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Title:
Three-dimensional finite elemental analysis of zygomatic implant in craniofacial structures

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Key words: zygomatic implants, atrophic maxilla, digital biomechanical model of the craniofacial-skeleton, three-dimensional finite elemental analysis, stress distribution
Abstract

The objective of this study is to analyze stress distribution in craniofacial structures of zygomatic osseointegrated implants. An integrated system for DICOM data was utilized to create a three-dimensional model of craniofacial structures. The stress analysis was merely comparative, allowing us to relate the amount and distribution of the main stresses.

The stress analysis was performed using the three-dimensional finite elemental analysis method. The system allowed visual confirmation and analysis of stress distribution as well as the convenient and simple construction of a digital biomechanical model that provided details of anatomical structures in regions of interest. To compare zygomatic implants with or without connected implants supporting the superstructure. Stresses in severely resorbed maxillae with connected implants were not concentrated around the alveolar bone supporting zygomatic implants. Stresses without connected implants tended to be generated in the zygomatic bone, at the middle part of zygomatic implant and at the joint of the fixture-abutment.

Stress due to occlusal forces is mainly supported by the zygomatic bone, is transferred predominantly through the infrrazygomatic crest and is divided into the frontal and temporal process of the zygomatic bone in various directions.
Introduction

Severely resorbed maxillae present a challenge for conventional osseointegrated implant installation. The zygomatic implant, introduced by Brånemark et al.\(^8\), allows for the surgical installation of osseointegrated implants to restore resorbed maxillae without major grafting procedures\(^{12,16}\). In the author’s experience with 22 zygomatic implants since 1998, no implants have been lost and all remain functional.

Brånemark suggested that zygomatic implants should be installed in combination with at least two conventional implants in order to distribute the functional load and to prevent rotational loads. Zygomatic implants have been reported to bend under horizontal loading, which could lead to mechanical failure. However, biomechanical stresses in supporting craniofacial bones around zygomatic implants have not yet been described. This suggests that it would be potentially useful to analyze the biomechanical load distribution in supporting bones around zygomatic implants.

To investigate mechanical stresses in supporting bones around implants, various studies have been conducted using photoelastic stress analysis\(^7\), strain-gauge analysis\(^4\), mathematical
analysis\textsuperscript{18}, and finite elemental stress analysis\textsuperscript{24}. Among those methods, finite elemental stress analysis is useful to quantify internal stresses in anatomical intricacies of the craniofacial region.

An integrated system for three-dimensional data utilization in craniofacial applications that allows three-dimensional scanning, solid modeling and finite element analysis has now been developed by the authors. This digital system has been utilized to create a three-dimensional finite element solid model of craniofacial structures from CT scanning data. This model was used to analyze zygomatic implants with and without conventional implants supporting the superstructure. The model was then strained to simulate typical occlusal loads. Data analysis examined stresses of the implants, superstructures and surrounding osseous structure.

The objective of this study was to develop a digital biomechanical model of the craniofacial skeleton and to use that model to analyze stress distribution in relation to zygomatic osseointegrated implants.

**Materials and methods**

*Craniocfacial model construction*
A three-dimensional finite element solid model of the human skull was constructed based on CT data\textsuperscript{5,6}. The edentulous maxilla of a 68-years-old man was arbitrarily chosen. The complexity of the atrophic maxilla suggested a zygomatic implant. The craniofacial part of the skull was scanned using a clinical CT scanner (SOMATRON Plus 4 Volume Zoom, Simens AG, Erlangen, Germany) in the transverse plane with both a slice thickness and a scan increment of 1 mm, resulting in 98 slice images. The CT-DICOM data were analyzed with three-dimensional scanning software (RapidForm\textsuperscript{TM}, INUS Technology, Inc., Seoul, Korea), and the images were segmented by thresholding from the left maxillary bone to the supraorbital margin. This generated a polygonal isosurface and shell and fit NURBS surfaces. Three-dimensional reconstructions of these parts were edited and optimized polygonal surfaces were exported to the downstream application. The maxilla and zygoma consist of both trabecular and cortical bones, and the correct representation of the mechanical properties of these different types of bone in finite element models is important for accurate results. The output data were transferred to three-dimensional computer aided design software (Solidworks, SolidWorks Corp., Concord, Massachusetts) for finite element solid model conversion (Fig. 1).
**Implant model construction**

Edentulous maxillae with out of premolars and molars, combined with severe bone resorption criteria for zygomatic implants, an anterior in combination with two standard implants, offer adequate support for fixed restorations. Details of the implant model is given below. A Bränemark System® (Norbel Biocare AB, Gotebörg, Sweden) 60 mm zygomatic implant and a multi-unit abutment 5 mm in height, two standard 3.75 × 13.0 mm implants and multi-unit abutments 3 mm in height, prosthetic superstructures were conceived as a gold alloy symmetrical curved bar with a section of 10 × 8 mm, and were constructed using three-dimensional computer aided design software. Prosthetic superstructure models have been proposed to analyze the various types of full arch and single fixed prosthetic restorations.

