Development of 3D Printed Heart Model for Medical Training

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Abstract Three-Dimensional (3D) printing is emerging as an enabling technology for a wide range of new applications. This study focuses on the medical application of 3D printer using basic fundamental 3D printing mechanisms. The objective of this study is to develop a heart model with specific requirements for medical training using Flyingbear P902 3D printer and Flex Thermoplastic Polyurethane (TPU) filaments as the depositing materials. The study involved two trials with the same operation procedure and 3D printer specifications. The first trial utilized non-transparent TPU filament and the second trial utilized transparent TPU filament. The application of this technology in developing a heart model was evaluated based on the requirements fulfilled by both printed heart models in both trials. The problems (such as inflexibility and less transparency), limitations and proposed solutions are discussed. The emergence of cardiovascular diseases such as congenital heart disease, coronary artery disease, surgical and catheter-based structural disease make 3D printing a new tool to design, plan and carry out challenging cardiovascular interventions.

Keywords 3D printing · Coronary artery · Heart model · Transparent filament · Thermoplastic polyurethane (TPU)

1 Introduction

3D printing technology, also known as rapid prototyping (RP) is the technique used to build structures of arbitrary geometries by depositing printing material in successive layers on the basis of digital design under the computer control [4].

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Development in rapid prototyping technology has opened up new opportunities in the advancement of medicine when combined with medical imaging [1]. This technique has been applied in dentistry, plastic surgery, orthopaedics [5] and cardiovascular diseases such as congenital heart disease, coronary arteries disease and mitral valve disease [2, 6]. Although the use of 3D printing in cardiovascular treatment is still relatively new, advancement in this discipline is occurring at a rapid rate that a contemporary review is warranted. In medical industry, 3D printing provides touchable structures to be used by trainee doctors prior to treating real patients and allows procedures to be planned without having to directly inspect the patient [2].

Realizing on its huge potentials in medicine, 3D printing technology is applied in this study to develop a heart model for medical training. Hollow, transparent and flexible are the specific requirements set for the heart model. Other than that, it was also designed to have coronary arteries surrounding its surface. Coronary arteries study is vital since it contributes to the highest percentage of the overall heart disease known as coronary artery disease (CAD). Atherosclerosis is the most common CAD that involves blood blockage due to the plaque deposit in the arteries [3]. For that matter, catheter insertion procedure through the narrow arteries is the medical training intended from the heart model development. The training is beneficial for familiarizing with coronary arteries intricacy before conducting real surgery. It thus reduces the risk of treatment failure significantly.

1.1 3D Printer Technology

Fused Diffusion Modelling (FDM) 3D Flyingbear P902 printer was used in this study. The printer specification is shown in Table 1.

Fabrication speed, resolution, quality, cost, build volume, surface finish and part strength are the parameters involved in addictive manufacturing (AM) process of 3D printer. Among these parameters, fabrication speed and resolution are the most critical properties.

1.2 Transparent Flexible Filament

The Magma Flex TPU Transparent Filament (thermoplastic elastomer) is used in this study to create a flexible and transparent heart model. This is a family of plastics that can be melted and shaped via FDM process and has similar characteristics to rubber. This type of filament is chosen to fulfill the flexibility (high strength, high elongation at break and high elasticity) and transparency requirement of the heart model. Table 2 shows the specification of the material used.

Table 1 Specification of flyingbear P902 3D printer

Brand	Flyingbear P902
Print size	220 × 220 × 280 mm
Layer thickness	0.05 mm
MAX printing speed	150 mm/s
Material type	PLA, ABS, PETG, Wood, PVA, Flexible Filament
Material specification	1.75 mm in diameter
Positioning accuracy	Z 0.004 mm, XY 0.012 mm
Nozzle diameter	0.4 mm
Recommended extruder temperature	210 °C (the maximum 260 °C)
Hot bed temperature	60–110 °C
Best ambient temperature	≥ 25 °C
Power requirements	110 V/220 V, 250 W, 50 Hz, 0.89 A
Connection	SD card or USB
File print format	STL, G-Code
Compatibility	Windows, Mac
Slicing software	Cura, Repetier-host
Machine weight	10 kg

Table 2 Specification of magma flex TPU filament transparent material

Material type	Flex TPU/transparent
Print temperature	200–230 °C
Heated bed temperature	50–60 °C
Length	335 mm
Diameter	1.75 mm ± 0.03 mm
Recommended printing speed	20/60 mm/s

Flexible filaments however, are inherently harder to print than rigid filaments since they are easily tangled into the extruder, having a harder time to be pushed and pulled by the motors and to be retracted during the printing process.

2 Procedure

The flowchart in operating 3D printer is shown in Fig. 1. 3D heart model was firstly designed using computer-aided design (CAD) software called Solidworks 2013 × 64 Edition as shown in Fig. 2a.

