Biomechanical three-dimensional finite-element analysis of maxillary prostheses with implants. Design of number and position of implants for maxillary prostheses after hemimaxillectomy


Abstract. The present study analyzed stress distributions in craniofacial structures around implant-supported maxillary prostheses. Using post-hemimaxillectomy computed tomography (CT) of a patient, the authors constructed a three-dimensional (3D) solid model using Digital Imaging and Communications in Medicine data (DICOM data) for maxillofacial and cranial bones. The effects of different prosthesis designs on stress distributions in craniofacial bones and osseous tissues around the implants were biomechanically investigated using 3D finite-element analysis. Maxillary prostheses were designed with 2 implants in the zygoma on the affected side and 2–3 implants in the maxillary alveolar bone on the unaffected side, without using a cantilever. Zygomatic implants provided suitable stress dispersal to the zygomatic and craniofacial bones on the affected side. This information is useful for designing maxillary prostheses.

Key words: zygomatic implants; maxillectomy; digital biomechanical model of the craniofacial skeleton; three-dimensional finite-element analysis; stress distribution.

Accepted for publication 2 June 2010

After maxillectomy, the maxilla and the buttresses are lost, and the oral cavity communicates with the nasal cavity and a maxillary sinus\textsuperscript{21}. This operation greatly impairs articulation and mastication\textsuperscript{15}. Maxillary obturator prostheses have a long history of effectively resolving the functional, cosmetic and psychological problems associated with the defects caused by maxillectomy, but the mobility of maxillary obturator prostheses impairs function. Mobility of maxillary prostheses is affected by the size and character of the defect, the height and contours of the residual alveolar ridge and palatal shelf,
the availability of undercuts, and most importantly, by the health and position of any remaining teeth. In cases that have required extensive resections, significant problems regarding the retention, support and stability of maxillary obturator prostheses are encountered after ablation of the retractive maxillary anatomy. In such cases, the main issues are the restoration of functional recovery, for example by adjusting the level of occlusion, and improving the quality of life, prognosis and success rates for implanting maxillary prostheses.

Zygomatic implants were originally designed for reconstruction of the atrophic, edentulous maxilla. They have also been used to support and aid the retention of maxillary prostheses after maxillectomy, which is otherwise difficult. Clinical application of zygomatic implants has been developed primarily for the treatment of the maxilla showing severe resorption. The extent of stresses such as increasing occlusal force is high, but dynamic techniques for examining stress due to supporting implants are not available.

Few biomechanical studies have examined these prostheses with implants. In the present study, the authors analyzed stress distributions in craniofacial structures around implant-supported maxillary prostheses.

Stress was analyzed using three-dimensional (3D) finite-element analysis distributions in implant-supported maxillary prostheses. Using post-hemimaxillectomy computed tomography (CT) of a patient, the authors constructed a 3D solid model using Digital Imaging and Communications in Medicine (DICOM) data for maxillofacial and cranial bones. They simulated the prostheses design with implants for this patient with a computer. The information acquired from this study will contribute to designing maxillary prostheses with implants, leading to higher success rate.

Materials and methods

Construction of craniofacial bone models

Using 3D finite-element analysis, biodynamics were examined for a maxillary prosthesis with 1 or 2 zygomatic implants after right hemimaxillectomy for malignant maxillary tumor and a left alveolar bone prosthesis with 1–3 implants. Typical occlusal loads were simulated, and stress distributions in the maxillary prosthesis model with zygomatic and normal implants and surrounding osseous structures were examined.

A 3D, finite-element, solid model of the human skull was constructed based on randomly selected clinical CT data from a 63-year-old Japanese man with edentulous maxilla. Data were obtained after right hemimaxillectomy for malignant maxillary tumor.

The craniofacial part of the skull was scanned in the transverse plane using a SOMATRON Plus 4 Volume Zoom scanner (Siemens AG, Erlangen, Germany), with 1.0 mm slice thickness and 1.0 mm scan increment, resulting in 180 slice images. Mimics 10.11 image-processing software (Materialise, Leuven, Belgium) was used to generate 3D external shapes of the craniofacial and alveolar bones. Output data were transferred to Solidworks 3D computer-aided design software (SolidWorks Corp., Concord, MA, USA) for conversion to a finite-element solid model (Fig. 1).

Maxillary prosthesis models

Branemark System standard implants (Norbel Biocare AB, Goteborg, Sweden) with dimensions of 3.75 mm × 13.0 mm and 3.0 mm high multi-unit abutments were used. The superstructure was mod-

![Craniofacial and maxillary prosthesis model](image1.png)

- Craniofacial and maxillary prosthesis model -

One zygomatic implant

Two zygomatic implants

- Maxillary prosthesis model -

Fig. 1. Front and isometric views of the finite-element craniofacial model after hemimaxillectomy and mesh models of maxillary prostheses. Maxillary prosthesis models with 1 and 2 zygomatic implants and superstructure mesh models.
eled as a symmetrically curved gold alloy bar with a section of 10.0 mm × 8.0 mm and constructed using Solidworks.