The selection criteria for the zygomatic implant are the distance between the crest of the alveolar process of maxilla near the palate and the jugale point of the zygomatic bone. Ideally, the zygomatic implant should be placed as posteriorly as possible, with the zygomatic implant head as close to the alveolar crest as possible. Simultaneously, the zygomatic implant from the alveolar crest passes through the maxillary sinus close to the crest of the zygomatic bone and its apex perforates the cortical bone of the zygomatic bone close to the
incisura as described previously\textsuperscript{12}. The zygomatic implant was installed 18.2 mm in the zygoma and 6.3 mm in the maxilla (Fig. 2). Two standard implants were placed 5.2 and 12.3 mm from midsagittal plane, inclined 16\degree and 8\degree away from the horizontal plane.

Bone-implant interfaces were treated as fully bonded (i.e. osseointegrated implants) surfaces.

These models were coincident relations and were read into a finite elemental program (COSMOS/Works, Structural Research & Analysis Corp., Los Angeles, California) for mesh generation, the number triangles describing the outer shapes needed to be drastically reduced (Fig. 1). The mesh generation resulted in a total number of about 112,000 elements and 177,000 nodes. The average element size was as follows: 3.8 mm for the Maxillofacial model; 1.0mm for the Implant model. The mechanical properties of components in these models were based on previous studies as shown in Table 1\textsuperscript{20}. All models were assumed to be isotropic, homogenous, linearly elastic materials, and static.

\textit{Loading}

Loading consisted of a simulated bite force applied as a distributed vertical load of 150N to the occlusal surface to zygomatic implant axis and a lateral load of 50N to the palatal surface of superstructure\textsuperscript{6,11}. Furthermore, a distributed bite force of 300N was applied to the
insertion area of the masseter muscle on the zygomatic arch and zygomatic process of the maxilla to simulate the action and pass downwards and backwards. Boundary conditions, movement was restricted with symmetrical to the midsagittal plane. For the top cutting plane, the restraint was chosen to simulate the presence of the rest of the skull. Both loading and boundary conditions of the finite elemental models are shown in Figure 3.

**Results**

Stress analysis was performed using the three-dimensional finite elemental analysis method of von Mises stresses. The analysis of the digital biomechanical model in this study was merely comparative, allowing us to relate the amount and distribution of the main stress in the craniofacial region, in the zygomatic implants and in the prosthetics superstructure for different restorative situations.

In the Figures, the stress visualization is illustrated by pseudo-colors on the geometrical model: the dark blue areas represent the unstressed regions while the red areas represent the more stressed regions, and all plots are compared on the same chromatic scale as reported on the right side of each Figure.
Stress due to occlusal forces is mainly supported by the zygomatic bone, is transferred predominantly through the infrazygomatic crest and were divided into the frontal and temporal processes of the zygomatic bone in two directions. A stress in craniofacial model is not concentrated at perforate the cortical bone of the zygomatic bone and surrounding maxillary alveolar bone.

A higher stress in the implant model is generated at the middle of the zygomatic implant (the confines of the lateral wall of the maxillary sinus) and the joint of the fixture-abutment.

A comparison between the stress distributions in the craniofacial model and in the implant model with or without a connected standard implant supporting the superstructure (these models induced by different restorative typologies) is shown in Figure 4. Four cases were considered.

A higher stress under a vertical load is generated in the implant model at the middle of the zygomatic implant with combination, the craniofacial model allowing a better distribution of stress in the maxillary alveolar and zygomatic bones in combination and single (Fig. 5).

Furthermore, a lateral load is generated in the craniofacial model at the zygomatic arch with single and in the implant model at the middle part of zygomatic implant with single (Fig. 6).
Stress distribution in craniofacial and implant models under a lateral load tends to be generated rather than a vertical load. To compare zygomatic implants with or without connected implants supporting the superstructure. Stresses in severely resorbed maxillae with connected implants were not concentrated around the alveolar bone supporting the zygomatic implant. Stress distribution without connected implants tends to be generated over the entire zygomatic bone and the middle part of zygomatic implant and is concentrated at the joint of the fixture-abutment.

Based on CT-DICOM data, the system allowed visual confirmation and analysis of stress distribution as well as convenient and simple construction of a digital biomechanical model of the craniofacial skeleton model that provided details of anatomical structures in the regions of interest, such as the maxillary sinus, maxilla and zygomatic bone.

