Original Article

A 3-Dimensional finite element analysis of patient-specific implant (with strut abutments) interface on stress concentration on the implant and surrounding bone in bilateral maxillary deformities

ABSTRACT

Purpose: To determine the efficacy and longevity of patient-specific implants (PSIs) with strut abutment design to rehabilitate bilateral maxillectomy defect.

Materials and Methods: Finite Element Analysis was performed on a PSI with strut abutments to repair a patient's bilateral maxillectomy defect due to COVID associated mucormycosis.

Results: The von Mises stress recorded was maximum in the zygomaticomaxillary buttress region, and displacement values were noted to be highest in the posterior-most strut, although both parameters were within acceptable limits, which is favorable.

Conclusion: The authors draw the conclusion that a PSI with strut abutments is a workable therapeutic modality for patients with these kinds of abnormalities based on this information.

Keywords: Bilateral maxillectomy defects, finite element analysis, patient-specific implant

INTRODUCTION

The maxilla, which is a component of the orbits, the zygomaticomaxillary complex, the nasal unit, and the stomatognathic complex, is the functional and aesthetic cornerstone of the midface. Maxillary reconstruction is a difficult task in both functional and aesthetic restoration.[1]

The coronavirus disease 2019 (COVID-19) pandemic caused a massive surge in the number of cases diagnosed with fungal osteomyelitis of the jaws, especially in Southeast Asian countries. The most commonly diagnosed causative organism was from the *Mucor* species, and the most common type of involvement was of the rhinomaxillary region of the face. The treatment of this subsequent disease led to an upsurge of patients with maxillectomy defects, as was never faced by the fraternity of oral and maxillofacial surgeons priorly. Even more challenging thereafter was the planning of the reconstruction and rehabilitation.

Access this article online	
Website: www.njms.in	**Quick Response Code**
DOI: 10.4103/njms.njms_155_23	

Many methods have been described in the literature to reconstruct maxillectomy defects. Large maxillary deformities were traditionally repaired by obturating the deformity with a prosthetic appliance.[2,3] Prosthetic appliances were the only method available to fulfill the functional and aesthetic

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Received: 31 August 2023, **Revised:** 31 December 2023, **Accepted:** 07 January 2024, **Published:** 24 July 2024

How to cite this article: Datarkar AN, Pardiwala AF, Relan P, Daware S, Gadve V, Deshpande A, *et al.* A 3-dimensional finite element analysis of patient-specific implant (with strut abutments) interface on stress concentration on the implant and surrounding bone in bilateral maxillary deformities. Natl J Maxillofac Surg 2024;15:268-72.

requirements of such a complex deformity prior to the introduction of more advanced reconstructive techniques. The functional and aesthetic outcomes were both far from ideal. Edgerton and Zovickian[4] reviewed early attempts at autogenous reconstruction of the maxilla and reported a palatal reconstruction technique using cervical flaps. Local flaps from the forehead, upper lip, face, pharyngeal, turbinate, and tongue were the first reconstructive techniques used. Later, tube flaps from the upper extremity, thorax, and abdomen were used.[5,6] Several local flaps for maxillary and palatal reconstruction have been described in great detail. They have typically been helpful for small defects or to supplement other tissue-transfer methods used to rebuild larger deformities. A variety of osteocutaneous free tissue transfers have been used for palate, midface, and maxilla reconstruction, including scapula, fibula, radial forearm, rectus abdominus, iliac crest, and latissimus dorsi flaps.[7]

The first option in any surgeon's repertoire is that of autogenous grafts. However, they frequently come with unpredictability in resorption and significant donor site morbidity. There are a few other feasible alternatives, one of which is patient-specific implants (PSIs). The development of 3-dimensional (3D) printing and additive manufacturing, as well as subsequent advancements in those technologies, have had a favorable impact on the biomedical sector, resulting in the use of PSIs in the surgical repair of craniofacial abnormalities. PSIs that are specific to each defect are created using additive manufacturing technology in conjunction with advanced imaging modalities like computed tomography (CT).

Conventional removable prosthesis (CRP) used to be a favorable choice for maxillectomy defects, but it requires steady abutments to supply retention forces, which will generate adverse stresses to the abutments and superstructures. Patient-specific implants have the potential to provide an effective approach to retention for CRP. To our knowledge, the stress distribution of PSI-retained prostheses has not yet been analyzed.

