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Effect of alveolar bone support on zygomatic implants – an FEA study

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Key Words

Zygomatic implants; finite element analysis, FEA; stress distribution

Abstract

The objective of this study was to investigate the influence of maxillary alveolar bone on the stress distribution of zygomatic implants. A three-dimensional finite element model was created of half of a skull. Two zygomatic implants were modelled, placed in the skull supported by the zygomatic bone and the maxillary alveolar bone and connected by a fixed bridge. This model was duplicated, and the area of the maxillary alveolar bone supporting the implants was removed. Occlusal and lateral forces were applied to both models and the maximum von Mises stresses were recorded. Higher maximum stresses were noted in the model with no alveolar support. Occlusal stresses were higher than lateral stresses in the model with no alveolar support. Low stresses were noted in the zygomatic bone in both models. In conclusion, maxillary alveolar bone support is beneficial in the distribution of forces for zygomatic implants.

Introduction

Zygomatic implants are used in the severely atrophic maxilla to support fixed or removable prosthodontics. Intra and extra-sinus positions for zygomatic implants have been described, both with high success rates¹⁻³. These provide an alternative for patients who do not have sufficient maxillary bone to retain conventional dental implants and for whom grafting procedures are unsuitable⁴.

Brånemark originally proposed that the zygomatic implant should be placed, via the sinus, into the zygomatic bone with support from the maxillary alveolar or palatal bone coronally³. This, along with cross arch stabilization from other conventional and zygomatic implants provides a sound foundation for a fixed arch bridge. Since then, new protocols have been developed, showing similar success rates for bridges supported only by zygomatic implants and in some cases immediately loaded^{5, 6}. Malo *et al* reported on a case series of zygomatic implants placed without any support from the maxillary alveolar or palatal bone⁷. Zygomatic implants have been used to restore function to patients following partial maxillectomies, where all of the support was derived from the zygomatic bone⁸. In light of these developments, the relevance of the alveolar or palatal bone for zygomatic implants is called into question.

Finite element analysis (FEA) has proven a useful tool in the past to investigate the distribution of stresses in and around conventional dental implants⁹. FEA breaks down a complex body into smaller components, each of which can be modelled mathematically¹⁰. These components are termed elements and are connected by nodes. As forces are applied to the overall body of known material properties, the stresses can be calculated at any given point. This study investigated the importance of the alveolar bone in supporting zygomatic implants using a finite element model.

Materials & Methods

Model construction

A CT scan of a consenting edentulous adult female undergoing zygomatic implant placement was used as the basis for a three dimensional model. The CT slices were extracted from the scan using the Mimics software package¹¹ and thresholded for the Hounsfield values corresponding to bone. In areas where thin bone was present, including the sinuses and floor of orbits, the scan slices were reviewed by the first author, and missed bony outlines were manually drawn in Mimics. A three dimensional surface model of the left side of the CT scan was then exported as a standard tessellation language file (STL). By only using one side of the skull, models could be created and analyzed using fewer elements, thus reducing the model complexity. The STL model was edited using Netfabb, and holes or defects in the surface model were repaired¹². The repaired STL model was opened in the Rhinoceros software package¹³. Here a series of non-uniform rational B-splines (NURBS) were fitted around the STL surface. The non-uniform rational B-splines surface model was imported to Solidworks¹⁴ as a solid model, which was used for the finite element analysis.

Solid models of the zygomatic implants were created in Solidworks based on the manufacturer's information leaflets and diagrams. They incorporated a bend at the coronal end to simulate the angled head of the implants. As the implants were going to be continuous with the bone in the FEA process, the threads were omitted. They were placed in the model of the skull so that they penetrated the alveolar bone in the canine and premolar areas and inserted into the zygomatic bone. A bar of 6 x 10mm in cross section was constructed in Solidworks along the line of the maxillary arch to

connect the implants and represent a fixed bridge. The heads of the implants were extended to reach the bridge, representing abutments (Figure 1).

The skull, implants and bridge were assembled, creating a model of a fixed bridge supported by zygomatic implants (Figures 2 & 3). This model was duplicated and holes of diameter 5.5mm were made around both implants as they passed through the maxillary bone. This left a gap of 0.5mm around the implants in the maxillary alveolar bone, preventing the implants being supported in this area (Figure 4).

