IJAPIE-2016-04-210, Vol 1(2), 47-52

INTERNATIONAL JOURNAL OF ADVANCED PRODUCTION AND INDUSTRIAL ENGINEERING

(A Blind Peer Reviewed Journal)

Temporal Bone Fabrication using FDM Technique: Issues and Opportunities

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Abstract: *Study and dissection of cadaver bones is one of the best way to enhance the skills of surgeons, thus improving the rate of succession in surgery. Dissecting cadaver temporal bone is best teaching technique in otolaryngology. Due to several constraint in the easy availability of cadaver temporal bone like ethical, legal, religious, etc. it is not possible to ensure frequent availability of cadaver temporal bone for study and dissecting purpose. However, nowadays due to development of innovative processes like Additive Manufacturing (AM), it is possible to fabricate a part with higher accuracy irrespective of its geometrical complexity. AM process is being frequently used in different applications like medical, aerospace, tooling etc. However, the data preparation phase is a critical stage in the fabrication of medical parts through AM processes, because it affect the final geometrical features. In this study, a detailed data preparation phase is discussed and implemented for the fabrication of temporal bone with FDM based AM process. It consists of three main categories i.e. image acquisition, image post processing, 3D printing. FDM fabricated bone part is further dissected to demonstrate the capability of proposed method by checking features in the fabricated model. Features such as foraminae, canals, suture lines, ossicles are ensured in an artificial model. A patient specific anatomical model can be printed with proposed method, can be used as pre-surgical planning, mock surgery, educational or demonstration purpose. Fabricated model can be used to demonstrate surgical operation viz. simple mastoidectomy, modified mastoidectomy, and radical mastoidectomy.*

Keywords: *Anatomical Model, Rapid Prototyping, Fused Deposition Modelling, Mock Surgery, Pre-Surgical Planning, Temporal Bone.*

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1. INTRODUCTION

The temporal bone is one of the most complex part of the body. Highly skilled otolaryngologist are required for carrying ear surgery. Otolaryngologist skills can be best developed by performing mock surgery on temporal bone. Currently, mock surgery of temporal bone is performed on cadaver temporal bones, availability of cadaver temporal bones are very limited, they also carry infectious agents such as mycobacterium tuberculosis, hepatitis B and C viruses and prions associated with encephalopathies such as Creutzfeldt-Jakob disease, one can avail the temporal bone only if the body is donated to the hospital or body is unclaimed in the case of an accident. The cost of cadaver temporal bone also vary in many countries, and few of them have prohibited the use of cadaver temporal bone due to the moral and ethical ground or for religious reasons [1]. However, medical research institute have rights whether to accept the body or not. It may be possible that the donor is suffering from some dangerous disease that can be transmitted to the surgeon while practicing on temporal bone. Temporal bone is shown in Fig. 1.

To avoid this situation, artificial temporal bone can be fabricated. Fabricating temporal bone is difficult because of the complex internal anatomical structure. Hence, it is fabricated using the Additive Manufacturing technique.

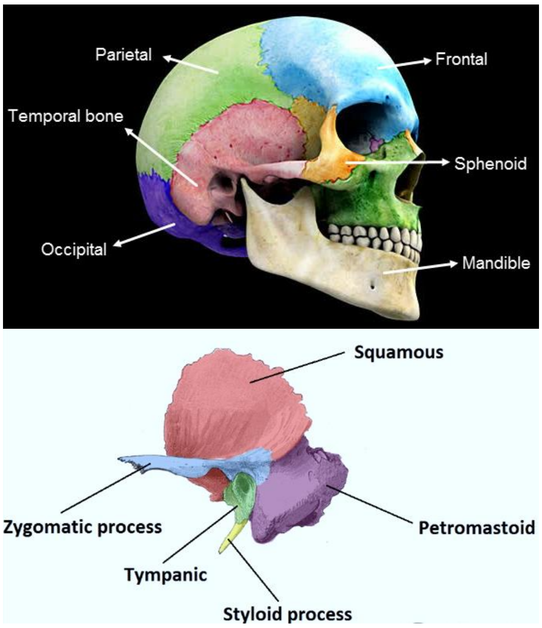


Fig. 1. Temporal Bone.

