Low-Cost 3D-Printed Grown-up Congenital Heart Defect Models from CT Angiography

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Abstract

Background: 3D-printing (3DP) has been found to be a promising adjunct in the care of patients undergoing cardiac surgery. The value of accurate, patient-specific models is becoming apparent in preoperative planning, patient and trainee education. However, high costs and complex workflows are major limitations preventing surgical centers from adopting 3DP into routine practice.

Methods: We detail a low-cost, simple workflow for the creation of cardiac models in grown-up congenital heart disease. A 30-year old male patient with Transposition of the Great Arteries underwent balloon atrial septostomy followed by arterial switch operation as a newborn required reoperation because of aortic root and ascending aorta dilatation. Using Computed Tomography Angiography (CTA) imaging that was acquired as part of gold-standard care, segmentation was performed. Virtual models were then processed and prepared for 3DP. Using a commercially available desktop 3D printer, a full-sized heart model was printed with the polymer polylactic acid.

Key words:

3D printing; congenital heart defects; simulation; preoperative planning; CT angiography

Results: A personalized, stackable heart model was 3D-printed in less than two days, costing approximately $10. Experienced surgeons were satisfied with the accuracy of the model, which was used by the surgical team for preoperative planning, and in educating the patient on their condition and the proposed procedure.

Conclusion: We have described a unique methodology to rapidly 3D-print cost-effective cardiac models using CTA. These models provide holistic benefits in patient care, from the gaining of informed consent to intraoperative guidance.

Introduction

3D printing has been utilised with success as a preoperative planning tool in creating patient-specific cardiovascular models before various procedures, from smaller percutaneous interventions [1,2] to Congenital Heart Defect surgical repairs(3–5). Its widespread use has thus far been limited due to high costs, which has been detailed in multiple reviews and reports [6–8]. To date, combination of 3D printing, Computed Tomography Angiography (CTA) and Grown-up Congenital Heart Disease is uncommon.

In Grown-up Congenital Heart Disease (GUCH), these models, specific to each patient's unique anatomy are potentially beneficial as they improve understanding of spatial anatomical relationships, and can be used as a counselling tool in the therapeutic relationship.

Herein, we present a novel approach to 3D printing cardiac models with a significant costs reduction. In the present study, we have applied the techniques of medical image processing to CTA.

Methods

Case report

A 30-year old male patient with Transposition of the Great Arteries underwent balloon atrial septostomy (Rashkind procedure) followed by arterial switch operation (Jatene procedure) as a newborn. Since then, he remains in the cardiac control. Recently, he reported small exercise intolerance (NYHA I/II). Control transthoracic echocardiography showed aortic valve stenosis and pulmonary valve stenosis. Performed standard CTA showed dilatation of ascending aorta with dilatation of aortic root. Because of clinical symptoms and risk of aortic dissection patient was qualified for elective reoperation.

Segmentation

CTA imaging was acquired in DICOM format and imported to our work station for analysis. The workflow represented in Figure 1 was then applied. The DICOM image series was loaded into 3D Slicer(9) (version 4.5; Harvard, US, 2016), an open source medical image processing software, and segmentation was performed. Thresholding was used to provide semi-automatic segmentation, and various thresholds were windowed to target areas of myocardium. The segmentation resulted in Region of Interests (ROIs) which overlapped one another. The Boolean operation of subtraction was performed on the ROIs to combine all myocardial tissue into a single labelmap. Following the semi-automatic segmentation, the ROIs were inspected and manually finished to maximize accuracy. Corrected ROIs were exported from 3D Slicer into stereolithographic (STL) files that represent three-dimensional meshes of cardiac tissue.

Mesh Modeling and Preparations for Printing

The resultant meshes were complex and required simplification prior to further processing. This was executed in Blender (version 2.87c; Blender Foundation, Amsterdam, Netherlands, 2016), a free software used to edit 3D models, with the "Decimate" modifier to reduce the number of faces in the mesh.

