



Quantitative and qualitative comparison of low- and high-cost 3D-printed heart models

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Abstract: Current visualization techniques of complex congenital heart disease (CHD) are unable to provide comprehensive visualization of the anomalous cardiac anatomy as the medical datasets can essentially only be viewed from a flat, two-dimensional (2D) screen. Three-dimensional (3D) printing has therefore been used to replicate patient-specific hearts in 3D views based on medical imaging datasets. This technique has been shown to have a positive impact on the preoperative planning of corrective surgery, patient-doctor communication, and the learning experience of medical students. However, 3D printing is often costly, and this impedes the routine application of this technology in clinical practice. This technical note aims to investigate whether reducing 3D printing costs can have any impact on the clinical value of the 3D-printed heart models. Low-cost and a high-cost 3D-printed models based on a selected case of CHD were generated with materials of differing cost. Quantitative assessment of dimensional accuracy of the cardiac anatomy and pathology was compared between the 3D-printed models and the original cardiac computed tomography (CT) images with excellent correlation ($r=0.99$). Qualitative evaluation of model usefulness showed no difference between the two models in medical applications.

Keywords: Accuracy; assessment; cost; heart disease; three-dimensional printing (3D printing)

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Introduction

Congenital heart disease (CHD) is a type of birth defect that involves structural anomalies in the heart and major blood vessels (1). Depending on the severity of the condition, it can cause hemodynamic and functional consequences in patients, requiring corrective surgery to repair the heart (2,3). Furthermore, the forms of CHD are very diverse, including, but not limited to, double-outlet right ventricle (DORV), tetralogy of Fallot (ToF), ventricular septal defect (VSD), atrial septal defect (ASD), truncus arteriosus, single ventricle, etc. (3,4). In most cases, these conditions co-exist and vary from individual to individual, and there is

thus no one-treatment-fits-all surgical option (5). It is imperative then for clinicians to achieve a comprehensive understanding of the patient's cardiac anatomy during pre-operative assessment to prevent unexpected findings during the surgery, and subsequently reduce surgical time and mortality (6-20).

Despite this need, current visualization techniques lack the ability to provide a comprehensive viewing of the cardiac anatomy due to the medical images being interpreted from two-dimensional (2D) flat screens. Three-dimensional (3D) printing has consequently been introduced to produce models of exact replication of the heart that are both tangible and tactile (7-25). Due to the

excellent geometric information that 3D-printed heart models provide, this technology has been reported to facilitate the preoperative planning of corrective surgery, improve patient-doctor communication, and enhance the learning experience of medical students (5-13,26-35). A recent multicentre study holistically explored the clinical significance of 3D-printed heart models by examining the practices of an international sample of surgeons and cardiologists from different hospitals. In 19 out of 40 cases, the 3D-printed heart models were found to be the deciding factor in altering the surgical decision (34).

Despite these advantages, the medical application of 3D printing in the domain of complex CHD is still under research and requires further validation. Several centres have adopted this technology and published case reports and series to share their experience in using 3D-printed heart models (5-12,22-24,27,33,36). The general consensus is that the cost of 3D printing remains one of the main hurdles impeding the wider application of this technology in medicine (9,19,35,37). There have been a few studies which reported on the generation of 3D-printed models using low-cost materials (6,23,24,38). However, there is no indication of whether these low-cost models are as accurate or useful as the more costly models. This study aimed to provide insights into the reduction of costs in 3D printing through the optimization of 3D printing material selection. Thus, we compared the more expensive 3D-printed model (Tango Plus) and the low-cost model [thermoplastic polyurethane (TPU)] in terms of dimensional accuracy and medical applications.