Additive Manufacturing is one of the most demanded technology this century. With the use of this technology, one can create an object with any complexity with reduces manufacturing lead time [2]. Since the part is fabricated by adding layer by layer, it is also known as layer manufacturing or 3D Printing [3, 4]. CAD model is prepared for the part to be fabricated using modelling package, i.e., SOLIDWORKS, CATIA, Rhino, PTC CREO, etc. Model is then tessellated and sliced by selecting optimum build orientation [5, 6, 7]. After slicing tool path is generation and part is fabricated by adding layers upon layers, typical AM cycle is shown in Fig. 2. AM techniques can be broadly classified into three categories, i.e., Solid Based (FDM, POLYJET and LOM), Liquid Based (SLA, SGC and CLIP) and Powder Based (SLS, 3D Printing, LENS and SLM). Out of these techniques, FDM is having great potential because of its low cost. Additive Manufacturing has numerous application in various fields viz. design, engineering analysis and planning, manufacturing and tooling, bio-medical applications [8].

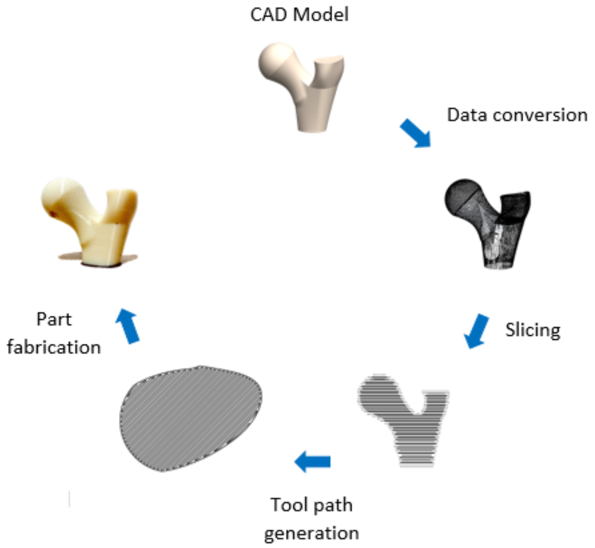


Fig. 2. Typical AM Cycle.

Various attempts have been made for AM of bio-medical parts. Bio-medical AM model can be used for medical education, pre-surgical planning, custom made implants, tissue engineering, design and development of the medical device and instrument [9][10]. Creating accurate 3D model of any bio-medical object is a difficult task because of its complex anatomical structure. A bio-medical model can be generated through following steps i.e. image acquisition, image post-processing, 3D printing, Fig. 3 [11].
Some researchers have tried to make an artificial temporal using powder technique but FDM techniques are usually neglected. Jordan et al. have developed artificial temporal bone using 3D printing technique. They have used different types of infiltrants agents to improve the hardness of the artificial bone. Different infiltrants agents used were Cyanoacrylate with Hydroquinone (CAH), Beta-Methoxyethyl Cyanoacrylate (BMCA), Neopentyl Glycol Diglycidylether (NPGD), Saline (NACL) [12].

