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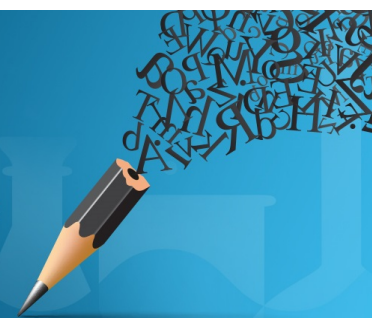


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Reimagining Innovation in Cranial Reconstruction: Virtual Planning and Cost Effectiveness of Additive Manufacturing

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Abstract. This study aims to reconstruct cranial defect for virtual surgical planning and assess the cost-effectiveness of four different additive manufacturing techniques whenever 3D printing of cranial mould is required for actual reconstruction purpose. 3D images of the skull with cranial defect were obtained and segmented using an image processing software followed by generation of a virtual 3D model. The defect part was reconstructed to obtain a patient-specific implant. Computer aided design software was then used to design a mould. The mould was transferred to four different additive manufacturing machines of fused deposition modelling (FDM), selective laser sintering (SLS), multi-jet modelling (MJM) and stereolithography (SLA) to assess the material consumption and printing time for cost estimation purpose. The implant fit the defect part and the mould was successfully fabricated from the designed implant. 3D printing of a mould using an FDM technique significantly reduced the material consumption, hence reduced the cost to be borne by patient. Virtual reconstruction allows surgeon to visualise the defect condition prior to actual operation, while exploration of the cost of different 3D printing techniques provides more option for patient with cranial defect to obtain regular cosmesis at a reasonable cost.

INTRODUCTION

Patients with cranial defect due to trauma, chronic disease or congenital disorder often opt for a surgical procedure to regain their regular appearance. The procedure which normally refers to cranioplasty is applied to correct the deformity by filling the defect region with synthetic or natural biomaterials [1]. Natural biomaterial is typically selected for small or medium defect while synthetic biomaterial which ranges from metal, ceramic, polymer and composite are required to treat large cranial bone defect.

Pre-visualizing a surgical intervention is crucial to define essential steps involve as the defect varies and depend on the anatomical condition of the patient. Implementation of virtual surgical planning for cranial reconstruction reduces the operative time although there is no difference in blood loss [2]. However, for different area of interest such as mandibular reconstruction, virtual planning does not necessarily reduce the cost and risk of complications [3], that more research is required to support the finding.

The advancement in computer aided design (CAD) and computer aided manufacturing (CAM) for biomedical application enable the creation of three-dimensional (3D) bio-model [4] at a relatively affordable price. CAD/CAM in combination with imaging modalities such as computed tomography (CT) and cone-beam computed tomography (CBCT) assist the creation of bio-model via acquisition of anatomical data, image segmentation and creation of virtual 3D model prior to 3D printing process [5]. The technology enables the

creation of artificial skull for surgical training. The created bio-model is preferred over a human cadaver model as issues such as ethics, legal and cross infection could be eliminated [6].

Using CAD/CAM, Hueh and co-workers [7, 8] proposed a new method for cranioplasty where patient's own bone was topped up with alloplastic material to cover the defect part. However, a negative mould (gypsum mould) needs to be fabricated based on the 3D printed cranial impression, as the designed implant could not be directly used due to biocompatibility issue. The fabrication of gypsum was an additional step that need to be performed which resulted in an extra cost and time. Although a direct printing of implant is desirable, a biocompatible polymeric feedstock is rather scarce that CAD/CAM in combination with conventional method (gypsum mould) was used to create a dimensionally accurate implant.

This study aims to improvise the step involves in fabrication of cranial implant where a 3D printed mould is proposed over a gypsum mould for cost reduction purpose. The cost when using four different polymer-based 3D printing techniques are also highlighted and compared.

METHODS

Data Acquisition, Generation of 3D Model and Virtual Reconstruction

Computed tomography (CT) images of patient with cranial defect were obtained from PAC server. The images were segmented using medical image processing software (Mimics, Belgium) prior to generation of 3D model. A cranioplasty plate was then reconstructed using 3D modelling software (3-matic, Belgium), Figure 1.

