Creation of a 3D Printed Model: From Virtual to Physical

2

Joseph J. Vettukattil, MBBS, MD, DNB, CCST, FRCPCH, FRSM, FRCP, Bennett P. Samuel, MHA, BSN, RN, Jordan M. Gosnell, BS, RDCS and Harikrishnan K.N. Kurup, MBBS, MD

Introduction

The complexity of congenital heart disease has led cardiologists and cardiothoracic surgeons to search for innovative methods to understand the spatial relationships in malformed hearts. The treatment of congenital heart disease requires an in-depth understanding of the three-dimensional (3D) relationships of cardiovascular structures. In the last several years, there have been significant advancements in transcatheter interventions in congenital and structural heart diseases [1]. However, the comprehension of abnormal cardiac morphology is dependent on quality imaging, namely cardiac computed tomography (CT), cardiac magnetic resonance (CMR), and 3D transthoracic (TTE) or transesophageal (TEE) echocardiography. In addition, the information gained from post-processed imaging datasets continues to be limiting as the 3D renderings are visualized on a two-dimensional (2D) screen. Interpretation of these images requires assumptions, where aspects of spatial relationships are left to the imagination without a tangible model. In this context, rapid prototyping, the technique where 3D computerized models of anatomical structures are converted into physical models, plays a significant role in filling this gap in cardiac medicine [1–7].

The management of congenital heart disease relies heavily on accurate imaging of the morphology and interrelationships between cardiac structures. Virtual preoperative models of congenital heart disease were first created from CMR datasets in 1988. Surface reconstruction software, originally developed for craniofacial and orthopedic surgical planning, was adapted for post-processing of preoperative CMR datasets. The reconstructions were consistent with echocardiography, cineangiography, 2D CMR, and intraoperative findings. However, they were not readily adopted for clinical use due to low-resolution images and lack of computing power [8].

3D echocardiography began to develop in the 1960s, and the first 3D scan of the heart was reported in 1974 [9]. Over the next two decades, improvements in resolution and computing power transformed the visualization of congenital heart disease. Although multiple options for 3D imaging became available, the representation of the 3D images on a 2D screen left depth and spatial relationships to the imagination. Research

J.J. Vettukattil (✉) · B.P. Samuel · J.M. Gosnell
H.K.N. Kurup
Congenital Heart Center, Helen DeVos
Children's Hospital of Spectrum Heath,
Grand Rapids, MI, USA
e-mail: Joseph.Vettukattil@helendevoschildrens.org

B.P. Samuel
e-mail: Bennett.Samuel@helendevoschildrens.org

J.M. Gosnell
e-mail: Jordan.Gosnell@spectrumhealth.org

H.K.N. Kurup
e-mail: drhari.kurup@gmail.com

J.J. Vettukattil
College of Human Medicine, Michigan State
University, Grand Rapids, MI, USA

K.M. Farooqi (ed.), *Rapid Prototyping in Cardiac Disease*,
DOI 10.1007/978-3-319-53523-4_2

into the ability of individuals to deduce spatial relationships, and mental rotation reveals vast intra-observer and inter-observer variability in interpreting 3D data [1–7, 10]. Rapid prototyping leaves no aspect of the spatial relationships to the imagination, which can be invaluable in children and adults with complex congenital heart disease [3].

Rapid prototyping was introduced in the early 1980s and applied by the manufacturing industry to design components for various products including aircrafts, computers, and vehicles [1, 11]. For these industrial applications, rapid prototyping has been utilized to assess the ease of future product assembly and evaluate the feasibility of developing newly designed products prior to mass production [11]. In medicine, 3D printing from radiological images to replicate anatomical structures was initially used in orthopedic and plastic surgery [1, 7]. The software was later adapted to accommodate CT and CMR datasets for rapid prototyping of cardiovascular structures. More recently, high-resolution cardiac imaging has ushered in an era where rapid prototyping or 3D printing of congenital heart disease is more feasible [8]. Within one complex congenital heart diagnosis, patients may have varied morphology and prognosis depending on the specific anatomy or associated comorbidities. 3D printed cardiac models can enhance the management of patients by improving interventional and surgical planning and perhaps lead to individualized device deployment targeting specific cardiac defects [6–11].

Typically, high-resolution cross-sectional CT and CMR are used as the source datasets to derive whole heart 3D printed models [10, 11]. 3D printing derived from 3D echocardiographic imaging is also feasible and accurately reflects cardiac morphology, albeit focusing on one part of the anatomy (Figs. 2.1, 2.2, 2.3, and 2.4) [12, 13]. The integration of multiple imaging modalities for hybrid 3D printing is an additional technique which can be used when one modality is insufficient to give a complete picture of the pathology [9, 14]. This technique utilizes the strength of each imaging modality to be incorporated separately into one model improving the accuracy of the hybrid 3D printedheart model.