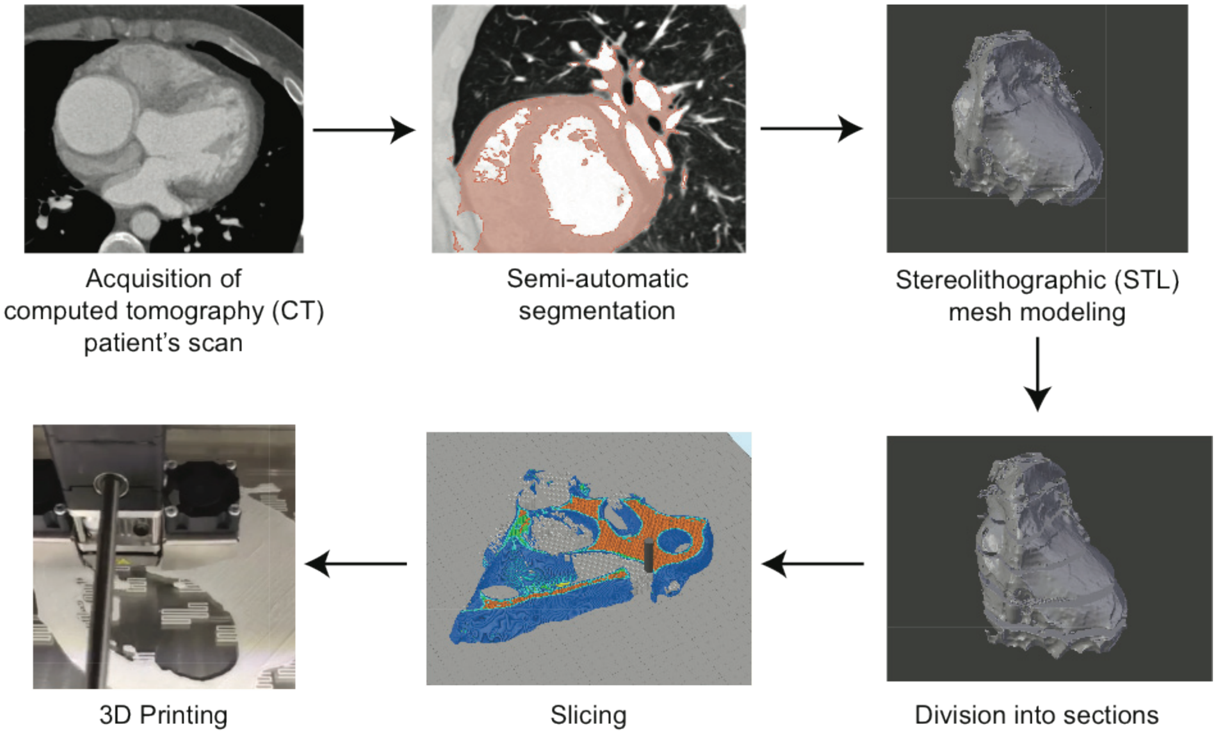

Fig. 1.
The 3DP workflow. Beginning at medical image acquisition, to segmentation, mesh modeling, and finally 3D-printing

Fig. 2.
The final 3D-printed model

The simplified models were subsequently divided into 6 subsections to visualize the interior anatomy of the patient's heart, including the chambers and outlets of the great vessels. This also allowed the model to be taken apart and reassembled when educating trainees on complex anatomy.

Printing

The processed models were imported into the open source slicing software, Cura (Version 2.4; Ultimaker, Geldermalsen, Netherlands, 2016). Slicing applications prepare virtual models for 3D printing by transforming them into a set of layers of defined height and saving in a format known as "G-code". G-codes consists of commands for 3D printers such as "move and extrude material" and "set extruder temperature".

