol was advocated and used by Duarte et al.\textsuperscript{14} They showed a 95.8% success rate after 30 months using 4 zygomatic implants, which were restored with a fixed bridge. Aparicio et al.\textsuperscript{15} placed 36 exteriorized zygomatic implants in 20 patients and followed them from 36 to 38 months. No failures were reported.\textsuperscript{16}

Implants are subjected to both vertical and lateral loadings, and to be successful, they must be able to withstand occlusal forces and their induced stresses generated in both the zygomatic bone and implant structure. It has been shown that when the implant is loaded, stresses arise within the zygomatic bone rather than the remaining alveolar crest, which is well adapted to deal with tensile and compressive stress.\textsuperscript{16} The aim of this study was to investigate the mechanical behavior of extrasinus zygomatic implant placement in the rehabilitation of the severely atrophic maxilla by means of 3-dimensional finite element analysis (3D FEA).

**Methods and Materials**

A dry skull for an edentulous and severely resorbed maxilla was scanned using cone-beam computerized tomography (ProMax 3D, Planmeca Oy, Helsinki, Finland). These scans were imported as a stack of images by ScanIP (Simpleware, Exeter, UK) for segmentation and 3D reconstructions. Four 50-mm Nobel Biocare Zygomatic implants (NobelBiocare, Göteborg, Sweden) including fixture, abutment, and abutment screw were also scanned using micro computerized tomography (GE, Niskayuna, NY). These implant scans were imported as a stack of images by ScanIP for segmentation and 3D reconstruction. Segments of the skull and the zygomatic implants were carried out according to their pixel density. All 3D reconstructions of the skull along with the zygomatic implants were produced as stereolithographic (STL) files, which were imported by ScanCAD (Simpleware, Exeter, UK) for placement of the zygomatic implants and their abutments in both sides according to the extrasinus protocol. In this protocol, 2 implants were placed at the locations of upper canines and second premolar on either side. All STL files (skull + 4 zygomatic implants along with abutments and abutments screws) were assembled to resemble the clinical setup. A U-shaped beam of 1×1 cm cross section made of cobalt-chrome alloy represents a cast prosthesis that was constructed by ScanCAD and connected to all abutments (Figure 1). The whole model was exported back to ScanIP for Boolean operations and finite element (FE) meshing (Figure 2); the model included 1 289 609 elements and 317 623 nodes.

The FE model was exported to Patran (MSCsoftware, Santa Ana, Calif) for optimization, allocation of materials properties, and setting loading and boundary conditions. The model was constrained posteriorly and superiorly from all directions (X=0, Y=0, Z=0, XY=0, XZ=0, ZY=0; Figure 3). The details of the workflow of this study are illustrated schematically in Figure 4. The occlusal loading was applied in 5 loading scenarios (case 1, 150 N at the occlusal anterior surface of the prosthesis; case 2, 150 N at the right occlusal posterior surface; case 3, 150 N at the left occlusal posterior surface; case 4, 150 N applied 45° to the fixtures at the right posterior lateral surface of the prosthesis; case 5, 150 N applied 45° to the fixtures at the left posterior lateral surface of the prosthesis). All materials included were considered to be homogenous, isotropic, and linearly elastic. Details of the mechanical properties of all materials included in the model are given in the Table. All analyses were carried out using Nastran (MSCsoftware), and all results were postprocessed and plotted with Patran. The FE solutions were all linearly elastic, and the comparative FE stress analyses were carried out to identify maximum von Mises stresses (the equivalent stress of principal stresses in X, Y, Z directions) and their distribution within the prostheses, zygomatic implants, and their supporting structures.

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\text{von Mises stress} = \frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]
\]

where \(\sigma_1, \sigma_2, \text{ and } \sigma_3\) are principal stresses and \(\sigma_1 > \sigma_2 > \sigma_3\).

**Results**

Five loading scenarios were investigated to evaluate the level of maximum von Mises stresses in the zygomatic implants and their supporting bone and prosthesis displacement. Applying 150 N anteriorly in the vertical direction resulted in a maximum von Mises compressive stress (294 MPa) concentrated at the tissue surface of the anterior part of the prosthesis (Figure 5a). However, the maximum von Mises stresses within the supporting bone (187 MPa) were concentrated at the zygomatic-frontal bone suture (Figure 5b). The application of 150 N vertically on the left and right posterior side resulted in maximum von Mises compressive stresses (>164 MPa) within the prosthesis, respectively. These stresses were concentrated at the abutment-prosthesis interface (Figure 6a and b). The supporting bone, under similar loading, had sustained maximum compressive stress <162 MPa at the periobital region and the lateral surface zygomatic bone (Figure 7a and b).

Lateral applications of 150 N on the right lateral side of the prosthesis resulted in higher von Mises tensile stress (>540 MPa) on the right and left sides under lateral loading (Figure 8a and b) compared with vertical loading on the
same sides, respectively. In both loading scenarios, maximum von Mises stresses concentrated at the canine location of the prosthesis at the internal line angle and also a high level of stresses developed at the fixture-zygomatic bone interface on the opposite side. Under lateral loading, the supporting bone suffered 3 times higher von Mises tensile stresses ($<411$ MPa) compared with the vertical loading (Figure 9). These stresses were concentrated at the implant-bone interface at the neck of the implant on either side and also some of the high stresses concentrated at the periorbital and zygomatic region. The displacement of the prosthesis under vertical anterior loading was higher ($<1$ mm) than posterior vertical loading ($<0.8$ mm; Figure 10).