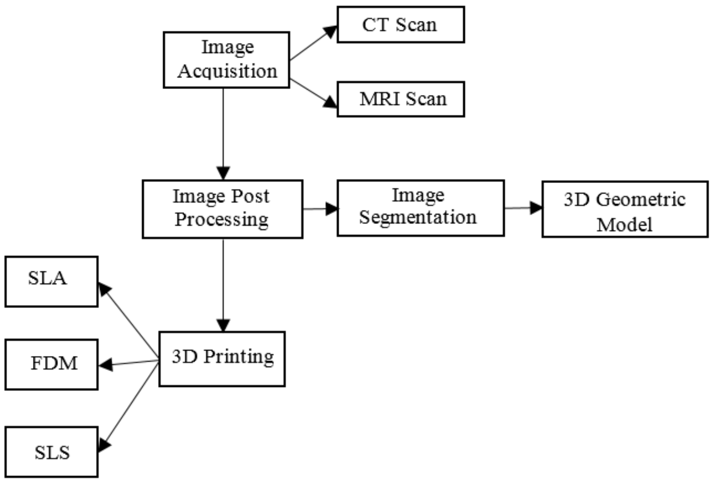


Fig. 3. Process to Create Biomedical AM Model.

In another work of Jordan et al., they have developed artificial temporal bone using 3D printing technique and have compared it with virtual haptic temporal bone. Likers scale test have been carried out for validation. It was seen that artificial temporal bone got a higher rating as compared to virtual model [13].
Austin et al. have created an artificial temporal bone model for surgical simulation. They have used two different CT scan of cadaveric temporal bone. High resolution CT scan with slice thickness of 0.3mm and other with micro CT. They have printed the temporal bone using SLA technique. Likers scale questionnaire was used to validate the internal anatomy of temporal bone [1].
In another work of Austin et al. they have created a model of artificial temporal bone for pre-operative simulation of pediatric mastoid surgery. Case report of 11 year old boy with contracted right mastoid and recurrent cholesteatoma status prior tympanomastoid surgery was considered [14].
FDM have several advantages as compared to other processes [2]. The cost of print is very less with FDM technique, however removal of support material is difficult for temporal bone as well as there are chances of delamination of layers of temporal bone and removal of support is also a major problem.

2. MATERIALS AND METHODS

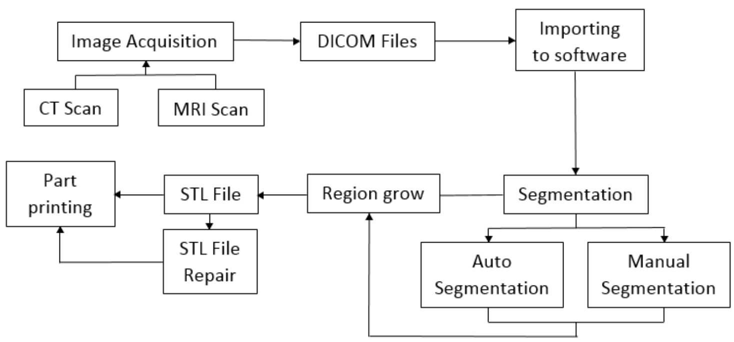
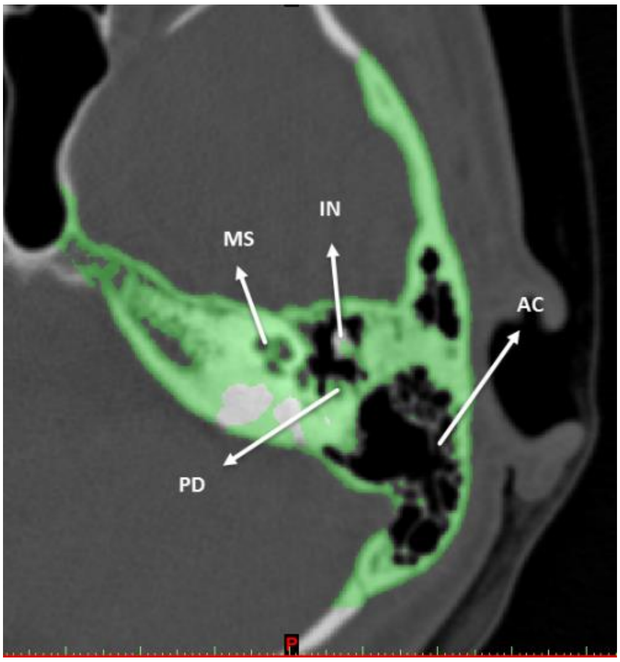
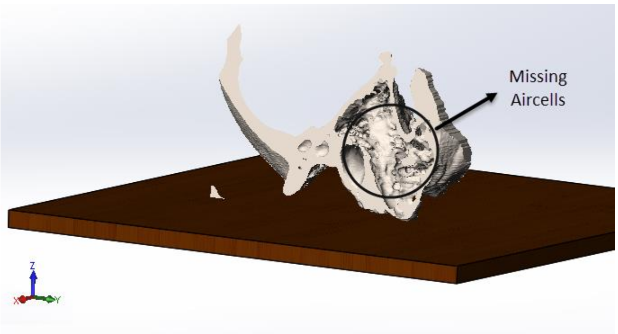