Mould Design and Cost Estimation

A mould was designed ($134 \times 150 \times 115$ mm) with embedded shape and size of the cranioplasty plate (Figure 2). A curvy parting surface was selected following the curvy line of the implant. Holes with 9.50 mm diameter were also designed and extruded cut at every corner of the mould. The designed mould was then converted to a standard tessellation language (STL) format for cost estimation purpose.

Production Time and Cost Assessment

The designed mould was transferred to various slicing software namely Cura (Ultimaker, Netherland), Objet Studio (Stratasys, United States of America), Preform (Formlab, United States of America) and Psw (EOS, Germany) to obtain printing duration and material consumption for cost estimation purpose. It should be noted that Cura, Object Studio, Preform and Psw are the slicing softwares for FDM, MJM, SLA and SLS, respectively.

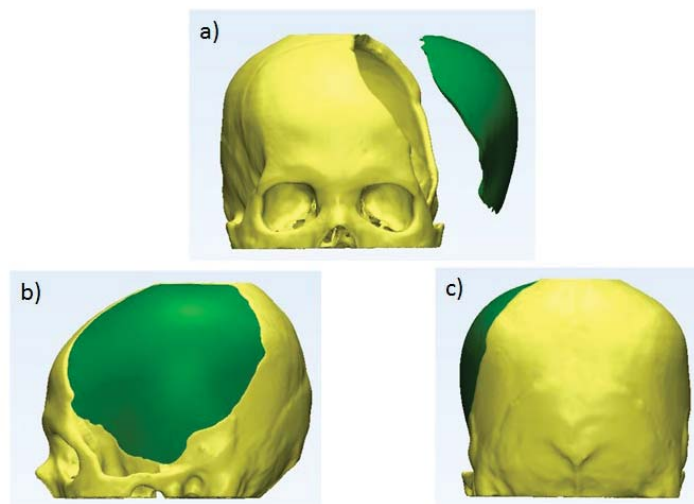


FIGURE 1. Designed of cranioplasty plate. (a): Front view, (b): Side view, (c): Rear view

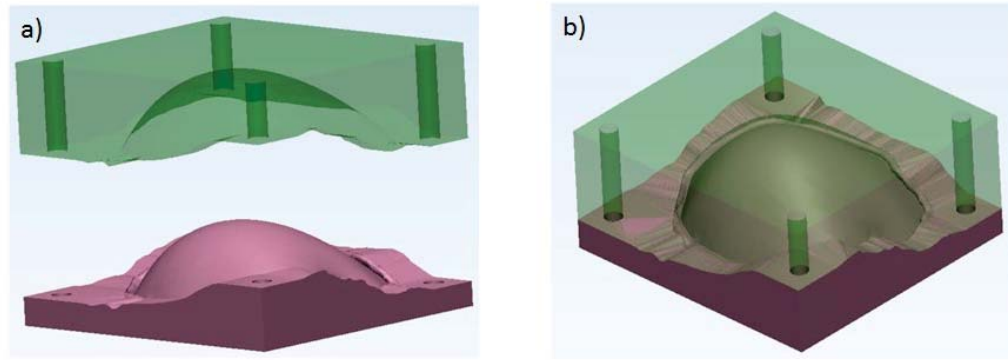


FIGURE 2. Preparation of mould. (a): Split core and cavity (b): Attached core and cavity

RESULTS AND DISCUSSION

Virtual reconstruction of cranial defect was performed using image processing and 3D modelling software. It was then followed by simulation of production time and cost using 4 different slicing software for 3D printing purpose. In this study, polymeric feedstock-based 3D printer was employed for simulation. It should be noted that, 3D printing using polymeric feedstock-based 3D printer is favorable due to its relatively affordable as compared to other 3D printing techniques. FDM works by depositing molten thermoplastic, while MJM functions by jetting photo sensitive liquid polymer follows by UV curing. SLA creates object by selectively cure thermoset photo sensitive polymer, while SLS selectively laser sintered polymeric powder. In term of technology, SLS is the most expensive machine follows by MJM, SLA and FDM.