Technical note

Ten cases of de-identified cardiac computed tomography angiogram (CCTA) with CHD were retrospectively obtained from the radiology archives of two public hospitals. Of the 10 cases, 2 cases with good image quality and contrast enhancement were chosen for image segmentation. Case 1 features DORV and sub-aortic VSD, whereas case 2 demonstrates ASD. Both cases were imported to a separate workstation for segmentation using a commercially available software package, Mimics Innovation Suite software (Materialise HQ, Leuven, Belgium). Thresholding- and region-growing tools were applied to isolate the regions of interest (i.e., the blood pool) from the unwanted structures (i.e., bones, soft tissues, lungs). The mask was also manually edited if the selected region did not correctly reflect the

blood pool region. The digital model of the blood pool was then exported in standard tessellation language (STL) to 3-matic, a companion software in Mimics Innovation Suite software, in order to hollow out, smoothen, and split the digital model into two compartments. An arbitrary thickness of 2 mm was also added into the blood pool surface to prevent the model from collapsing during 3D printing.

The digital models of both cases were sent for 3D printing using a low-cost material. Due to cost consideration, only the digital model of case 1 was printed using the more costly material. Tango Plus material was chosen as the “expensive” material, as it is able to reproduce models that are flexible and compressible, very much like human heart tissues. Case 1 was hence printed with a commercial Stratasys PolyJet printer (Objet Eden 260VS, Stratasys, United States), with a total printing and cleaning-up time of approximately 10 hours. The cost for 3D printing of the heart in Tango Plus was around AUD 300.

TPU 95A was chosen as the “low-cost” material. It is durable and semi-flexible, although not as flexible as Tango Plus. Both the STL files of these two cases were printed with Ultimaker 2 Extended+ 3D printer from Ultimaker BV (Geldermalsen, The Netherlands) using fused filament fabrication (FFF) technology, with an average total printing and cleaning-up time of approximately 100 hours. The average cost for 3D printing of the heart in TPU 95A was around AUD 50.

The dimensional accuracy of the 3D-printed heart models was investigated. A contrast-enhanced CT scan was performed on both the Tango Plus and TPU models of case 1 using a contrast-enhanced CT chest protocol. Both models were immersed in a water-contrast mixture of 10% contrast and 90% water to obtain a CT attenuation of 200 Hounsfield units (HU) which is similar to routine CCTA (*Figure 1*). Measurements were taken at 10 different anatomical locations using the “ruler” feature in the Horos software (Horos Project, licensed under the GNU Lesser General Public License, version 3.0), which is an open-source Digital Imaging and Communications in Medicine (DICOM) viewer. The results were compared with the measurements obtained from the original CCTA. In order to reduce observer bias, each measurement was repeated 3 times by 2 independent observers. It was found that the Tango Plus heart model deviated from the measurements in the original data by a 0.23 mm average, whereas the TPU model deviated from the measurements in the original data by a 0.54 mm average. However, measurements from both