Fig. 4. Methodology Adopted For Fabrication Temporal Bone Model.

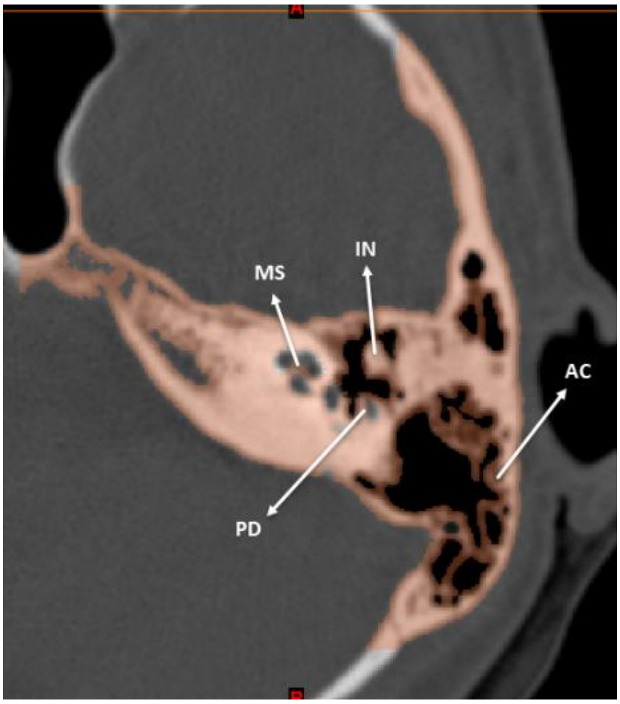
The medical imaging technique was used for the creation of a geometric model of the temporal bone. CT scan of a normal human with a slice thickness of 0.625mm was used for a creation of the geometric model of the temporal bone. MDCT (Philips) was used in this study. Digital Imaging and Communications in Medicine (DICOM) files obtained from CT scan was then transferred to medical image processing software, Mimics (Materialise, Belgium) for a creation of the 3D geometric model. After selecting proper thresholding value, auto segmentation is done to separate bone from surrounding structures. Segmentation is done based on the density of the pixel in CT scan. If the value of the density of pixel doesn't lie between the thresholding values of bony structure then that region will not be considered as bony structure. So in such cases, manual segmentation is needed to model the missing features. After auto segmentation and manual segmentation, complete 3D model of a skull is created by connecting proper voxel, Fig. 5



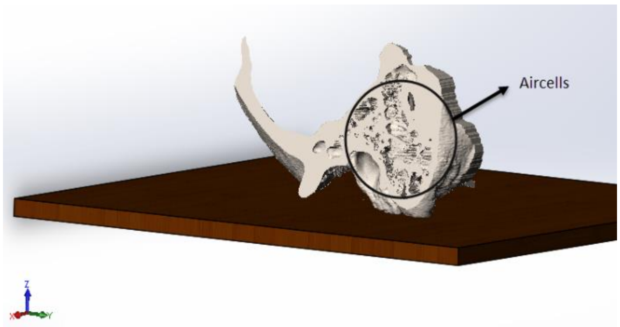
(a)



(b)



(c)



(d)

Fig. 5. a, b: Missing Features In CT Scan, Geometric Model; c, d: Complete Features In CT Scan, Geometric Model; IN- Incus, AC- Aircell, PD- Pyramid, MS- Modulus.

