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Modelling and structural analysis of skull/cranial implant: beyond mid-line deformities

V PHANINDRA BOGU[1]*, Y. RAVI KUMAR[2], ASIT KUMAR KHANARA[3]

[1, 2] Department of Mechanical Engineering, NIT Warangal, Telangana, India.
[3] Department of Metallurgy Engineering, NIT Warangal, Telangana, India.

Purpose: This computational study explores modelling and finite element study of the implant under Intracranial pressure (ICP) conditions with normal ICP range (7 mm Hg to 15 mm Hg) or increased ICP (>I5 mm Hg). The implant fixation points allow implant behaviour with respect to intracranial pressure conditions. However, increased fixation points lead to variation in deformation and equivalent stress. Finite element analysis is providing a valuable insight to know the deformation and equivalent stress. *Methods*: The patient CT data (Computed Tomography) is processed in Mimics software to get the mesh model. The implant is modelled by using modified reverse engineering technique with the help of Rhinoceros software. This modelling method is applicable for all types of defects including those beyond the middle line and multiple ones. It is designed with eight fixation points and ten fixation points to fix an implant. Consequently, the mechanical deformation and equivalent stress (von Mises) are calculated in ANSYS 15 software with distinctive material properties such as Titanium alloy (Ti6Al4V), Polymethyl methacrylate (PMMA) and polyether-ether-ketone (PEEK). *Results*: The deformation and equivalent stress results are obtained through ANSYS 15 software. It is observed that Ti6Al4V material shows low deformation and PEEK material shows less equivalent stress. Among all materials PEEK shows noticeably good result. *Conclusions*: Hence, a concept was established and more clinically relevant results can be expected with implementation of realistic 3D printed model in the future. This will allow physicians to gain knowledge and decrease surgery time with proper planning.

Key words: *intracranial pressure, finite element analysis, beyond mid-line defect, fixation points*

1. Introduction

Cranioplasty [7] deals with treatment of skull injuries and defects with an established surgical procedures. The main aim of these procedures is to restore the protective function of the skull and cranial aesthetics. To date various materials have been used for the treatment of cranial defects – Titanium alloy (Ti6Al4V), Polymethyl methacrylate (PMMA) and Polyether-ether-ketone (PEEK).

The medical imaging techniques, Computer Aided Design and Manufacturing techniques (CAD/CAM) offer new possibilities in fabrication of patient specific titanium and PMMA and PEEK implants with 3D printing technology. Most of the customized cranial implants are fabricated based on patient specific data [14], [1], [10], this data is in Digital Imaging and Communications in Medicine (DICOM) format obtained from Computed Tomography (CT) [9], [7], [11] and Magnetic Resonance (MRI). A typical spatial resolution in microns with less slice thickness is required to get better solid model for hard tissues. This acquired image data sets are processed and subsequently converted into Standard Tessellation language (STL) file formats that are required for 3D printing [10].

The skull is symmetrical for many humans. The skull injuries were categorized into symmetrical and asymmetrical defects [9]. In symmetrical defect, the malformation portion can be planned with an ordinary side of the skull [7], [9], [10] through Computer

* Corresponding author: V Phanindra Bogu, NIT Warangal, Mechanical Department, 506004 Warangal, India. Phone: +919866046824, e-mail: phanibogu@gmail.com
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Aided Modelling software (Rhinoceros). The asymmetrical defect was not full filled by mirroring technique. These asymmetrical defects and complex deformities which include multiple injuries deal with reverse engineering technique [9], [5], [18]. A slight modification of reverse engineering technique is required to model an implant for beyond midline defects.

PMMA, PEEK and titanium alloys are most commonly used materials [10], [4], [3], [12], [21], [14] in the fabrication of customized patient specific implants [5], [12], [17]. However, these materials are substantially bio-compatible, successfully implanted for skull and femur bone injuries. The PEEK is successfully implanted in Mexico for an oncology patient [3]. Furthermore PEEK and PMMA [3], [21] materials are safe, lightweight and easy to use. These materials do not produce blemishes on computed tomography (CT), which makes it easy to follow-up the oncology patient.

The pressure inside the cranial cavity is called intracranial pressure (ICP) [2], [13]. It varies with age, body position and affects the cranial implant after surgery. The normal range of ICP is 7–15 mm of Hg [2], [20] for an adult human being. An effective way of analysing implant design is by performing finite element (FE) based simulations [6], [16], [21], [19]. This methodology can be employed to assess the deformation and equivalent stress in the implant with respect to variables in the design.