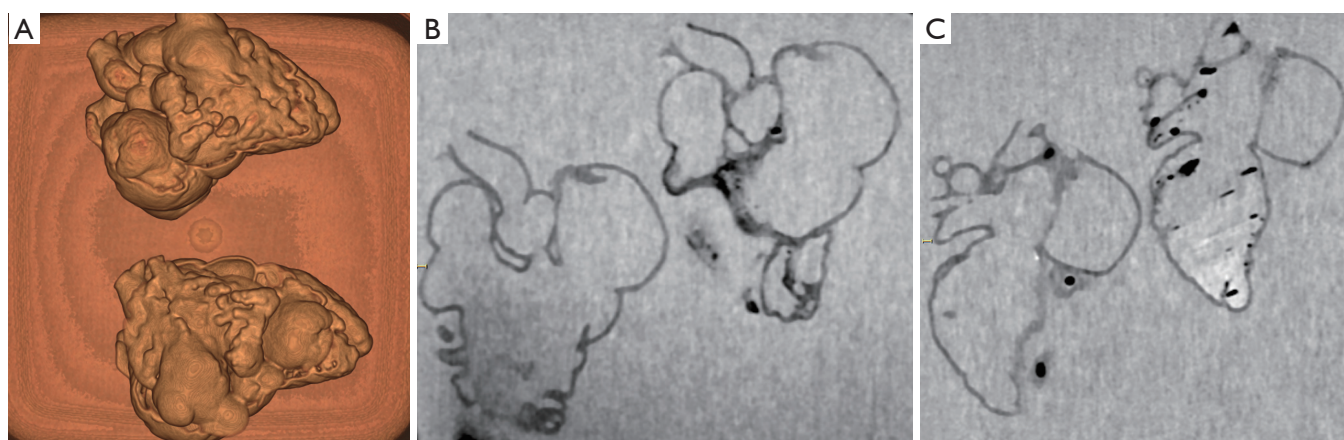


Figure 1 Cardiac CT scan of 3D-printed heart models using different printing materials. (A) 3D reconstruction showing the 3D-printed models without contrast medium (top: Tango Plus material, bottom: TPU material). (B,C) Coronal reformatted contrast-enhanced CT images showing 3D-printed models with Tango Plus (left) and TPU (right) materials. More air bubbles are seen in the model with TPU material. TPU, thermoplastic polyurethane.

models were strongly correlated with those of the original CCTA ($r=0.99$), as demonstrated in *Figures 2* and *3*.

In order to compare the clinical significance of the two models, surveys were conducted involving 3 medical professionals (1 cardiac surgeon, 1 cardiologist, and 1 cardiothoracic radiologist). During the meeting with them, they were asked to qualitatively assess the original CCTA of cases 1 and 2 prior to the evaluation of the 3D-printed models, and allowed to discuss where the heart lesions were. Questionnaires were then distributed to the medical professionals to discover their opinions of both models. Each participant received 2 identical sets of questionnaires, 1 for the Tango Plus model, and 1 for the TPU model. They were requested to choose between responses of “yes”, “maybe”, and “no” with regards to the efficacy of the 3D heart models in the following areas: degree of reliability of the model, usefulness in preoperative planning, usefulness in medical education, and usefulness in communication within clinical practice. All the participants found both the models useful in the above-mentioned areas, and they found no difference between the models in terms of their medical applications. On the 3-point scale questionnaires, each respondent rated the TPU model exactly the same as the Tango Plus model. *Table 1* contains the responses from each respondent with regards to the medical application of the 3D-printed heart models. It is worthwhile to note that no participant selected “no” in any of the questions, indicating that both 3D-printed models were perceived positively in

terms of their efficacy.

Discussion

The application of 3D printing has proliferated since its first introduction in the medical field, however mainly in the maxillofacial and orthopaedic specialties. In the past few years, 3D printing has increasingly gained attention within the cardiovascular domain, due to the potential ability of the technology to improve the patient management of cardiovascular disease (6,8,29,32). In spite of the promising results that 3D-printed heart models have shown in the current literature, the diffusion of this novel technology has been limited mainly due to its cost (9,19,35). To the best of our knowledge, there is currently no study investigating the efficiency and accuracy of the low-cost 3D printed models and whether they are comparable with the more expensive models. This preliminary study demonstrated that the low-cost models can be as useful as the expensive models in medical applications. However, its accuracy in replicating cardiac structures is less than the expensive models, and its mean difference does not fall within the mean difference reported in the other relevant articles (39). Further studies that include more cases are needed to validate this result. The low-cost model also requires a much longer duration for 3D printing—about 10 times longer than the high-cost model. Hence, it is probably not as practical when it comes to management of urgent cases.