Material Properties

The material properties for the skull, implants and bridge were assumed to be homogenous and linearly elastic¹⁵. The material properties used for bone were derived from averaged values from cadaver studies of the skull^{16, 17}. The properties of the zygomatic implants and bridge were based on those for commercially pure titanium as zygomatic implants are made from commercially pure titanium at present. The values used are shown in Table 1.

Mesh Creation and analysis

A mesh was generated from the solid models and consisted of 133,179 elements and 27,455 nodes for the model with alveolar support and 124,256 elements and 26,049 nodes for the model without alveolar support. The superior elements (at the top of the skull) of the model were fully restrained. The medial elements (at the midline of the skull) were restrained using a slider/roller restraint to simulate the presence of the other side of the skull. This allowed movement in the supero-inferior plane and the antero-posterior plane but no medio-lateral movement at the midline. Forces were applied to each model individually in the molar area of the bridge at varying angles to

the occlusal plane to assess the effect of changes in force direction. The magnitudes of the forces directed normal to the occlusal plane and at 30° in a buccal and palatal direction were varied to assess the effect of changes in force magnitude. Magnitudes of 50N to 600N were analysed. A three dimensional finite element analysis was run and maximum von Mises stresses were recorded for each model under the various loads. Graphical representations of the von Mises stresses were produced to demonstrate the location of the stresses in the implants, bridge and skull.

Results

The maximum von Mises stresses recorded for each model is shown in Table 2. The distribution of these stresses in the models and the implants are shown in figures 5 to 10. In all cases, the maximum stress increased linearly as the applied force was increased (Figure 11). The maximum stress was located at the head of the distal implant in the model with no alveolar support. In the model with alveolar support, the maximum stress was located at the area where the abutment and bridge met. The stresses applied to the zygomatic bone were low in both models, when compared to the stresses applied to the implants.

The magnitudes of the maximum stresses were higher in the model with no alveolar support. The maximum stress, when an occlusal force was applied, was more than doubled when alveolar support was not present compared to when alveolar support was present.

The effect of varying the angle of a 150N load for each model relative to the occlusal plane is shown in Table 3 and figure 12. In the model with alveolar bone support, the maximum stress is lower with occlusally directed forces than with

laterally directed forces. In contrast, the maximum stresses for the model without alveolar support are higher with occlusally directed forces than with laterally directed forces.

Discussion

Zygomatic implants were originally used to provide anchorage for prostheses in patients who did not have sufficient maxillary bone to support dental implants and were not suitable for bone augmentation procedures¹⁸. They have shown high success rates, comparing favourably to conventional implants⁴. The largest area of support for zygomatic implants comes from the body of the zygomatic bone, where the apex of the implant is embedded¹⁹. The conventional protocol for zygomatic implant placement passes the remainder of the implant internally through the maxillary sinus and alveolar bone³. The head of the implant emerges through the palatal aspect of the alveolar process of the maxilla¹.

Finite element analysis is a technique that can be used to investigate the internal stresses in a body with complex geometry. Computed tomography can create anatomically accurate three-dimensional images of the skull, which can be used to create a computer model. When combined with relevant material properties, this can be used in a FEA to simulate forces applied to the skull⁹.

The material properties of the skull have been studied by Peterson *et al* in 2003 and 2006. Some FEA studies have varied the material properties of the skull, depending on each area's radiodensity⁹. Interestingly, this approach has not been shown to yield significantly higher accuracy compared to using average material properties for the skull¹⁵. For this reason, the skull was considered to be homogenous in the current study and average values for the material properties of bone were taken

from cadaver studies.

Ujigawa *et al* used an FEA model to investigate the force distribution along zygomatic implants in a model with normal anatomy²⁰. They simulated a 150N occlusal force and a 50N lateral force. Their model also incorporated a force of 300N, applied to the zygomatic bone and arch, to simulate the action of the masseter muscle. The study showed large von Mises stresses in the zygomatic bone and suggested that most of the occlusal force was transmitted to this area. However, it is difficult to know what proportion of the observed stress in the zygomatic bone had derived from the occlusal force rather than the masseteric force.