Models of maxillary prostheses with different numbers of implants were prepared for the right maxillary defect. On the affected side, 1 or 2 implants were placed in zygomatic bone on the affected side: Z-1 group, 1 implant (Z-1); and Z-2 group, 2 implants (medial implant, Z-M; distal implant, Z-D). The following three implants were placed in the left unaffected alveolar bone: L-1, in the maxillary lateral incisor; L-2, in the maxillary first premolar; and L-3, in the maxillary first molar. The maxillary prostheses with 2 zygomatic implants in the zygomatic bone on the affected side were compared with alveolar bone on the unaffected side using different numbers of implants. Type 1 used 3 implants (L-1, L-2 and L-3) in the left alveolar bone. Types 2–4 used two implants (Type 2: L-2 and L-3; Type 3: L-1 and L-3; Type 4: L-1 and L-2). Types 5–7 used 1 implant (Type 5: L-1; Type 6: L-2; Type 7: L-3) (Fig. 2). Under the condition of tilted implant placement, zygomatic implants were tilted 90° relative to the plane of resection, and left implants were tilted 90° relative to the vertical plane. Maxillary prostheses with these designs were compared and analyzed.

Craniofacial and maxillary prosthesis models were craniofacial bone model (craniofacial model) and maxillary prosthesis models. These models were observed to be coincidentally related and were read into a finite-elemental program (COSMOS/Works; Structural Research & Analysis Corp., Los Angeles, CA, USA) for mesh generation. The number of triangles describing the external shapes needed to be drastically reduced (Fig. 1). Mesh generation yielded a total of approximately 170,000 elements and 260,000 nodes. Average element size was 4.0 mm for the craniofacial model and 1.0 mm for the implant model. The mechanical properties of components of these models were based on the results of previous studies5.

**Loading**

Loading involved the application of a simulated bite force as a distributed vertical load of 150 N to the occlusal surface at the zygomatic implant axis, and a lateral load of 50 N to the palatal surface of the superstructure20. A distributed bite force...
of 300 N was applied at the insertion area of the masseter muscle on the zygomatic arch and the zygomatic process of the maxilla to simulate movement of the masseter muscle in occlusion, passing downwards and backwards. With regard to boundary conditions, a fixed bond (i.e., osseointegrated implants) was assumed between the bone and implants along the entire interface, meaning that under the load applied on the implants, relative motion between the bone and implant did not occur. For the top and back cutting plane, restraints were selected to simulate the presence of the rest of the skull. Both loading and boundary conditions of finite-element models are shown in Fig. 3.

Comparative stress analysis was performed using the 3D finite-element method regarding von Mises stresses, defined by the following equation. The amounts and distributions of main stresses on maxillary prostheses with zygomatic implants in the craniofacial region were compared for different restorative situations:

The von Mises stress

\[ \frac{1}{2} \left( (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right) \]

Where \( \sigma_1, \sigma_2, \sigma_3 \) is the principal stress and \( \sigma_1 > \sigma_2 > \sigma_3 \).

Results

Figure 4 shows the visualization of stress using pseudo-colors on the geometrical model. In the maxillary prosthesis model, stress tended to be generated over the zygomatic bone on the affected side and the front of the prosthetic superstructures. Stress was concentrated at the implant-abutment joints. In the craniofacial model, stress due to occlusal forces was distributed by dispersion to the zygomatic bone on the affected side, transferred predominantly through the infrazygomatic crest, then divided in two directions into the frontal and temporal processes of the zygomatic bone.

The craniofacial model allowed better distribution of stress on maxillary alveolar bone on the unaffected side and zygomatic bones on the affected side in maxillary prostheses with zygomatic implants (Fig. 5). Compared with maxillary prostheses with 1 zygomatic implant, maxillary prostheses with 2 zygomatic implants exhibited lower stress distributions at implant-abutments joints and the surrounding zygomatic bone under all loads.

The authors compared maxillary prostheses with 2 zygomatic implants in the zygomatic bone on the affected side with alveolar bone on the unaffected side with different numbers of implants (Fig. 6).

---

**Fig. 4.** Isometric and frontal views of craniofacial and maxillary prosthesis models with distribution of von Mises stresses. Dark-blue areas represent unstressed regions, while red areas represent the most stressed regions. All plots were compared on the same chromatic scale, which is shown on the right-hand side. Maxillary prostheses models are proposed to analyze the extent of by support provided 1 and 2 zygomatic implants in the affected side. Simulated bite force was applied to distribute the vertical loads to the occlusal surface. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)
Fig. 5. Comparison of von Mises stresses by position in the craniofacial and maxillary prosthesis model. The Z-1 group has 1 zygomatic implant (Z-1), and the Z-2 group has 2 zygomatic implants (medial, Z-M; distal, Z-D). In the left alveolar bone, the following implants were placed: L-1 (in the maxillary lateral incisor), L-2 (in the maxillary first premolar), and L-3 (in the maxillary first molar). Md is the midpoint of jugale (Ju) and zygomaxilare (Zm) (right side, R-Md; left side, L-Md).