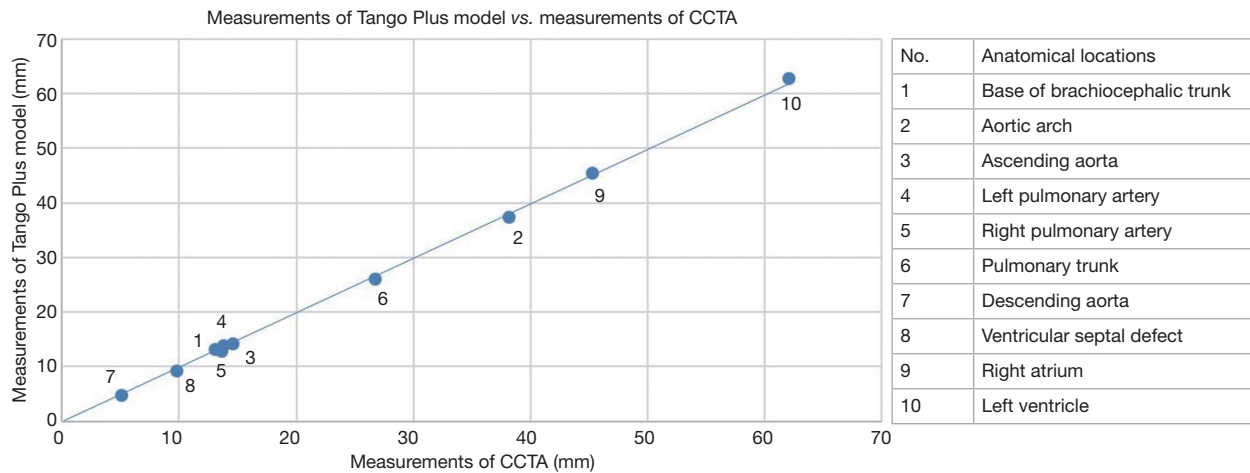


Figure 2 Scatter plot of measurements of the Tango Plus model against measurements of CCTA. The data points were assigned with numbers to represent different anatomical locations. CCTA, cardiac computed tomography angiography.

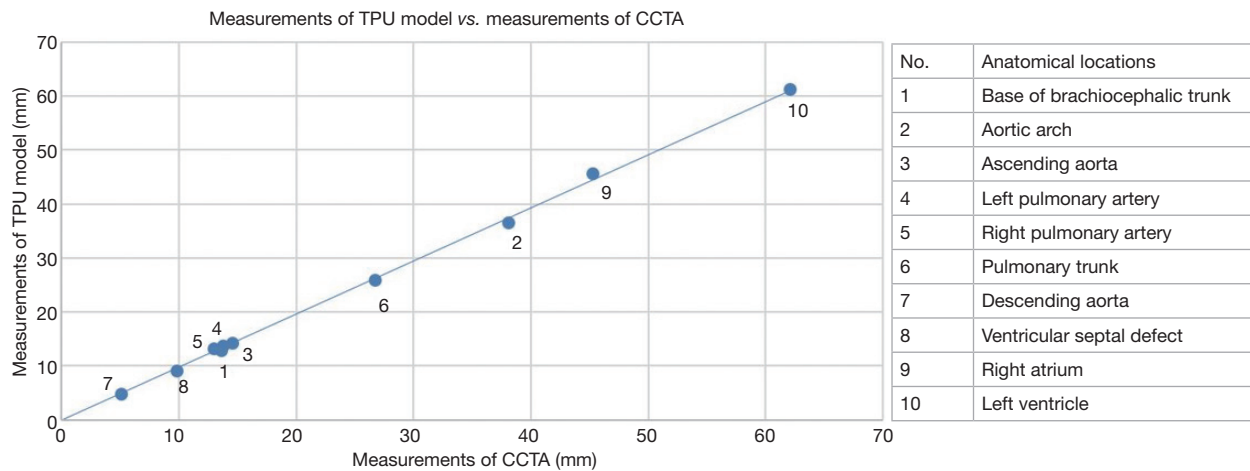


Figure 3 Scatter plot of measurements of the TPU model against measurements of CCTA. The data points were assigned with numbers to represent different anatomical locations. TPU, thermoplastic polyurethane; CCTA, cardiac computed tomography angiography.

In the free-text response questions, the participants made a few suggestions about how the 3D-printed models may be improved to bring more benefits in medical field:

“(Display of) thinner structures like valve leaflets and chordae tendineae, especially for adult valve reconstructive surgery.”

