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Integration of Computed Tomography and Three-Dimensional Echocardiography for Hybrid Three-Dimensional Printing in Congenital Heart Disease

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Abstract Three-dimensional (3D) printing is an emerging technology aiding diagnostics, education, and interventional, and surgical planning in congenital heart disease (CHD). Three-dimensional printing has been derived from computed tomography, cardiac magnetic resonance, and 3D echocardiography. However, individually the imaging modalities may not provide adequate visualization of complex CHD. The integration of the strengths of two or more imaging modalities has the potential to enhance visualization of cardiac pathomorphology. We describe the feasibility of hybrid 3D printing from two imaging modalities in a patient with congenitally corrected transposition of the great arteries (L-TGA). Hybrid 3D printing may be useful as an additional tool for cardiologists and cardiothoracic surgeons in planning interventions in children and adults with CHD.

Keywords 3D echocardiography · Computed tomography · 3D imaging · 3D segmentation · Registration · Integration · 3D reconstruction · Cardiac imaging · Clinical application

Background

The detailed visualization of the pathomorphology of the heart in children and adults is of utmost importance in the diagnosis and management of congenital heart disease (CHD). Although multiple three-dimensional (3D) imaging modalities are currently available, the 3D structure is viewed on a two-dimensional screen, which lacks depth perception and other spatial information. Three-dimensional printing of patients' hearts has become more common in recent years as part of an emerging, experimental field for enhanced visualization of

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individual cardiac structures and characteristics. Interventional cardiologists and cardiothoracic surgeons may benefit from the ability to plan the interventional approach that is most appropriate for the patient using the 3D-printed models. Moreover, patient safety may also be greatly improved by better diagnostic capability and procedural efficiency [1–3].

Three-dimensional printing of cardiovascular models has been derived from computed tomography (CT), cardiac magnetic resonance (CMR), and 3D echocardiography, which are powerful imaging modalities that have individual strengths [1–4]. Computed tomography is an accurate modality for demonstrating extracardiac anatomy in children and adults with CHD. The superior spatial resolution of CT provides clear borderline definition with enhanced visualization of small structures such as the coronary arteries and aortopulmonary collaterals. The stenosis of the native vessels and obstruction of extracardiac conduits can also be better visualized on CT than other imaging modalities [4, 5]. In contrast, CMR has superior temporal resolution and provides highly accurate measurements of ventricular volumes and mass as it is more suitable for analyzing moving structures [4, 6]. Three-dimensional echocardiography is superior to other imaging modalities in reconstructing the morphology of the valves and for detailed visualization of the sub-valve apparatus [7, 8]. Although echocardiography is useful in demonstrating the anatomy of the different phases of the cardiac cycle, CT and CMR offer better blood pool to myocardial contrast [9].

As each imaging modality has different strengths, which can impact the quality and accuracy of the 3D model, our aim was to demonstrate the feasibility of integration of CT and 3D echocardiography to derive a hybrid heart model for 3D printing. A 55-year-old male with congenitally corrected transposition of the great arteries (L-TGA), ventricular septal defect (VSD), and pulmonary atresia who was on regular follow up in the adult congenital cardiac clinic was selected for hybrid 3D printing due to his complex cardiac morphology. A previously obtained CT of the thorax for evaluation of post-operative complications and 3D transesophageal echocardiogram (TEE) for evaluation of valve regurgitation was determined to be of adequate quality for integration and hybrid 3D printing.

Methods

Case Details and Acquisition of Data

A 55-year-old male with L-TGA, VSD, and pulmonary atresia was palliated with modified Blalock-Taussig shunt in infancy, subsequently underwent repair with left ventricle (LV) to pulmonary artery (PA) conduit at the age of 16 years. His medical history included transvenous permanent pacemaker implantation at the age of 40 years for progressive sinus node dysfunction, and closure of a 17 mm residual atrial septal defect with a 18 mm Amplatzer® Septal Occluder (St. Jude Medical, St. Paul, Minnesota, USA).

At the time of presentation, he described experiencing progressive tiredness and exercise limitation over the past couple of years. He had a poorly functioning systemic right ventricle with significant atrial arrhythmias, unresponsive to amiodarone and digoxin. A cardiac catheterization was performed to characterize hemodynamics and assess the degree of left ventricular outflow tract (LVOT) obstruction into the PAs. A 3DTEE was also performed to assess the morphology and function of the atrioventricular (AV) valves, which demonstrated a moderately well-functioning systemic ventricle with mild tricuspid valve (systemic AV valve) regurgitation. There was evidence of severe LVOT obstruction and moderate to severe systemic AV valve regurgitation due to the pacemaker wires. Severe mitral valve regurgitation was also noted.