A 3D printed heart model may be used to teach patients and their family members about the congenital heart defect and plan for repair. Currently, a 2D representation, such as a drawing on a piece of paper or whiteboard, is used to explain the procedure to patients and their family members. The visual and tactile feedback provided by 3D printed heart models markedly improves the understanding of complex structural heart defects and may be beneficial to teach medical students, residents, nurses, and other

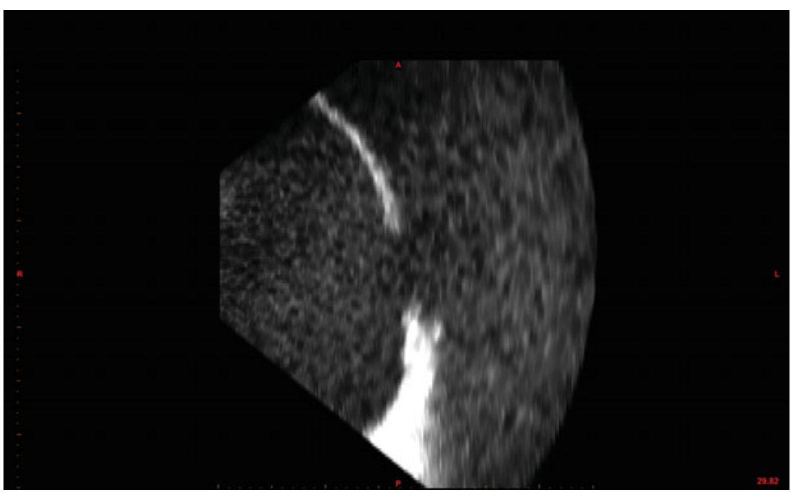


Fig. 2.1 Imported image from a 3D echocardiography dataset for 3D printing performed for evaluation of an atrial septal defect

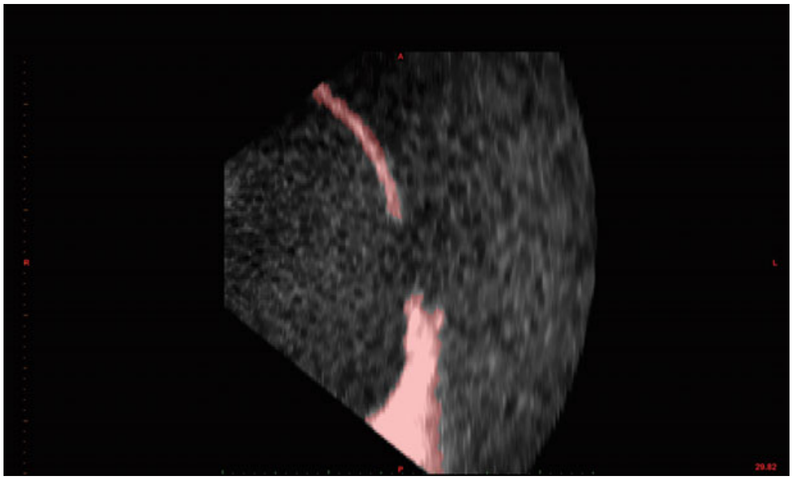


Fig. 2.2 The atrial septum was segmented using Materialise Mimics® Innovation Suite

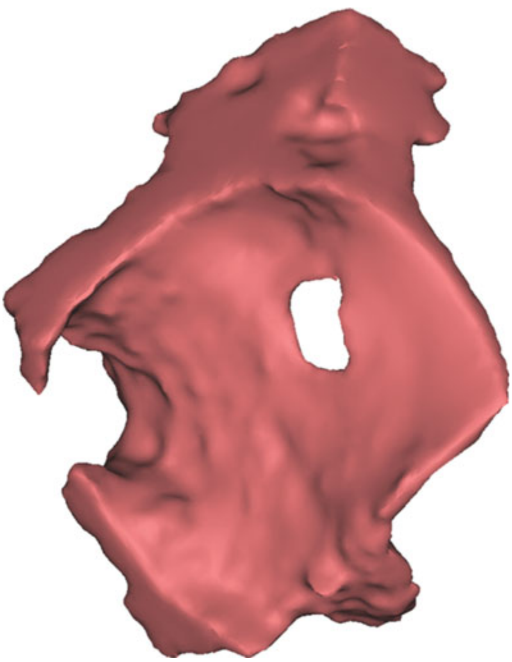


Fig. 2.3 Mimics® Innovation Suite was used to reconstruct a 3D rendering of the atrial septum, which is shown with the visible atrial septal defect