This points out one of the limitations of the 3D-printed heart models generated purely based on CT scans: very fine structures cannot be well-defined, as they are best seen on echocardiographic images. A study by Gosnell *et al.* integrated CT and echocardiographic scans to produce a 3D-printed heart model with an excellent replication

of valve leaflets (*Figure 4*) (40). This method exploits the strengths of the two imaging modalities and combines them, producing a 3D-printed model that can display more anatomical and pathological information.

The accuracy of the 3D-printed models relies heavily on the quality of the original CT scan, especially on how well the entire blood pool is enhanced by the contrast medium. If the blood pool is not enhanced properly, manual editing is required to meticulously select the region of interest, making the process more prone to human error. One of the participants suggested it would be beneficial to develop CT imaging protocols to enhance the quality of the scans, thus

Table 1 Responses of the perceived efficacy of the 3D-printed heart models

| Questions | Cardiologist | | Radiologist | | Cardiac surgeon | |
|---------------------------------------------------------------------------------------------------------------------------------|--------------|-----------|-------------|-----------|-----------------|-----------|
| | Cheap | Expensive | Cheap | Expensive | Cheap | Expensive |
| Does the model accurately display the cardiac structures? | Yes | Yes | Yes | Yes | Yes | Yes |
| Is the model helpful in planning interventions and pre-surgical simulation? | Yes | Yes | Yes | Yes | Yes | Yes |
| Is the model helpful for you to appreciate procedural difficulties and assess the likelihood of success/failure of the surgery? | N/A* | N/A | N/A | N/A | Yes | Yes |
| Is the model helpful in intra-operative orientation? | Yes | Yes | Yes | Yes | Yes | Yes |
| Can the model reduce operative time? | Maybe | Maybe | Yes | Yes | Yes | Yes |
| Is the model useful in enhancing your/patients understanding? | Yes | Yes | Yes | Yes | Yes | Yes |
| Can the model improve consultation experience? | N/A | N/A | N/A | N/A | Yes | Yes |
| Can the model shorten the consultation time? | N/A | N/A | N/A | N/A | Maybe | Maybe |
| Can you describe pathology better with the model? | Maybe | Maybe | Yes | Yes | Yes | Yes |
| Do you prefer using a 3D model or medical images to communicate with patients? | Both | Both | Both | Both | 3D model | 3D model |
| Satisfaction score (out of 10) | 7 | 7 | 10 | 10 | 9 | 9 |
| Would you recommend 3D printing to your colleagues? | Yes | Yes | Yes | Yes | Yes | Yes |

*, N/A means not applicable, therefore the question was not included in the questionnaire.



Figure 4 3D-printed model with the cardiac contour derived from a CT scan, and atrioventricular valves (green and red) derived from an echocardiographic scan. Reprinted with permission from Gosnell *et al.* (40).

reducing errors in the 3D-printed models.

It is important to bring attention to several limitations in this study. First, the study lacks generalization as there were only 2 types of 3D printing materials being investigated. There are various types of 3D printing materials in the

market with different properties and costs, and their cost-effectiveness as a material for 3D-printed heart models has not yet been studied. It should not be assumed that the properties of TPU 95A and Tango Plus material can be generalized to all the other low- and high-cost 3D printed models. Second, the quantitative measurement of the 3D models' accuracy was only carried out in one dimension: the axial plane. It is yet to be determined whether 3D printing distorts the cardiac anatomy in coronal and sagittal planes, and whether the accuracy of the 3D models is consistent in all three dimensions. This being the case, the calculated mean difference of the 3D-printed models is not completely indicative of the accuracy of the entire model. Third, detection bias may be present in the qualitative assessment due to the fact that all three participants were informed of the purpose of the study prior to the survey.

In conclusion, this technical report shows our preliminary experience in creating low-cost patient-specific 3D-printed models of CHD with similar accuracy and clinical applications as costly 3D-printed models. With further developments in 3D printing techniques and cost

reductions in 3D printing materials, 3D printing will inevitably be incorporated into the diagnostic approach of daily clinical practice.

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Footnote

Conflicts of Interest: The authors have no conflicts of interest to declare.

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