The production time for cranial mould fabrication is depicted in Table 1. The processes started from acquisition of CT scan data from PAC server, followed by segmentation and virtual reconstruction via medical imaging and 3D modelling software as well as estimation of 3D printing duration via various slicing software to be printed using FDM, SLA, SLS and MJM. The total time taken for data acquisition, segmentation and virtual reconstruction were 4 hours. However, the printing duration varied due to the setting orientation of the mould on a build plate and complexity of the process.

TABLE 1. Production time for cranial mould fabrication

Processes	FDM	SLA	SLS	MJM
Acquisition of CT data from PAC server (hour)	1	1	1	1
Segmentation and virtual reconstruction (hour)	3	3	3	3
3D printing and post processing (hour)	65.5	71	17	16
Total production time (hour)	69.5	75	21	20

SLA process exhibited the longest printing duration (71 hours) that the mould can only be transferred to operation theatre on day 4. The fastest printing duration was depicted by MJM process that the mould can be transferred to operation theatre on day 2. The simulated production time could be used as reference for better patient management as well as to reduce the patient's waiting time. It should be noted that prolong hospital stay could expose patients to hospital acquired infection [9] that secondary treatment might be required. MJM and SLS possess larger build plate than FDM and SLA that both mould core and cavity can be printed at one shot. However, longer duration is required to print similar mould using SLA and FDM as the core and cavity need to be printed separately. The position of core and cavity on build plate of SLA versus SLS machines are presented in Figure 3. In SLA machine, the core and cavity of the mould were positioned in vertical direction due to its smaller build plate as compared to SLS machine.

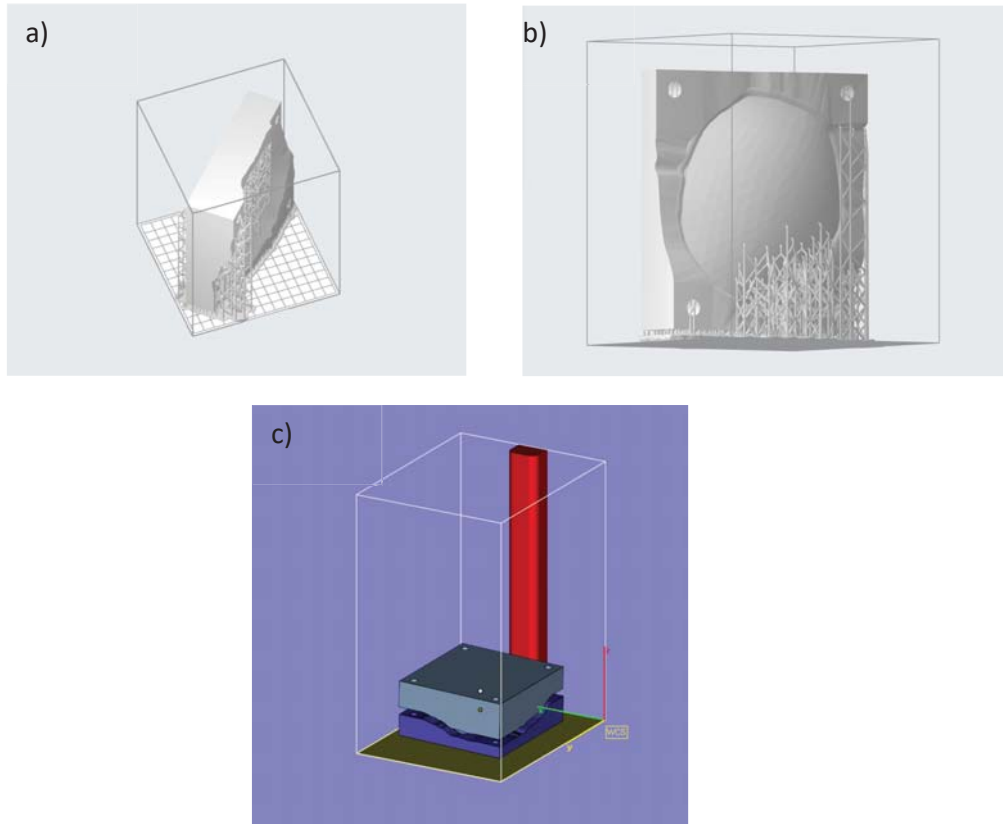


FIGURE 3. Position of mould. (a): Core in SLA (b): Cavity in SLA (c): Core and cavity in SLS

On the other hand, the cost of material for cranial mould fabrication are summarized in Table 2. SLS machine consumed more material as compared to other machine. It should be noted that the feedstock for FDM is in filament form, while SLA and MJM are in liquid form, while the material for SLS is in powder form. Overall, the material cost for cranial mould printing using FDM was the cheapest (estimated MYR 669) in comparison to other machines. The presented material cost is the cost when using a standard grade of material.