The file of the complete 3D model design from CAD software was converted to Stereolithography (STL) format. Upon conversion, the STL file was transferred to Ultimaker Cura 3.0.4 to create the tool path on the build platform. This process allowed support structure to be formed and the model scale to be changed

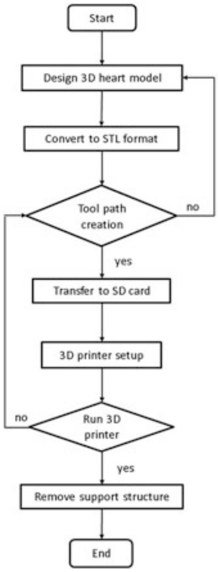

Fig. 1 Flowchart of the 3D printer operation

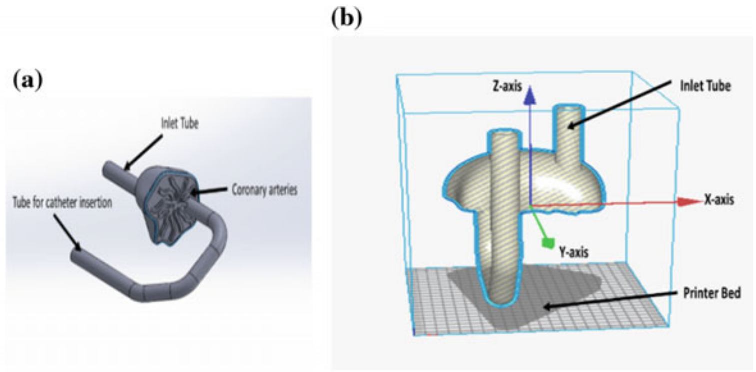

Fig. 2 **a** Development of heart model using solidworks. **b** Tool path creation using Ultimaker Cura 3.0.4

accordingly as shown in Fig. 2b. The output was then saved in the Secure Digital (SD) memory card to be transferred to the 3D printer. The specifications shown in Tables 1 and 2 were set to the 3D printer.

After the specifications were properly set and the filament was inserted into the extruder, the machine was run automatically as shown in Fig. 3b. Each layer was laid successively until the heart model including the support structure was completed. Each layer printed was about 0.3 mm in thickness (the thickness is

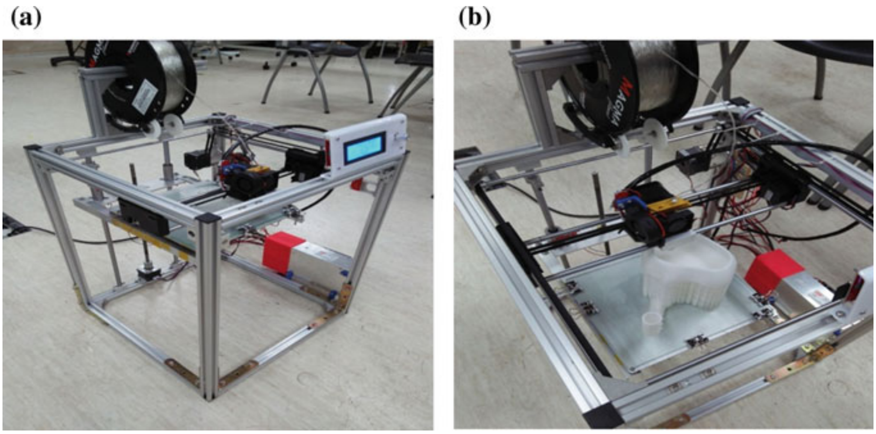

Fig. 3 **a** The setup of 3D printer. **b** 3D printing in progress

adjustable) for both heart models. The machine in progress was monitored from time to time to ensure no errors were made.

The printed object was removed from the platform after the printing was complete and was allowed to properly set before removing the support structure.

3 Result and Discussion

The attainment extent of 3D printing technique in developing a heart model was evaluated based on the number of specific requirements fulfilled by the heart models. The purpose of having flexibility and elasticity are to allow the heart structure to beat rhythmically at a specific rate range. The chamber and coronary arteries are required to be hollowed to allow air flow, fluid flow and catheter insertion practice. Transparency is compulsory for observing fluid flow structure formed inside the heart chamber and also for catheter insertion practice. This study was conducted in two trials. The first trial used non-transparent flexible filament as the printing material. Transparency and coronary arteries features were not yet considered at this stage. The second trial was the improved version of the first trial using a more flexible and transparent material.

3.1 Heart Model Using Non-transparent Flexible Filament

The first heart model was successfully printed without any disturbance during the printing process. The product is shown in Fig. 4. The model however had defect in term of flexibility or elasticity despite of the flexible material used. As a result, the