The temporal bone is then accurately cut from surrounding bony structure from suture lines. The model was then transferred to 3 Matics design module were all sharp edges are refined and smoothen and final geometric model is created. The developed geometric model is then converted into STereoLithography (STL) files and errors in the STL file are removed in 3 Matics module. Corrected STL file is transferred to 3D printer software (Stratasys Insight Software) for slicing, after selecting optimum build orientation and process parameters, it is printed using FDM technique on Stratasys Fortus 400mc printer. ABS material is used for printing temporal bone. The support material is used for overhanging features. 3D printed bone is then dipped into the solution for removal of support material, sonic pulse accelerates the speed of dissolving the support material. Artificial temporal bone model was then dissected using surgical drill burr, to validate its geometric accuracy. Features such as foraminae, canals, suture lines and plates were evaluated in the 3D printed bone. External acoustic canal and internal acoustic canal is measured in an artificial model as well as in CT scan. Dissection of the artificial bone was done by an experienced surgeon to evaluate the features.

3. RESULTS

3.1. EXTERNAL FEATURES

Artificial temporal bone model is created Fig. 6, which can be used for mock surgery, pre-surgical planning, and surgical simulation.

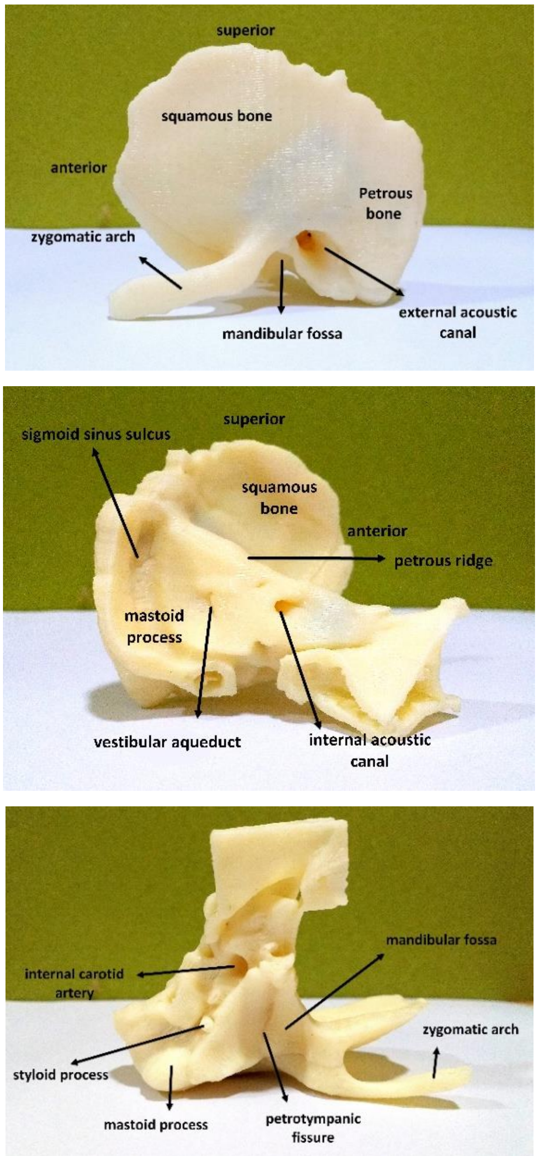


Fig. 6. Artificial Temporal Bone.