The models were sliced and sent to an Ultimaker 2+, a readily available consumer grade 3D printer. The models were printed using polylactic acid (PLA), an inexpensive 3D printing material retailing for $30 for one kilogram. As the cardiac model had been previously divided into 6 parts, they were printed sequentially, resulting in 6 print jobs.

Results

The cardiac model was 3D-printed using the techniques described above. The total printing time was 35 hours, with the model costing approximately $10. The model was used to counsel the patient in the relevant cardiac anatomy and physiology, and was used to gain informed consent and to counsel the patient in possible complications of the procedure. The patient then completed the questionnaire, where he expressed high levels of satisfaction with his personalized 3D-printed model. The model was then manually interrogated by the treating team as an adjunct to the CTA in the planning of the procedure. The quality of the model was deemed to be satisfactory by experienced cardiac surgeons, who reported that routine use of patient-specific cardiac models would be beneficial for the preoperative planning of complex cases.

Discussion

The large variety of congenital heart disease and related specific problems on the one hand and the strict space limit of practice guidelines on the other, present a challenging task for modern cardiology. The remarkable improvement in survival of patients with CHD has led to a continuously growing number of GUCH patients, in particular those with more complex disease. Many of them who underwent surgery in childhood will require reoperation in adulthood for various reasons [10].

3D-printing allows complex anatomical structures to be represented in new ways. In cardiac surgery, there is obvious merit in the visualization of complex Grown-up Congenital Heart Defects, especially after surgical correction in the past, where structural anatomical defects vary widely even within the same classification of disease. Following arterial switch, the variation between structures is even greater, and conventional imaging techniques are often inadequate. Combining 3D-printing with conventional imaging allows for greater insight into each patient's unique anatomy before the first cut is made. The treating team would be better placed to pre-empt possible obstacles to the planned approach, resulting in better short-term outcomes, such as reducing time under anesthesia and length of ICU stay.

It is of note that applications of 3D-printing in cardiac surgery extend beyond the treatment of Grown-up Congenital Heart Defects. Novel methods of repair of valvular defects require greater understanding of patient anatomy in three-dimensional space which traditional imaging is unable to provide, in particular for complex cases. Although valvular anatomy is traditionally visualized using echocardiography, modelling the base of the aorta or pulmonary trunk would facilitate more a precise fitting of prosthetic valves prior to surgery. In addition, isolated models of the left or right chambers can be used to visualise the atrioventricular valves.

The major challenges in applying 3D-printed models to routine clinical care are the high costs of production and the lead time required to produce the models preoperatively [11]. Models are patient-specific, allowing previously mentioned advantages. However, this requires skilled technicians to prepare each case, which is another limitation of the current levels of technology. Due to the human hours required to prepare a 3D model in addition to print time, 3D printed models are time consuming to produce. This makes its application to urgent cases unrealistic. These emergencies may benefit from other recent technological advancements such virtual reality or augmented reality. These technologies require the previously mentioned segmentation techniques to develop 3D models, without the print time. On the other hand, early reports show that models applied in virtual reality are not superior to physical ones [12].

The approach presented in our paper significantly reduces the costs of developing full-sized cardiac models from several hundred dollars(13) to approximately $10. The reason for the marked improvement in costs is in the type of 3D-printing technology used. Fused Deposition Modeling (FDM), the technology utilised in creating our cardiac models, is the technique utilised by most inexpensive, consumer grade machines. The materials required are also far more affordable, resulting in cost-effective models. However, FDM is more labour intensive and time-consuming than selective laser sintering (SLS), stereolithography (SLA) or PolyJet.

Conclusions

CTA is a readily available source of medical image data that can be used to segment and 3D-print patient-specific cardiac models.

Reducing costs of 3D-printed models will increase the adoption of the technology in health services worldwide, with a view to more precise planning and control during complex surgical procedures. Low-cost patient-specific anatomical models represent an important step towards the goal of personalized medicine, not only as an adjunct to preoperative planning, but in empowering patients in learning about their disease and understanding their anatomy.

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