The purpose of this study was to perform a biomechanical evaluation of the PSI concept, using finite element analysis (FEA) subjected to the physiological and pathological loading conditions in the mouth, to provide clinically relevant information about failure and fatigue of the implant structure, stress shielding of the bone tissue, and the effects of osseointegration in the scaffolds.

MATERIALS AND METHODS

Approval was obtained from the institutional ethics board before embarking on this study. Written and verbal consent was obtained from the case subject to participate in this study and also for publication of the photographs taken of the case subject to be uploaded in the article while concealing their identity in an appropriate manner. In this study, a maxillofacial model was constructed firstly using the data obtained from a CT scan of a 25-year-old male with COVID-associated mucormycosis bilateral maxillectomy defect, as shown in the 3D CT image in Figure 1.

The intraoral clinical image of the patient before the placement of the implant is depicted in Figure 2.

The head of the volunteer was scanned with a clinical CT scanner (Siemens Somatom Sensation) with a slice thickness of 0.625 mm, and the data was saved as Digital Imaging and Communications in Medicine (DICOM) files. The subject was explained about the purpose of this study and consent was obtained for the use of the data. The DICOM data was imported into the software of Geomagic Freeform, and every bone was separated, respectively, in transverse, sagittal, and coronal planes slice by slice so that those could be isolated and the models could be constructed by region growing. Then, the models were exported as type STL (StereoLithographic) files, which were imported into the software of Dassault Systemes to generate elemental subparts of various shapes like rods, beams, etc., connected to each other in three planes by triangles.[8]

The process of dividing the structure into a discrete number of elements and nodes is designated as discretization. Nodes and elements together are known as mesh. A mesh pattern is created. To increase accuracy division is increased, number of elements is increased. If the number of elements in a model is increased, it would result in fine meshing. The method employed is similar to the techniques of Koch *et al*.[9] whose approach was based on nonlinear finite elements

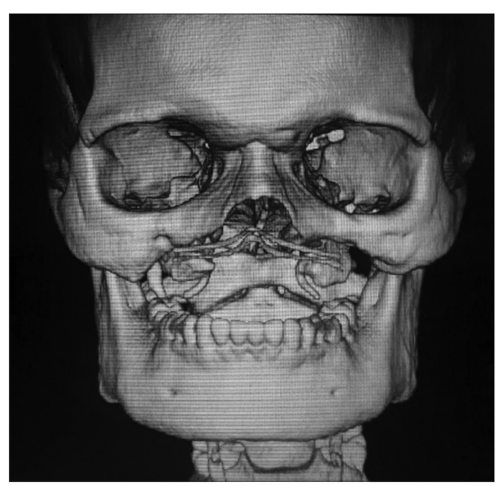

Figure 1: 3D Reconstruction depicting bilateral maxillectomy defect

Figure 2: Clinical intraoral image of bilateral maxillectomy defect

and, therefore, provides a continuous approximation of the facial geometry. An increase in accuracy is accompanied by an increase in the complexity of mathematical calculation and system requirements. Greater variations of stresses were divided into elements.

Post-discretization material properties are designed for elements. Material properties designated are Young's modulus or modulus of elasticity, Poisson's ratio, density, yield strength, etc., Amongst the above properties, Young's modulus and Poisson's ratio are more significant.

Before simulation in the model, the boundary conditions were assigned. After the boundary condition was assigned, loading was performed to stimulate the conditions. Loading is to be performed at specific nodes, and it is designated in terms of forces or displacement created by force. Vertical loads of 250 N and 135 N were applied at the posterior and anterior struts of the implant, respectively, as seen in Figure 3.