However, layered structure can be observed in the model. External features such as external acoustic canal, internal acoustic canal, zygomatic process, sigmoid stylus, suture lines can be seen in artificial bone which will help the surgeon for proper orientation while dissection. Surgical drilling is done to explore the internal features. Drill response of ABS is less than actual bone since the density of ABS is less than bone density. Artificial bone also produces dust while drilling same as bone dust. Proper care should be taken while dissecting the artificial bone. Foraminae, suture lines can be identified easily in the model

3.2. INTERNAL FEATURES

Aircell provide cushion effect to the internal ears Fig. 7. Aircell are having overhanging features hence, it requires support material while printing. Removal of support from aircell is a big challenge. Temporal crest, spline of henle landmarks are present which helps in drawing MacEwen's triangle. i.e. entry point for simple mastoidectomy. Simple mastoidectomy, modified mastoidectomy and radical mastoidectomy were performed to evaluate incus, malleus, stapes, round window, lateral canal, posterior canal, superior canal, cochlea, facial nerve. Aditas was the entry point for the second region. Sinus plate, dural plate, sinodural angle can be located easily.

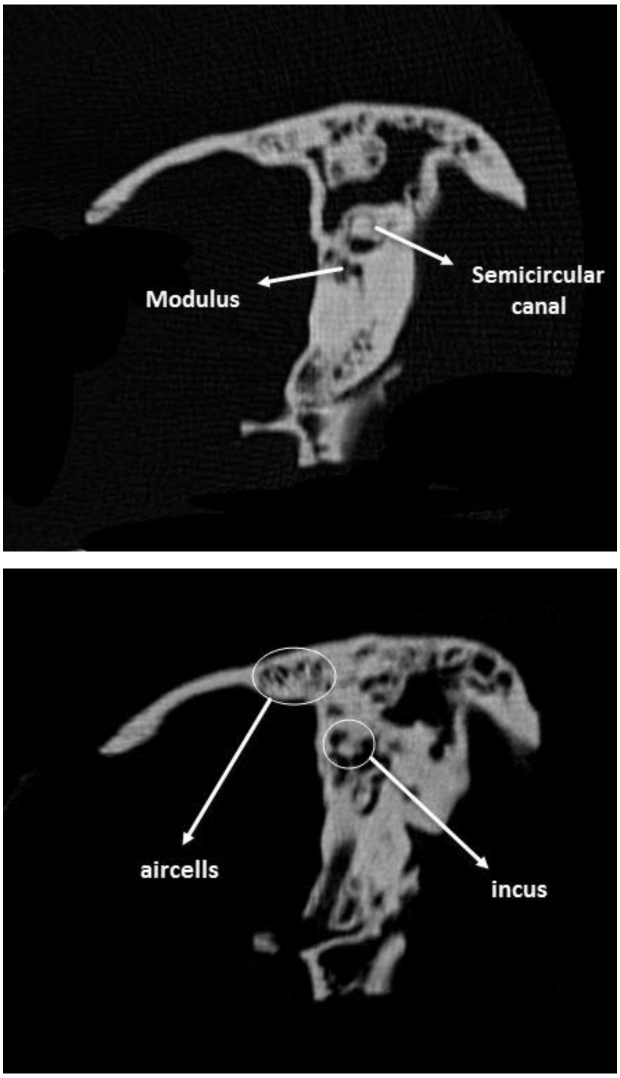


Fig. 7. CT Scan of Artificial Temporal Bone (ABS).

4. DISCUSSION

Replica of temporal bone can be fabricated using AM technique. Most of the landmarks and features were easily identified. Almost all internal anatomical structures are preserved in the model. For processing of DICOM files many software are available, some are free and some are paid. Mimics (Materialise, Belgium) Software is been used for this study. Each software is having its own advantages and limitation. Some free software's are 3DSlicer, ITK Snap, VTK software. Manual segmentation helped in adding all the missing features in the model. Creating suture lines and local smoothing is done in 3 Matics module. Removal of support from the mastoid region is one of the most difficult step in the whole cycle since vibrating pulse were not able to reach each and every section. For easy removal of support temporal bone is cut along an arbitrary plane. The bone is then fabricated into two pieces as shown in Fig. 8.

Fig. 8. Printed Temporal Bone in Two Half.