**DISCUSSION**

The rehabilitation of the atrophic maxilla is challenging because of limited bone volume, the complications associated with bone-grafting procedures, patients’ morbidity, and cost impli-
The minimum number of conventional implants to support a fixed prosthesis in the upper arch is 4 implants\(^{19-21}\); however, in the severe atrophic maxilla, this procedure is not possible without a major bone grafting or sinus augmentation. Since zygomatic implants were introduced as an alternative to bone augmentation, 3 different surgical protocols have been described in the literature on the placement of zygomatic implants: intrasinus implants with sinus window, intrasinus implant with sinus slot, and extrasinus (exteriorized) protocol.\(^{22}\)

It was reported that the intrasinus placement of zygomatic implants might cause some long-term complications such as sinusitis, notwithstanding the usefulness of this technique in the rehabilitation of atrophic and reconstruction following maxillectomy in cancer patients.\(^{23,24}\) The extrasinus technique was introduced to reduce the complications associated with the intrasinus protocol and also to gain better functional positioning for abutments when severe bone resorption exists. It allows longer implant placement and better plaque control carried out by patients whose manual dexterity may be compromised. Moreover, despite the reduced bone support around extrasinus zygomatic implants, stress distribution might not be invariably different or less favorable compared with intrasinus zygomatic implant; however, this still needs further biomechanical testing to get better insight into the stress profiles and magnitudes for both protocols.

In this study, 4 zygomatic implants were placed symmetrically in an exteriorized position lateral to the maxillary sinus with minimum 15-mm thickness of zygomatic bone coverage. All implants were splinted with a cast cobalt-chromium prosthesis of 10-mm cross section subjected to 5 different loading scenarios. This splint had great positive impact by reducing peak stresses within the supporting zygomatic and alveolar bone. No veneering restorative material was included like a composite or ceramic in this model because of the size of the model and the difficulty in generating a mesh with a good aspect ratio. Undoubtedly, including veneering restorative material is important, and this factor will be considered in a separate research paper.

The support and mechanical stability lent by the zygomatic and alveolar bone as well as the splinting of all implants were enough to reduce maximum von Mises stresses within the supporting bone and limit the zygomatic implant displacement. The prosthesis sustained the maximum von Mises stresses under vertical and lateral loading because of its high rigidity. These stresses were mainly concentrated at the abutment-prosthesis interface and internal line angles of the prosthesis, particularly under lateral loading.

The zygomatic bone provides bicortical bone fixation, and although this was not proved to be effective in reducing marginal bone loss, implant coverage by the zygomatic bone reduced maximum stresses and shift peak stresses more coronally toward the implant neck and prosthesis.\(^{25-27}\) Although there was some disparity in stress distribution and magnitude among the different loading scenarios, it was clearly demonstrated that stress distribution within the zygomatic bone was more favorable than the implant-prosthesis complex. However, stresses induced by lateral application of occlusal forces caused higher stresses than vertical loading. The
presence of 4 long-splinted implants played a great role in reducing the impact of lateral loading on bone stresses and prosthesis displacement, in which the latter was comparable with vertical loading. The principle of having zygomatic implants placed by the extrasinus protocol is relatively new, and the clinical data to support this treatment modality as an alternative to the intrasinus protocol or placing conventional implants in grafted bone are meager. The lack of occlusal material such as acrylic or composite resin has an impact on stress magnitudes and distribution, owing to its low modulus of elasticity and occlusal configuration. Subsequently, this has resulted in increased prosthesis stresses and displacement. This numerical analysis has indicated favorable stress distribution within the supporting zygomatic bone. The limited clinical data available, so far, support the clinical protocol of having 4 zygomatic implants used in the rehabilitation of severely atrophic maxilla.²¹,² 8–30 Notwithstanding the limitations of this research work, FE data have shown that zygomatic implants play a significant role in the reduction of maximum stresses within the zygomatic bone and eliminate the risk of high stress concentration along the bone-fixture interface within the zygomatic and alveolar bone, which might be an indication for minimum marginal bone loss provided all zygomatic implants are well maintained throughout their service. This seems to be consistent with previous FE research findings.³¹,³²

**CONCLUSIONS**

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

1. The zygomatic bone suffered lower stresses than the alveolar bone and prosthesis-implant complex under both vertical and lateral loading.
2. Lateral loading caused higher levels of bone and prosthesis stresses than vertical loading.
3. It is recommended to carry out further stress analysis research for the intrasinus and the extrasinus zygomatic

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**FIGURES 8–10.**

**Figure 8.** Maximum von Mises stress distribution within the prosthesis and its supporting zygomatic implants under 150 N on the right (a) and left (b) posterior lateral occlusal loading. **Figure 9.** Maximum von Mises stress distribution within the skull under 150 N right (a) and left (b) posterior lateral occlusal loading. **Figure 10.** Prosthesis displacement under 150 N vertical anterior (a), right posterior (b), and left posterior (c) occlusal loading.
implant placement protocols to highlight the differences from the biomechanical points of view.

ABBREVIATIONS

3D FEA: 3-dimensional finite element analysis
FE: finite element
STL: stereolithographic

ACKNOWLEDGMENT

The authors would like to express their gratitude to Mr Christopher Healy for his kind help in getting the computerized tomography scans ready for this study.

REFERENCES