The PEEK and titanium alloy implants are commonly produced and fabricated by 3D printing. Lack of standardized methodologies, potentially leads to unsuccessful treatment associated with clinical and financial implications. The aim of this study is to model the cranial implant for beyond mid-line defects and to investigate the mechanical behaviour of skull implant at various loading conditions with respect to fixation points.

2. Modelling of an implant: Beyond mid-line defect

The DICOM (Digital Imaging and Communications in Medicine) images are processed in MIMICS software [11], [19] to get mesh file of the skull. The patient skull was assumed to be symmetrical along its mid-sagittal plane (Fig. 1a), the replication of missing bone fragment (red colour skull) mirrored from original skull. However, frontal bone of skull is not filled properly (Fig. 1b). This case comes under beyond mid-line defect.

Contour profile of an implant is not obtained through the projection of mirrored data of skull. The modified reverse engineering technique is [5], [18] (uses surface interpolation, such as a NURB (Non uniform rotational B-spline) surface [4], [9]) an approximation method to develop the surface for cranial hole with proper fitting.

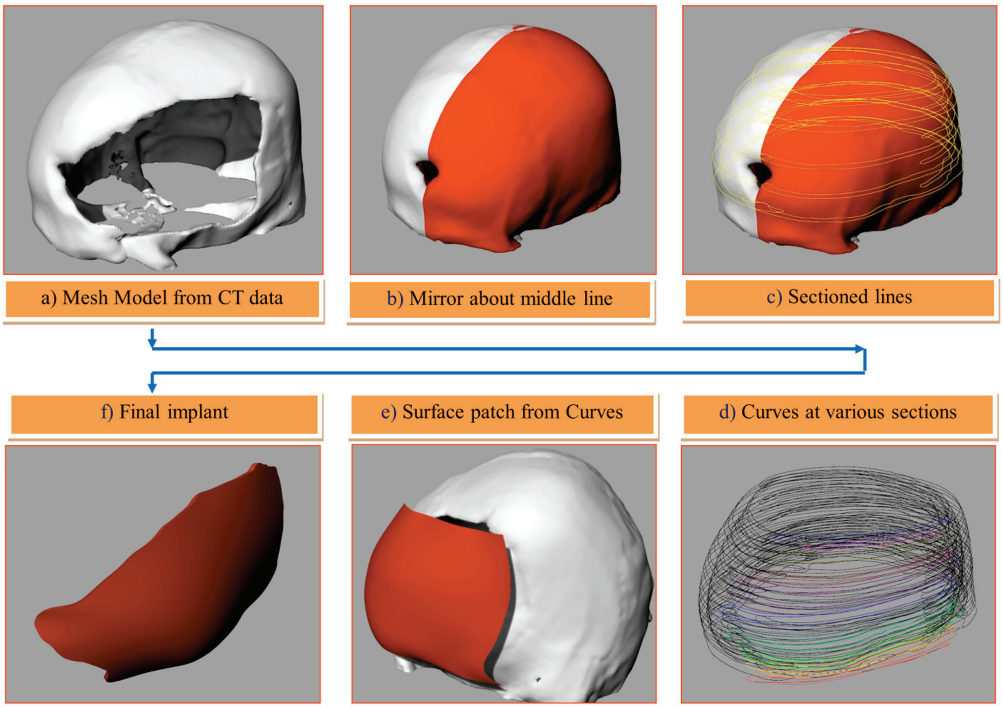

Fig. 1. Flow chart for modelling of the skull implant

This technique is applied to control the surface by using profile curves and to fill frontal portion of skull. Before modelling of an implant, skull is sectioned at various levels based on height (Fig. 1c) and a total of 24 sections are considered (Fig. 1d). On each sectioned layer a profile curve is drawn and the shape of profile curve follows based on sectioned layers of mirrored skull. From Fig. 1d, black line indicates sectioned layer and colour line indicates profile curve.

The surface patch is generated with profile curves (Fig. 1e) and a best-fitted surface is obtained through a trimming operation. The surface was extruded perpendicularly at a length of 4 mm and chamfered the edges with 30–45 degrees (Fig. 1f). These chamfered edges are utilized to fit an implant appropriately with the skull [1], [17].