Image acquisition of the 3DTEE was performed using the Philips X7-2 t transducer with the Philips iE33 ultrasound system (Philips Medical Systems, Andover, Massachusetts, USA) with frame rate of 9 – 45 Hz, contrast of 40 dB, 52 % gain with 4 beat reconstruction and 1 beat acquisition. As a result of volume capture over the course of 4 cardiac cycles, the temporal resolution was maximized avoiding 3DTEE specific stitch artifacts as well as traditional ultrasound related imaging artifacts. The morphology of the AV valves was well characterized, but the mitral valve details were slightly obscured due to the pacing wires going across it. However, as the 3DTEE acquisition was considered to be of diagnostic quality, it was selected for 3D printing.

The contrast enhanced CT was performed on a SOMATOM Definition Flash computed tomography (CT) scanner (Siemens, Erlangen, Germany) and the images were acquired in the Cartesian digital imaging and communication in medicine (DICOM) format. Helical scanning from the lung apices through the diaphragm was performed following the administration of intravenous contrast. Axial images were reconstructed with 2.5 mm slice-thickness and reconstruction interval. The CT images accurately depicted the myocardial blood interface and characterized the dimensions of the arteries and conduit. The information from the 3DTEE and CT was decided to be adequate quality to perform hybrid 3D printing of the malformed heart and demonstrate the feasibility of such an innovative technique.

Integration, Segmentation, and Generation of the Model

After completion of multiplanar reformatting, the anonymized datasets were imported into a specially designed post-processing software (Mimics® Innovation Suite, Materialise NV, Leuven, Belgium). Diastolic images from both CT and

3DTEE were chosen to facilitate proper integration of the datasets. This cardiac phase was pre-selected for segmentation by the cardiologist and surgeon involved in the patient case. The extracardiac anatomy was derived from the contrast enhanced CT dataset. The tricuspid valve (systemic atrioventricular valve) and mitral valve leaflets were derived from 3D TEE. Each dataset was segmented via thresholding and interactive editing operations using automatic, semi-automatic, and manual segmentation methods. A thresholding line was used to identify the signal intensity or Hounsfield units of the CT data to identify the blood pool and blood/tissue border. In 3D TEE, the thresholding line was used to identify the blood/tissue border based on the intensity of the echogenicity or echodensity of the valve leaflets. The signal intensity of each valve was separately segmented to create a mask focused on the specific cardiac valve excluding other cardiac structures and artifacts. There was a varying degree of manual editing to create an accurate representation of the cardiac morphology. Careful editing and correction was required for the ultrasound dataset as signal dropout or shadowing is a common error during segmentation. The accuracy of the segmented 3D TEE data was verified by superimposing the post-processed data on to the original dataset.

Upon completion of segmentation, 3D rendering was performed for visualization and integration. The mask of the blood pool created from CT was hollowed out to resemble the actual cardiac anatomy. The accuracy of the segmented CT data was verified by superimposing the post-processed data on to the original dataset. Using anatomical landmarks of the hinge points of the valves, the atrioventricular valve data were properly integrated to the CT-derived model and united as a single geometry using a software called 3-matic® (Materialise N.V.). The two datasets were manually merged and then rendered together for visualization and measurements (Supplemental File 1). This was facilitated by the definition of the mitral and tricuspid valve annuli, which enabled an accurate integration.

The integrated dataset was imported back into Mimics and superimposed on the original CT dataset to verify the accuracy of the 3D rendering. This showed agreement between the 3D rendering and the valve tissue and landmarks in the imaging. The Mimics® software was then utilized to smooth the surface of the anatomy to reduce pixelation and any other errors/gaps in the model. This was done to ensure that it was suitable for 3D printing before exporting the file in the stereolithography (.stl) format. This format was also carefully reviewed by the cardiologist and surgeon involved in patient care. Hybrid 3D printing was completed using a 3D printer with the HeartPrint® flex material (Materialise NV). The printing technology has an accuracy of 0.1 mm, which is better than the acquired images.

The segmentation was performed by a certified echocardiography sonographer under the guidance of an interventional cardiologist with vast experience in CHD. The segmentation and 3D rendering was completed in approximately 20 h. The printing of the hybrid dataset inform the .stl format took approximately 10 h.