Load Name	Load Image	Load Details
Force.1		Value: 250 N, Force X: = 0 N, Force Y: = 0 N, Force Z: = 250 N Start Step: Static Step.1 End Step: Static Step.1
Force.2		Value: 135 N, Force X: = 0 N, Force Y: = 0 N, Force Z: = 135 N Start Step: Static Step.1 End Step: Static Step.1

Figure 3: Image depicting application of vertical loads

All materials involved in the models were assumed to be isotropic, homogenous, linearly elastic, and static. The implants in contact with the bone were assumed to be completely osseointegrated. The properties of materials used in this study, including Young's modulus and Poisson's ratio, were obtained from early literatures,[10] and that of the bones were calculated according to Zannoni *et al*.'s study. They have proved that Young's modulus has a fixed relationship with the apparent density of bones, which is equivalent to the gray value of the bones in CT images. So, Young's modulus differs depending on the area of bony materials.[11]

After the initial process is completed, the model is ready for analysis. Before analysis, the software checks the model or cross-verifies preprocessing. Stiffness is measured. An integral part of this step is the displacement of the node in three planes.

The displacements of each node in each of the three planes of space are then determined by solving a basic equation.

The displacement can be solved by the equation,

$F = [K]\, U$

F = Nodal force matrix

U = nodal displacement matrix and $[K]$ = global stiffness matrix

The nodal displacement was computed, and stresses were calculated.

The solution was derived, results were displayed and analyzed

RESULTS

The von Mises stress (VM) is a type of equivalent force that is frequently employed in the field of biomechanics. It can clearly represent the stress changes over the entire model, allowing the researchers to immediately identify the model's most risky region. In this work, the distribution of loads was evaluated using VM stresses on the supporting bones, superstructures, and struts. On the models, pseudo-colors are used to depict the stresses. The unstressed zones are shown in dark blue, whereas the most stressed sections are shown in red. The highest VM stresses were seen to be in what would have been the patient's zygomaticomaxillary buttress region, although none of the stresses absorbed were in the red zone, as shown in Figure 4. On loading, maximum displacement was recorded in the posterior-most strut of the implant, but that too was clear of the danger zone of the spectrum of stresses, as depicted in Figure 5.