TABLE 2. Material cost for cranial mould fabrication

Item	FDM	SLA	SLS	MJM
Consumption of material	446 g	1262 mL	2400 g	2395 g
Price per unit (MYR)	1.50/g	1.19/mL	0.58/g	1.33/g
Material cost (MYR)	669	1514	1392	3191

The production cost to fabricate a cranial mould is shown in Table 3. Variable cost includes design cost, material cost and labour cost for printing and post processing. The design and labour cost for printing and processing might differ and depend on the complexity of the mould. Whereas fixed cost includes machine tools and fixture which in this case was set at MYR 300/mould. The fabrication cost for cranial mould using 3D printing techniques ranged from MYR 1318 to 4011. The printing duration and cost simulation could be used as references to plan a surgery by considering the urgency of the operation and patient's background.

TABLE 3. Costs for cranial mould fabrication

Item	FDM	SLA	SLS	MJM
Variable cost				
Data acquisition and design	200	200	200	200
Material cost (MYR)	669	1514	1392	3191
Labour cost for printing and post processing (MYR)	129	140	955	300
Fixed cost				
Machine tools and fixture/mould	300	300	300	300
Overhead charges (MYR)	20	20	20	20
Total cost/mould	1318	2174	2867	4011

For better understanding, the innovation in cranial reconstruction resulted from this study as opposed to previous method explored by Hueh and co-workers are exhibited in Figure 4. Printing of cranioplasty plate was eliminated in the proposed method which was changed to negative mould printing prior to implant preparation and fixation.

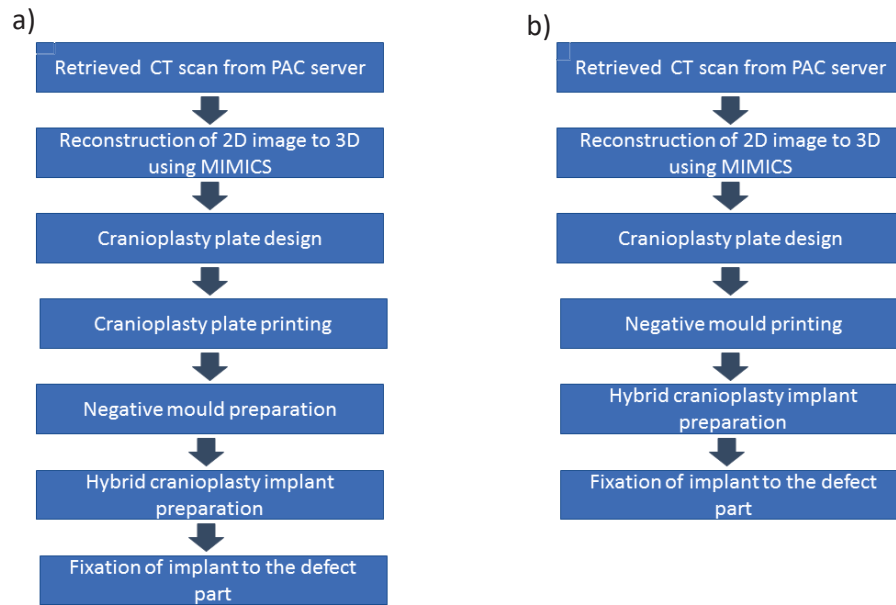


FIGURE 4. Preparation of cranial implant. (a): Method explored by Hueh and co-workers (b): Improved method as simulated in this particular study

CONCLUSION

This study explored an innovation in cranial reconstruction for virtual planning and simulated the cost effectiveness of various 3D printing method for preparation of a mould to be used for cranial implant fabrication. The FDM was the most affordable technique for the purpose. However, it was relatively time consuming that proper arrangement of the patient needs to be performed prior to operation to allow patient to regain their regular appearance at a reasonable cost.

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