The masseteric force was omitted from the current study as the effects of the occlusal forces in isolation were being investigated. In contrast to the results of Ujigawa *et al*, only small stresses in the zygomatic bone were noted. Forces were instead distributed through the maxilla and throughout the facial skeleton. This suggests that less force is distributed to the zygomatic bone than was previously suspected when alveolar support is present.

Miyamoto *et al* investigated the force distribution for zygomatic implants in a hemi-maxillectomy FEA model²¹. Their model showed the stress distribution for implants that were not supported at all by the maxilla. Again, a large masseteric force was incorporated into the model. High stresses were noted in the zygomatic bone, however the stresses on the segments of the implants supported by the zygomatic bone were small when compared to the rest of the model. This correlates with the findings of the current study and supports the concept that the high stresses were caused by the masseteric force, rather than the implants.

Forces ranging from 50N to 600N were used in the current study. Although physiological bite forces have not been measured for zygomatic implants, forces of

450N have been observed in conventional implant supported bridges²². The forces up to 600N were intended to exceed those recorded *in vivo*.

The maximum stresses observed in the model with alveolar support were lower than those in the model with no alveolar support regardless of the direction that the force was applied. However, support from the alveolar bone had the greatest impact on the maximum von Mises stresses when occlusally directed forces were applied. This is clinically significant as most masticatory forces are directed occlusally²³.

The results of this study suggest that the support provided by alveolar bone is valuable for zygomatic implants. Although the amount of the implant that is supported by alveolar bone is very small compared to the zygomatic bone, it is much closer to the force that is being applied to the implant. This allows masticatory forces to be distributed throughout the maxilla and facial skeleton, rather than solely to the zygomatic bone.

In line with other FEA studies in implant dentistry, this study assumed that the bone supporting the implants was homogenous, isotropic and linearly elastic in all directions⁹. This assumption is not supported by laboratory studies of human skulls, but has been shown to be a valid method of estimating stress distribution using FEA¹⁶. It is important to understand that the magnitude of the stresses described cannot be directly transferred to the patient reliably. Despite this, the differences in stress distributions demonstrated between the two models show that the model with alveolar support was more effective at distributing the applied forces than the model without.

Within the limitations of the study, alveolar bone support for zygomatic implants reduces the internal stresses generated by occlusal and lateral forces, when compared to implants not supported by alveolar bone.

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Tables

Material	Property	Value
Bone	Elastic Modulus	$1.5 \times 10^{10} \text{ N/m}^2$
	Poisson's Ratio	0.34
	Mass Density	1678 kg/m^3
Titanium	Elastic Modulus	$1.05 \times 10^{11} \text{ N/m}^2$
	Poisson's Ratio	0.37
	Mass Density	4510 kg/m^3

Table 1. Material properties used in the finite element analysis. The elastic modulus is the ratio of the stress and strain of a body undergoing elastic deformation. Poisson's ratio is the ratio of the transverse strain and the longitudinal strain in an elastic body under longitudinal stress.

Model	Force	50N	150N	300N	600N
With Support	Occlusal	5.66	16.99	33.99	67.95
	30° Buccal	5.73	17.2	34.41	68.82
	30° Palatal	5.54	17.56	35.12	70.25
No Support	Occlusal	14.2	42.59	85.18	170.36
	30° Buccal	9.18	27.54	55.08	110.15
	30° Palatal	7.29	21.86	43.72	87.44

Table 2 – Maximum von Mises Stress (N/m² x10⁶) for models with and without alveolar support

Model	0° Buccal	30° Buccal	60° Buccal	90° (Occlusal)	60° Palatal	30° Palatal	0° Palatal
With support	19.96	17.2	16.95	16.989	17.03	17.56	19.96
No support	23.69	27.54	39.63	42.59	35.26	21.86	23.69

Table 3 – Maximum von Mises stresses ($\text{N/m}^2 \times 10^6$) for each model with a 150N load applied at varying angles to the occlusal plane

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Figure 6 a (Lateral), b (Frontal), c (Medial) – stress distribution in the models with alveolar support with a 30° buccally directed force

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Figure 12 - Maximum von Mises Stress ($\text{N/m}^2 \times 10^6$) for models with and without alveolar support with 150N force of varying direction relative to the occlusal plane