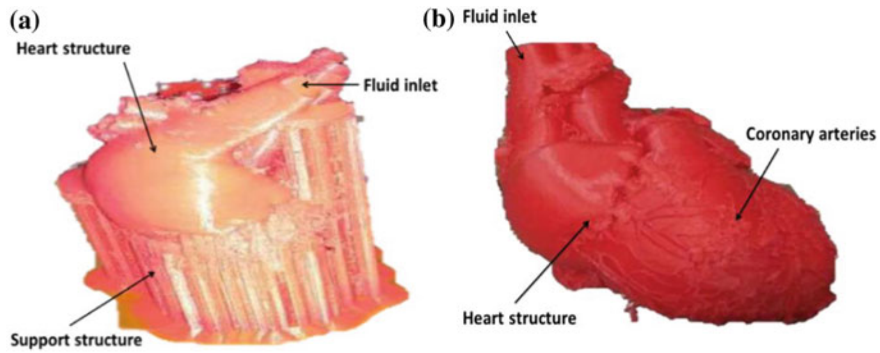

Fig. 4 **a** Printed heart model with support. **b** Printed heart model without support

heart model was unable to beat and act as a pump. In addition, the size formed was insufficient for use in medical training and the heart chamber was fully filled with the support structure instead of being hollowed. Leakage was another unexpected problem because of the thin heart wall. In other words, all of the requirements set above were not yet fulfilled in the first trial. Inflexibility was due to the less suitable material used while size insufficiency and support structure formation inside the heart chamber were due to the wrong setting at the tool path creation stage. These problems were improved by designing a new heart model using CAD software (Solidworks), replacing previous printing material with a more flexible and transparent material and obtaining the right size and support structure formation from the tool path creation program.

3.2 *Heart Model Using Transparent Flexible Filament*

The next model was designed to include a new feature: hollowed coronary arteries. Magma Flex TPU Flexible Filament Transparent (with a more flexible and transparent features) was used instead, to replace the previous material. The Tool Path creation setting using Ultimaker Cura 3.0.4 was properly set to obtain the right size product and to avoid unnecessary support system formation. Based on the improvements done above, the second version of the printed heart model had improved in term of size and had successfully fulfilled hollowed chamber and hollowed coronary arteries requirements.

The second version of the heart model nevertheless, was still less flexible and less transparent. The tiny holes formed as labelled in Fig. 5a are due to the small gap formed between the artery plane and the main curve on the surface fill as a result of the defect from the designing phase. This small defect however led to a serious leakage problem. The leakage would cause the pressure applied to be disturbed. Without the right pressure, the heart model was unable to beat

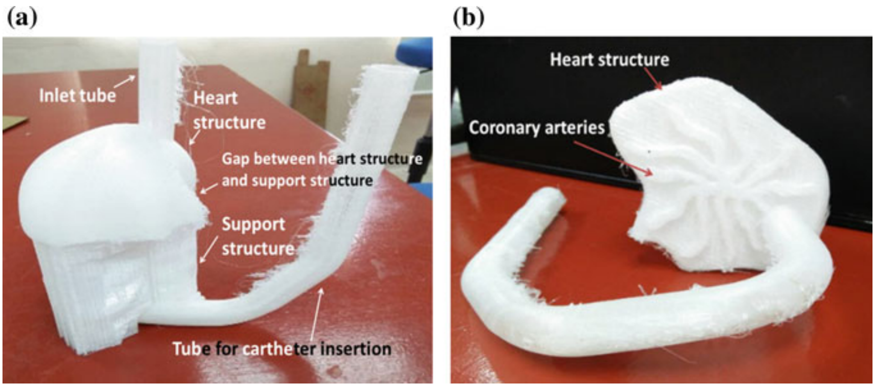

Fig. 5 **a** Transparent heart model with support. **b** Transparent heart model without support

rhythmically. Another new problem faced in the second trial was in the support structure removal. Coronary arteries structures were situated in between the heart surface and the support structures. Removing the support mechanically needed to be done carefully and delicately, to avoid damaging the arteries structure. Support structure is essential for creating certain geometries with overhangs in FDM since the melted thermoplastic was unable to be deposited in thin air. Surfaces printed on the support structure usually have low surface quality than the rest of the model. This can be observed in Fig. 5b.

The analysis of the problems shows that, printing three-dimensional heart model was challenging and would require multiple steps of improvements before the desired model could be achieved. Unlike other objects, medical objects usually have complex geometries and materials. There are a few suggestions for further improvements in the future. The stiffness and opaqueness were planned to be reduced by reducing the thickness of the model or by using a much more flexible material such as silicon. The serious leakage problem will be sealed by fixing the heart model design. The support structure issue will try to be resolved by using water-soluble support or the model is designed in such a way to minimize the need for supports. The usage of better versions of 3D printer or moulding techniques are also considered for future improvements.

4 Conclusion

This study investigates the application of 3D modelling and printing technology in the context of heart model. Based on the investigation, various factors need to be properly considered when printing complex medical objects especially the type of the materials used (for both model and support structure), the model design, the specifications, setting and also the type of 3D printer used. Other than technical issues, the application has limitations in term of commercialization. 3D printing is not competitive due to the high printing costs per part and counter to common perception, 3D printing involves considerable pre- and post-processing, which incur non-trivial labor costs. Furthermore, the process involves certain printable 3D files such as STL. An electronic CAD drawing only is not sufficient. Currently, there is no way to automatically convert the CAD drawing into a 3D file. Lastly, creating printable files involves two tacit steps: creating a three-dimensional volume model that can be printed and 'slicing' the model volume in the best possible way to avoid material wastage and prevent printing errors. However, it is suggested that, with further advances in 3D printing, it may serve as a useful clinical tool with the potential to benefit both engineers and medical doctors.

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