3. Material properties

The material properties are assumed to be linearly elastic, homogeneous and isotropic. For this study, Titanium alloy (Ti6Al4V), Polymethyl methacrylate (PMMA) and Polyether-ether-ketone (PEEK) materials [15], [16] are considered for finite element analysis.

4. Loading conditions

A static pressure of 7 mm Hg and 15 mm Hg [2], [13] are considered based on intracranial pressure conditions; the pressure was applied on the inner surface and evenly distributed over an area of implant (Fig. 2). These implants were fixed at holes for two different cases: with 8 fixation points (a, b, c, ..., g, h) and 10 fixation points (a, b, c, ..., g, h, i, j). These are categorized into case1 and case2.

5. Computational model

5.1. Meshing and validation

The STL file [10], [18] is discretized with tetrahedral elements [6], [16] by using ANSYS 15 software. Element size allows the edge length to be specified for entire model (Fig. 3). When tetrahedral element size decreases, the accuracy of a component, file size and number of elements increases. Therefore, the element size is fixed at 0.5 mm in both cases. However, the volume of model is compared before and after meshing and there is observed only a difference of 2–3% with fine mesh.

Table 1. Material properties for skull implant

Material properties for structural analysis			
	Titanium alloy (Ti6Al4V)	Polymethyl methacrylate (PMMA)	Polyetheretherketone (PEEK)
Young's modulus	110000 MPa	3000 MPa	4000 MPa
Poisson's ratio	0.3	0.38	0.4
Ultimate tensile strength	950 MPa	72 MPa	103 MPa
Yield strength	800 MPa	72 MPa	100 MPa
Density	4430e-9 Kg/mm^3	1180e-9 Kg/mm^3	1360e-9 Kg/mm^3

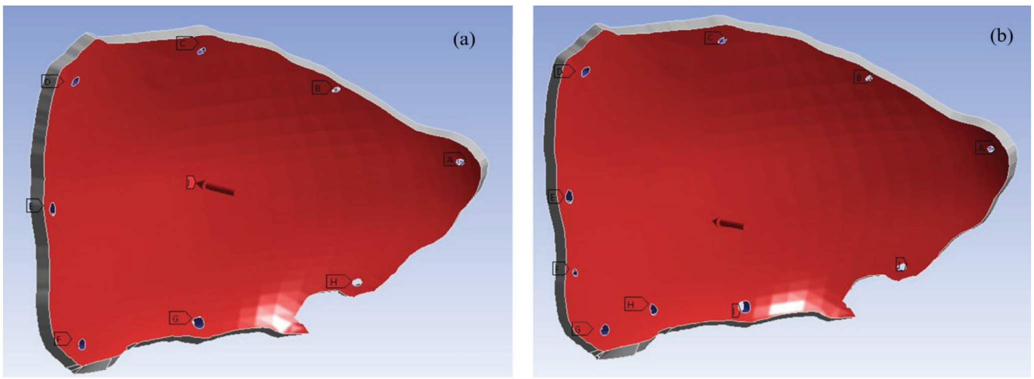

Fig. 2. Fixation points: (a) Case 1: 8 fixation points, (b) Case 2: 10 fixation points

Table 2. Loading data for finite element analysis

Loading data		
	Minimum load	Maximum load
Intracranial pressure	7 mm of Hg (9.34e-4 MPa)	15 mm of Hg (2e-3 MPa)

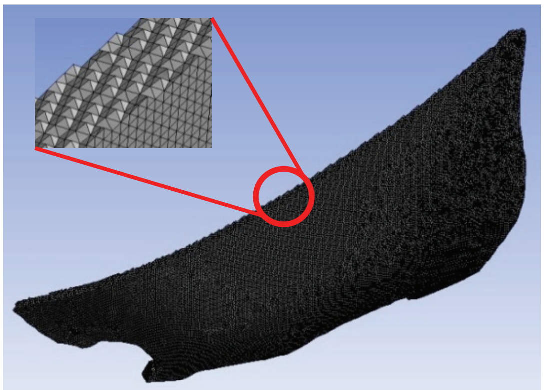

Fig. 3. Cut section model
with tetrahedral element size of 0.5 mm

The validation of numerical analysis on bio-realisticity models is quite complex, when targeting a patient. The verification of theoretical model becomes the fundamental aspect [22] and many predictions come into picture.