**Discussion**

Three-dimensional finite element analysis is a numerical stress analysis technique that is widely used to study engineering and biomechanical problems\textsuperscript{15}. Furthermore, it has the
following advantages: it is noninvasive to patients; the actual amount of stress experienced at
any given point can be theoretically measured; the material properties of craniofacial
structures can be assigned to the nearest one that possibly can simulate this environment in
vitro; invisibility regions such as the sinuses can be visualized graphically; the point of
application, magnitude, and direction of a force may easily be varied to simulate a clinical
situation; reproducibility does not affect the physical properties of the material involved; and
the study can be repeated as many times as the operator wishes. Brånemark suggests that
zygomatic implants offer an especially powerful treatment in prosthetic rehabilitation for
edentulous patients with maxillary atrophy and virtually eliminates the need for bone grafts in
the floor of the maxillary sinus. According to this analysis on the effects of zygomatic
implants in a digital biomechanical model of the craniofacial skeleton, stress due to occlusal
forces was mainly supported by the zygomatic bone, and it was not significantly influenced
by the anatomical structure of the maxilla. Thus it was demonstrated that occlusal forces
applied to the fixed prosthesis are transferred to the zygomatic bone. Or the stress was not
concentrated at anterior and posterior severe resorbed maxilla. When the zygomatic implant
was loaded with occlusal forces, the stresses were transferred predominantly through the
infrazygomatic crest and were divided into the frontal and temporal processes of the
zygomatic bone in two directions. This stress distribution of zygomatic implants is similar to the pattern withstanding occlusal stresses of the dentulous jaw\(^1,11\). Stresses were also seen to concentrate along the zygomaticomaxillary suture, and it is conceivable that higher stresses emanate from the suture \textit{in vitro}\(^2,23\). Furthermore, stress concentration under vertical and lateral loads without connected implants were generated at the joint of the fixture-abutment, and it was necessary to concentrate related to the marginal bone and loss around implants and mechanical failure of the components. From a biomechanical point of view, it is theorized that vertical and lateral loads on zygomatic implant will always be small, since the forces are transmitted in various directions due to the angulation and three-dimensional space of the zygomatic arch and the zygomatic implant. Consequently, zygomatic implants in combination with at least two conventional implants can prevent rotational loads and will distribute functional loads but can not avoid stressing the joint of the fixture-abutment which occurs on the lateral load.

In the implant model, the highest stresses occurred within the middle of the zygomatic implant (the confines of the lateral wall of the maxillary sinus). These were due to the higher modulus of the elasticity of titanium and peaked at 52N/mm\(^2\). As titanium alloys are
known to tolerate stresses up to 900N/mm² without irreversible deformation, the force of 150N applied to the system was unlikely to cause an implant failure. However, an in vivo fracture of the zygomatic implant has been reported, thus due caution should be exercised to prevent overloading and excess axial and lateral forces on implants and superstructures.

Histological analysis around the Jugale area of the zygomatic bone shows bone with an osseous higher density and wide cortical area. Due to this high bone density, zygomatic implants have gained a cortical anchorage with a good initial fixation. Van Steenberghe et al. reported in a recent study on cadavers that the mean length of the zygomatic bone was 14.1 ± 4.7 mm, allowing the insertion of zygomatic implants as described above. The strength of the anchorage in the zygomatic bone compensates for the bad quality and quantity of the bone in the posterior maxilla. In addition, the success of zygomatic implants placed in the zygomatic bone is secured by using at least four cortical portions. For these reasons, the zygomatic bone should be considered as a steady anchor for the rehabilitation of the severely resorbed maxilla.

In conclusions, a three-dimensional finite elemental analysis of the transfer of occlusal forces in zygomatic implants of the craniofacial part of the human skull has contributed to the
zygomatic implant surgical approach in order to archive better access and optimal implant placement.

Guidelines for zygomatic implants are as follows:

Stress due to occlusal forces is mainly supported by the zygomatic bone and it is not influenced significantly by restrictions due to the anatomical structure of the maxilla; prosthetic superstructure design should be assisted with standard implants in the anterior maxilla in order to concentrate stresses in the middle of the zygomatic implant and around the fixture-abutment joint.
References


Figure 1. Front and isometric views of finite elemental craniofacial meshing models. Implant meshing models with and without connected implant supporting the superstructures.
Figure 2. Schematic representation of the zygomatic implant model to anchor to zygoma and maxilla.
Figure 3. Front and lateral views of craniofacial and implant models. Boundary conditions and external loads are shown.
Figure 4. Isometric and frontal views of craniofacial and implant models with distribution of von Mises stresses. Prosthetic superstructure models have been proposed to analyze the different types of fixed prosthetic restorations with or without connected implants. Simulation of bite force applied as distributed the vertical and lateral loads to the occlusal surface.
Figure 5. Comparison by area of von Mises stresses on the vertical load.
Figure 6. Comparison by area of von Mises stresses on the lateral load.