Fig. 6. Comparison of von Mises stresses by position in the craniofacial and maxillary prosthesis model. Using two zygomatic implants, type 1: 3 implants (L-1, L-2 and L-3) placed in the left alveolar bone. Types 2–4: 2 implants (type 2, L-2 and L-3; type 3, L-1 and L-3; type 4, L-1 and L-2), types 5–7: 1 implant (type 5, L-1; type 6, L-2; type 7, L-3).
Discussion

3D finite-element analysis is a numerical stress-analysis technique\(^6\)\(^7\) that is widely used to study engineering and biomechanical problems. The advantages lie in the non-invasive nature of the process and the ability to assess theoretically the amount of stress experienced at any given point.

Based on CT-DICOM data from the maxillofacial patient, the system allowed visual confirmation and analysis of stress distribution, as well as convenient and simple construction of a digital biomechanical post-maxillotomy mode that provided details regarding anatomical structures in the regions of interest, such as the maxillary sinuses and craniofacial bones.

On comparing the distribution of stress in maxillary prostheses with 1–2 zygomatic implants, stress was observed to disperse more for prostheses with 2 implants. In these cases, the maximum stresses did not exceed 25 MPa, which induces bone damage according to Borchers and Reichart.\(^7\) The shape of the zygomatic defects complicated the placement of zygomatic implants perpendicular to the occlusal plane, and implants were thus often placed at an angle in relation to the occlusal plane. Nakamura and Shimada\(^6\)\(^5\) reported that when an implant is placed at an angle, vertical load functions as lateral load. This resulted in a bending moment when connections between implant-abutment joints and the interface between the alveolar bone and implants acted as fulcra, and metal fatigue caused abutment loosening\(^11\) and fracture. One study discovered that inclinations of 45–75° relative to the occlusal plane did not affect implant prognosis\(^8\) and several other studies have documented that the zygomatic bone is anatomically composed of thick trabecular structures that enable the tolerance of occlusal force.\(^10\)\(^22\).

When considering long-term prognosis, 2 implants are preferable to 1 implant in order to disperse the stress more efficiently.

On comparing maxillary prostheses with 1–3 implants in maxillary alveolar bone on the unaffected side, stress in alveolar bone around the implants exceeded 25 MPa if only 1 implant was placed in the alveolar bone on the unaffected side or if 2 implants were placed in the maxillary lateral incisor and maxillary first premolar regions with a cantilever-type superstructure. Excessive load can cause microscopic bone damage, which has been shown to increase the risk of bone fracture and make bone more fragile\(^11\)\(^14\) by damaging osseointegration between the implant and alveolar bone.\(^9\)

The prevention of excessive stress concentrations in osseous tissue around the implants thus requires the placement of 2 zygomatic implants in the zygomatic bone on the affected side and 2–3 implants in alveolar bone on the unaffected side. The superstructure should not be of the cantilever type. The prognosis for maxillary prostheses can also be improved by adjusting the occlusion to disperse stress in the anterior tooth region and affected side with vertical and lateral load application, respectively.

Based on this analysis of the effects of zygomatic implants in a digital biomechanical model of the craniofacial skeleton, stress due to occlusal forces was supported by the zygomatic bone in the craniofacial model. This stress distribution in implants resembles the pattern of withstanding occlusal stresses in the dentulous jaw. When zygomatic implants were loaded with occlusal forces, stress was transferred predominantly through the infrazygomatic crest and divided in two directions into the frontal and temporal processes of the zygomatic bone.

In maxillary prostheses with zygomatic implants, stress was dispersed around the zygomatic bone on the affected side, and stress distribution to the orbital cavity was confirmed. This suggests that occlusal force affects the orbital cavity. The maximum stress was ≤2 MPa, suggesting that the effects of occlusal force on the orbital cavity are minimal and that placement of implants in zygomatic bone on the affected side is feasible for dispersion of occlusal force.

In the present study, 100% osseointegration between implants and surrounding osseous tissue was assumed. Implants were placed in the zygomatic and maxillary alveolar bones on the affected and unaffected sides, respectively, and different designs of maxillary prostheses were compared. In clinical settings, radiographic and chemotherapeutic treatment of the atrophic posterior maxilla via immediate/early function and tilted implants: a prospective 1-year clinical study. Clin Implant Dent Relat Res 2005: 7: 1–12.


Geng JP, Tan KB, Liu GR. Application of finite element analysis in implant den-
Analysis of prostheses with implants

Please cite this article in press as: Miyamoto, et al., Biomechanical three-dimensional finite-element analysis of maxillary prostheses with implants. Design of number and position of implants for... Int J Oral Maxillofac Surg (2010), doi:10.1016/j.ijom.2010.06.011

Address:
Satoshi Miyamoto
Department of Oral Medicine
Oral and Maxillofacial Surgery
Tokyo Dental College
5-11-13 Sagano
Ichikawa city
Chiba 272-8513
Japan
Fax: +81 47 324 8577
E-mail: miyamotosato@tdc.ac.jp