Convergence studies are conducted on model with different element sizes to get optimum mesh density in terms of processing time and accuracy to validate the grid dependence. The results of all models are almost the same. However, the models of 2.333 million elements (case1) and 2.327 million elements (case2) converge faster (Table 3) than the others due to mesh quality. Therefore the same method is applied for all other models. There is no appearance of hourglassing due to less complexity of an implant.

This implant is merely recommended for preoperative planning as this study was not yet recommended by clinicians with a guideline. The results are presented here for future perspective and it is fundamentally difficult to validate with numerical analysis [8].

6. Results

A total of 12 combinations are obtained in two cases with respect to the type of implant materials and loading conditions. They are simulated and analysed to evaluate the total displacement and equivalent stress. The higher stress magnitudes were mainly concentrated at near to the centre of an implant.

6.1. Case1

It is observed that Ti6Al4V shows low deformation when compared with PEEK and PMMA. The deformation is 2.9068e-5 mm at minimum load and 6.2244e-5 mm at maximum load.

It is observed that PEEK shows minimum equivalent stress when compared with Ti6Al4V and PMMA. The equivalent stress is 0.21246 MPa at minimum load and 0.45494 MPa at maximum load.

Table 3. Mesh data for both cases: (a) 8 fixation points, (b) 10 fixation points

Implant data		
	Case1: 8 fixation points	Case2: 10 fixation points
Max element size	Edge length = 0.5 mm	Edge length = 0.5 mm
Nodes	437982	437225
Elements	2333003	2327897
Volume (mm^3)	20800	20782

Table 4. Deformation and equivalent stress analysis report for case1 (8 fixation points)

Structural analysis report	Case1					
	Titanium alloy (Ti6Al4V)		Polymethyl methacrylate (PMMA)		Polyetheretherketone (PEEK)	
	Min load	Max load	Min load	Max load	Min load	Max load
Deformation (mm)	**2.91e-05**	**6.22e-05**	1.03e-03	2.20e-03	7.62e-04	1.63e-03
Equivalent stress (von Mises) MPa	0.22649	0.48499	0.21606	0.46265	**0.21246**	**0.45494**

6.2. Case2

It is observed that Ti6Al4V shows low deformation when compared with PEEK and PMMA. The deformation is 2.0499e-5 mm at minimum load and 4.3616e-5 mm at maximum load.

It is observed that PEEK shows minimum equivalent stress when compared with Ti6Al4V and PMMA. The equivalent stress is 0.1801 MPa at minimum load and 0.38319 MPa at maximum load.

From Fig. 4, it is observed that in both cases the deformation and equivalent stress increase with an increase of intracranial pressure and decrease with an increase of fixation points.

6.3. Observation of Polyether-ether-ketone (PEEK) material at maximum load

Considering case1 at maximum load, the maximum deformation shows in between "e", "f", "g" points and stresses were developed near to "a", "f" points (Fig. 5).

Table 5. Deformation and equivalent stress analysis report for case2 (10 fixation points)

Structural analysis report	Case2					
	Titanium alloy (Ti6Al4V)		Polymethyl methacrylate (PMMA)		Polyetheretherketone (PEEK)	
	Min load	Max load	Min load	Max load	Min load	Max load
Deformation (mm)	**2.05e-05**	**4.36e-05**	7.21e-04	1.53e-03	5.34e-04	1.14e-03
Equivalent stress (von Mises) MPa	0.19258	0.40974	0.18302	0.38941	**0.1801**	**0.38319**

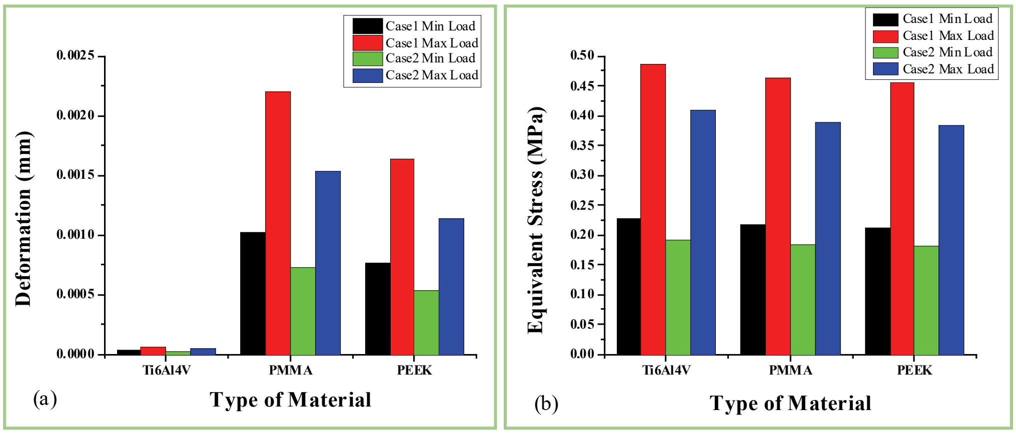

Fig. 4. (a) Deformation values for both cases at maximum and minimum load conditions, (b) equivalent stress values for both cases