Standard adhesive was used stick both the half of temporal bone. This technique ensures easy removal of support and support removal time is also reduced. It was observed that chip formation while drilling the bone was same as that of actual bone as shown in Fig. 9, thus proper precautions must be taken while drilling the artificial bone such as eye protector, gloves.

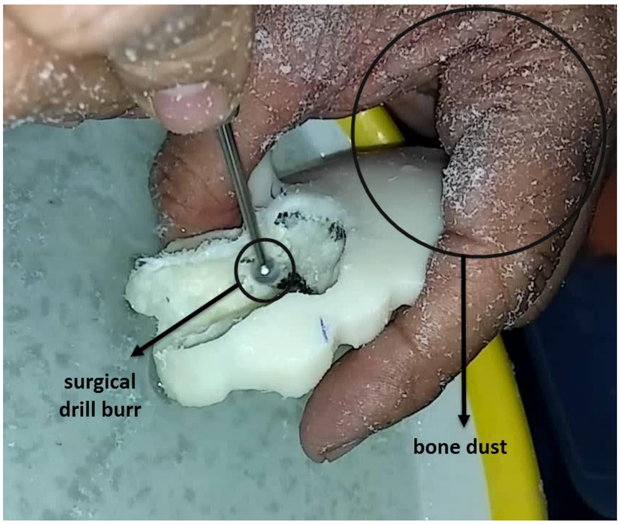


Fig. 9. Chip Formation (Bone Dust) While Dissecting Artificial Temporal Bone.

The most time consuming step in this whole cycle is the creation of geometric model. It took nearly 5 to 6 hours to create an anatomical model, the addition of features requires another 5 to 6 hours. STL file repair is also one of the challenging task. One needs a good knowledge about STL errors to correct STL file, wrong technique for removal of one error may lead to addition of another error in STL. Printing the model usually takes 6 to7 hours, support removal can take up to 10 to 12 hours. Thus, patient specific anatomical model can be made within 30 to 35 hours which can be used for pre-surgical planning, mock surgery. Using local smoothing sharp edges were removed from the model. ABS M30 (38.737 cm^3) material was used as print material and SR-20 (22.726 cm^3) material was used as support material. Artificial temporal bone will cost around ₹ 4000/-. With the use of low cost 3D printer cost of the artificial model can be reduced

Table 1: Features Ensured in Temporal Bone Model.

S. No	External Features	S. No	Internal Features
1.	External acoustic canal	1.	Incus
2.	Internal acoustic canal	2.	Malleus
3.	Facial Nerve	3.	Ossicles
4.	Zygomatic Process	4.	Canals
5.	Arnold’s nerve	5.	Cochlea
6.	Glaserian fissure	6.	Round window

Simple mastoidectomy, modified mastoidectomy, radical mastoidectomy can be performed in the artificial model. It has a great potential in serving as a training tool, pre-surgical simulation, and mock surgery. Medical student and practitioners can use this model for their training. It is free from any bacteria and infection virus as that of cadaver bone and availability of cadaver temporal bone is also a major problem [15]. Because of the limitation of layer thickness with FDM technique, stair steps can be easily visible with naked eye on the printed model, stair steps can be reduced by using SLA or SLS technique, but cost of the model will also increase. This study provides useful insights and can be served as a good substitute against dissection of cadaver temporal bone.

5. CONCLUSION

By using this study a process can be defined to create an anatomically correct model, which can be printed easily at low cost and minimum time with maximum anatomical features. This model can be used as a substitute of cadaver temporal bone. For educational, demonstration purpose. A patient specific anatomical model can also be made quickly and easily for pre-surgical planning and mock surgery.

Acknowledgement

Authors thankfully acknowledge Galaxy Scan Center for providing CT scan data, Dr. Prashant Naik (Naik’s Hospital, Nagpur) for his unconditional support and performing mock surgery. The authors would also like to thank SERB-DST for sponsoring the project on “Development of Additive-Subtractive Integrated RP System for Improved Part Quality” and allowing us to use the setup developed at IIITDM Jabalpur for Part Fabrication.

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