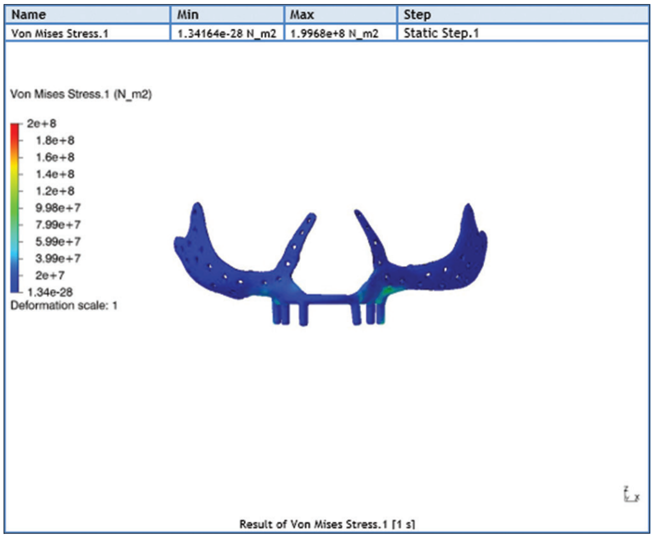

Figure 4: Color representation spectrum of von Mises stress distribution

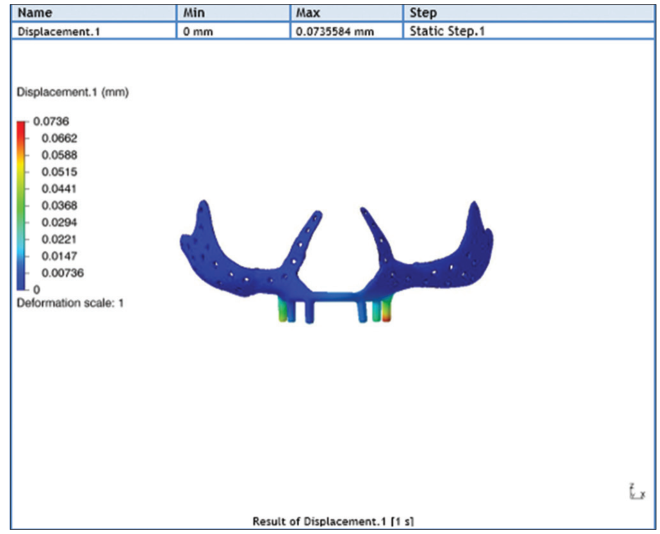

Figure 5: Color representation spectrum depicting displacement

DISCUSSION

Clough, in 1960 coined the term finite element method (FEM). The theoretical basis of FEM is to assign a structure into geometric shapes called an element. The property of a material and its relation to the surrounding structures is assigned. The loading and boundary conditions are estimated using a set of equations and arriving at solutions to understand the behavior of the object.[12] Engineering and biomechanics both make extensive use of the FEA, a digital approach. Because it is noninvasive and adaptable enough to simulate many sorts of deformities and accompanying reconstructive plans in the same model, this technology is becoming more and more popular among clinicians. There are many applications of FEA in the field of maxillofacial and reconstructive surgery, such as assessment of stress and micromotions along intraoral and extraoral distractors devices used in the mandibular distraction of post temporomandibular joint ankylosis deformed mandible patients[13] or patients suffering from hemifacial microsomia.[14] Evaluation of stress and strain distributions around loaded implants in atrophic maxilla by FEA has been used numerously in the past and has illuminated the way for evaluation of not only endosseous implants but also subperiosteal implants such as those in this very study.[15] In addition, the analysis process is colorful and visually appealing, enabling the researcher to evaluate and investigate any areas of interest.[16,17] The FEA studies in the past in the field of reconstructive surgery have highlighted the great potential for numerical simulations and 3D printing technology in artificial porous graft design and manufacture.[18] The present study focused on the problem of the biomechanical effects of prostheses supported by PSIs with a strut pattern of abutments in order to detect if the same could bear the average occlusal load of a healthy individual, taking into consideration the support offered by the zygomatic and nasal bones in a patient with bilateral maxillectomy defect. The osseointegration between the implant and alveolar bone can be damaged by excessive load, which has been demonstrated to increase the risk of bone fracture and make bone more brittle. Thus, PSIs must have extensions on the zygomatic and nasal bones in order to prevent excessive stress concentrations in the osseous tissue around the osseointegrated screw components of the implant. The zygomatic and nasal bones in the maxillofacial model supported stress caused by occlusal loading, according to this analysis of the impacts of PSIs in a computerized biomechanical model of the maxillofacial skeleton. The pattern of withstanding occlusal forces in the dentulous jaw is similar to the stress distribution in implants. Stress was primarily conveyed through the infra-zygomatic crest and partitioned into the frontal and temporal processes of the zygomatic bone when PSIs were loaded with occlusal forces. In maxillary prostheses with PSIs, stress was dispersed around the zygomatic and nasal bones. The maximum stress was 2 MPa, suggesting that the effects of occlusal force on the maxillofacial skeleton are minimal and that placement of extensions of the implants on zygomatic bone is feasible for dispersion of occlusal force.[19] In this study, it was assumed that was 100% osseointegration between the screws of the implant and the surrounding bone, which can be achieved by meticulous surgical technique.

The author finds that this treatment modality provides a convenient operator and patient-friendly solution that has a complete basis in scientific methodology based on the FEA results. Given that FEA is based on the mechanical properties of materials and the geometry of bones, it is well-known that these factors have a significant impact on the accuracy of stress distribution.[20] There is a paucity of existing literature in this particular spectrum of rehabilitation, as has been encountered in the great surge of patients reporting COVID-associated mucormycosis maxillectomy defects. It is the hope of the author that this study opens and widens the discussion to resolve the ultimate solution to this medical condition.

CONCLUSION

The technique in which pressures are distributed to the retainers and surrounding bones is a crucial aspect in determining whether a prosthesis will succeed or fail. This study will help medical professionals create the best prosthesis feasible for their patients in order to maximize their quality of life.

Data availability statement

The data that support the findings of the study are not openly available due to reasons of sensitivity and are available from the corresponding author upon reasonable request. Data are located in control access data storage at Government Dental College and Hospital, Nagpur.

Ethical clearance

Ethical Clearance was obtained from Government Dental College and Hospital, Nagpur Institutional Ethical Committee with Ref no IEC/05/67 dated 20/04/2022

Financial support and sponsorship

Nil.

Conflicts of interest

There are no conflicts of interest.

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