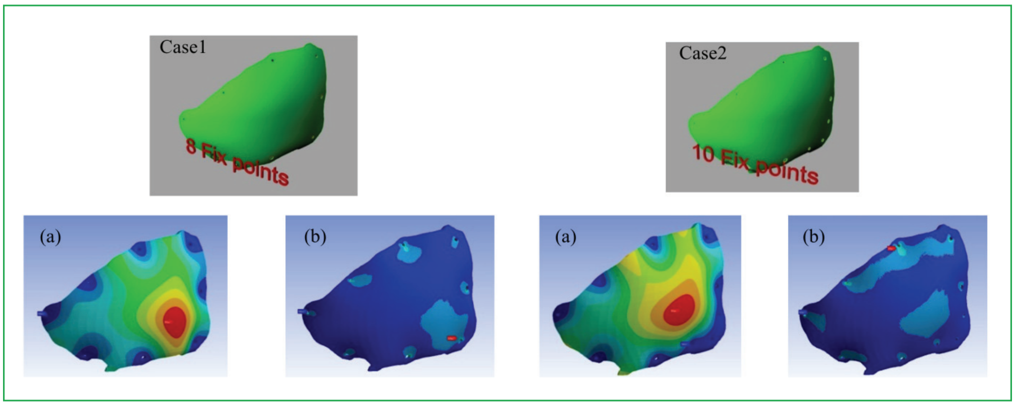

Fig. 5. Case1 and Case2: (a) deformation at maximum load, (b) equivalent stress at maximum load

Considering case2 at maximum load, due to addition of “i” and “j” points, the deformation moves towards “b”, “c”, “d” points from “e”, “f”, “g” points and stresses were developed near to “a” and “c” points (Fig. 5).

7. Discussion

The finite element study explored [21] the specific role of cranial implant at intracranial pressure conditions through computational simulations. The deformation and equivalent stress are induced in customized PEEK, PMMA and Ti6Al4V implants with respect to ICP and fixation points. A total of 12 fine mesh models were simulated and analysed. The effect of intracranial pressure on the implant at various conditions was studied and fixed at different points to attain stability with respect to skull.

The tetrahedral mesh is generated for STL file with the help of ANSYS 15 software [16], this is used for faster computation, ensures refinement of the mesh wherever necessary and maintains element size wherever possible. The volumetrical change of an implant is observed nearly 3–6% in coarse mesh and it leads to accuracy of results, due to this reason fine mesh is selected.

The deformation and stresses are changed with changes in ICP and fixation points (Fig. 5). From results, Titanium alloy (Ti6Al4V) and Polyether-ether-ketone (PEEK) implants show better results [3], [14]. Comparing both cases, low deformation is observed in PEEK material implant and low equivalent stress is observed in Ti6Al4V material implant (Table 4 and Table 5). PMMA stress values are near to PEEK material.

The stress distribution patterns in the implant with respect to different materials and various pressure conditions are comparable. Higher equivalent stress magnitudes are mainly concentrated at fixation points and deformation magnitudes are concentrated at the centre of PEEK implant (Fig. 5). Considering fixation points, the equivalent stress and deformation magnitudes change with respect to intracranial pressure.

The reverse engineering technique [9] is used to model the surface body from 3D scanned or STL file, this method is modified and applied to model the implant for beyond mid-line defects with respect to patient specific data [14]. Through this work, the implant cost will be reduced due to Rhinoceros software.

8. Conclusion

The modelling of an implant is done in Rhinoceros software with modified reverse engineering technique for beyond mid-line deformity and structural analysis was performed through ANSYS 15 software for Ti6Al4V, PMMA and PEEK materials at minimum and maximum load conditions.

It was observed from the results that the Ti6Al4V shows low deformation and PEEK shows low equivalent stress. However, PEEK ensures better results in all aspects. Much better results can be achieved with implementation of realistic 3D printed model in the future.

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