Results

The hybrid 3D model accurately demonstrated the morphology of the malformed heart (Fig. 1). The sizes of the cardiac chambers and the vessels corresponded to those obtained by CT evaluation. The left and right ventricular morphology could be accurately made out in the model, with the left-sided right ventricle depicting a trabeculated myocardium. The mitral valve morphology was less accurate as expected because of the interference by the pacing wires during image acquisition than the tricuspid valve morphology (Fig. 2). The model also depicted the Amplatzer device in the atrial septum (Fig. 3). The material used for printing was translucent, enabling visualization of the internal structures well. The model was printed depicting two planes of the heart in end diastole. The first model corresponded to a standard apical four-chamber view and the second one depicted an en face view of the AV valves as seen from the atrial and ventricular sides. The atrioventricular valves were colored red and green, and indicated that the dataset was derived from 3DTEE.

Discussion

Three-dimensional printing has the potential to enhance visualization of the morphology and provide tangible models of complex CHD [9]. The insight provided by three-dimensional modeling may increase procedural efficiency by improving surgical and interventional planning and decrease radiation exposure and procedural complications.

Fig. 1 The HeartPrint® Flex 3D printed model: the translucent material depicts the extracardiac structures and the cardiac contour from CT with the right (*green*) and left (*pink*) atrioventricular valve morphology derived from 3D TEE

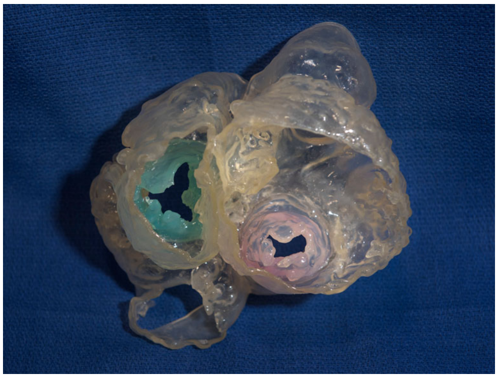

Fig. 2 The right (*green*) and left (*pink*) atrioventricular valve morphology derived from 3D TEE. The leaflets of the systemic atrioventricular valve (*pink*) are clearly defined; however, the mitral valve (*green*) was less accurate due to the data acquisition being impacted by interference by the pacing wires

The integration of the best aspects of two or more imaging modalities has the potential to create detailed and anatomically accurate 3D rendering and printed models. This may enable interventional cardiologists and cardiothoracic surgeons to improve diagnosis and plan appropriate transcatheter or surgical interventions. Customized patient treatment may also be feasible in complex CHD with the ability to fashion the conduit or patch adjusted to the size of the defect prior to the intervention. The precise definition of spatial relationships between structures is of utmost importance in the development of medical devices and to avoid inadvertent complications during their deployment. The hybrid 3D-printed models may be useful in educating patients regarding their specific CHD and the planned intervention. Medical students, residents, nurses, and other medical professionals may also benefit from the printed cardiovascular models with better visual and tactile feedback to understand complex congenital heart defects [10].

The main limitation of 3D printing is that it produces a static model of a dynamic organ making it difficult to understand the hemodynamic functioning of the heart. A printed model that is able to replicate the anatomic and physiological changes that occur during the cardiac cycle may be far more invaluable for diagnosis and management. The progressive development from a single phase static model to an integrated dynamic model incorporating both volume and function may better guide the understanding of complex congenital heart defects in the future. An integrated common virtual platform capable of dynamic modeling and holographic display is now within the grasp of medical technology [9].

Fig. 3 The Amplatzer device in the atrial septum is visualized on the 3D-printed model

Conclusion

This case illustrates the feasibility and proof of concept of printing 3D cardiovascular models derived from multiple imaging modalities with speculation on how this technology may have advantages in the interventional and surgical settings. An extensive comparative clinical trial is necessary to evaluate hybrid 3D printing for its impact on decision-making in surgical or interventional cases. The advantages of accurate 3D modeling from different modalities makes hybrid 3D printing a desirable tool in the field of advanced care of patients with complex CHD.

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Compliance with Ethical Standards

Disclosures The authors Gosnell, Samuel, Kurup, and Haw have nothing to disclose. Pietila is a full-time employee of Materialise NV. Vettukattil has a non-disclosure agreement with Materialise NV.

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