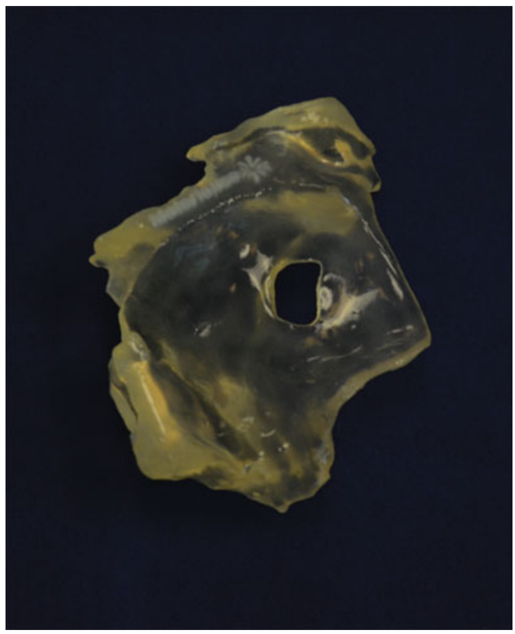


Fig. 2.4 Materialise Heart Print® Flex 3D printed model of an atrial septal defect from 3D echocardiography

medical professionals about specific congenital heart defects [1, 6–9, 11–16]. The 3D printed heart model is expected to enhance professional training, enable practicing procedures before performing them, and help design precise prostheses prior to an interventional or surgical procedure. In complex anatomical repairs where expert opinion is required, the 3D virtual and printed models can be shared rather than inconveniencing the patient to travel long distances.

The cost and time needed to create 3D printed models may vary widely depending on the complexity of the lesion and quality of the material used for printing. As a result, it is important to consider the indications or degree of complexity of congenital heart defects for 3D printing to maximize its utility and reduce commercial misuse [9].

Patient Selection and Image Acquisition

The field of congenital heart disease has undergone major treatment improvisations over the last 4 decades. For example, the arterial switch operation has been the treatment of choice for transposition of the great arteries for the past 30 years [17]. This congenital defect was previously managed by the Mustard or Senning procedure, which could functionally correct the altered hemodynamics. The Fontan operation as the final procedure in the common single ventricle pathway has also undergone major revisions in the past 40 years [18]. However, these patients who underwent palliative procedures in the past are now presenting with cardiac complications and require advanced imaging to help form a complete picture of their clinical status. It may be difficult for cardiologists and surgeons new to the field, or who are not trained in imaging, to interpret the cardiovascular images obtained by conventional modalities in these patients. 3D printing of such complex repaired defects facilitates the understanding of the anatomical substrate. 3D printed models help in planning the appropriate interventions well in advance, which can improve the interventionalists' or the surgeons' preparation for the procedure. The utility of 3D printing in planning catheter intervention in pulmonary venous baffle obstruction in Mustard repair has recently been demonstrated [11]. The size of devices, size, and shape of conduits or patches, and the accessory equipment required during the intervention can also be planned, contributing to the procedure going smoothly. This may reduce procedure time and risk of radiation exposure and aid in the prevention of inadvertent complications. Some of the specific congenital heart defects for which 3D printing can make significant differences in the management are described below.

Determining the morphology of the superior and inferior bridging leaflets as well as identifying any imbalance of the valve opening into the ventricles is critical in determining the suitability for biventricular repair in atrioventricular septal defects (AVSD) [19]. Ventricular size can be underestimated due to foreshortening on conventional imaging modalities. Visualization of AVSDs by hybrid 3D printing can provide insight into the actual ventricular volumes, the relationship of the bridging leaflets to the ventricles, presence of straddling leaflets, and associated anomalies. The size of the patch required and strategies to repair the left-sided cleft valve to prevent later regurgitation can also be planned [20]. 3D hybrid segmentation and printing is especially relevant in this setting given that valvular structures are best re-created using 3D echocardiographic images.

Double-chambered right ventricle (RV) is another congenital heart defect for which 3D printing may be useful. It occurs due to muscle bundles separating the RV inlet and outlet (pulmonary artery) from the body of the RV [21]. This malformation is found in up to 10% of patients with ventricular septal defects (VSD) on long-term follow-up. The RV is difficult to image and quantify because it does not conform to the geometric assumptions made for the left ventricle. The cardiothoracic surgeon requires vital information regarding how much extra volume may be added to the RV once the muscle bundles are resected, especially in patients with corrected complex congenital heart disease or 1½ ventricular repair. The tangibility offered by 3D printed models provides the surgeon with a hands-on experience of the actual muscle resection prior to the procedure. This can have far-reaching implications such as choosing between 1½ ventricular repair versus biventricular repair (Fig. 2.5a–e) [22].

Corrective surgery in double outlet right ventricle (DORV) may involve baffling of the VSD to the aorta or performing an arterial switch operation. One of the factors that influence the approach is the proximity of the ventricular septal margin to the aorta. However, DORV with subpulmonary VSD (Taussig-Bing anomaly) requires baffling of the VSD to the pulmonary artery followed by an arterial switch procedure.

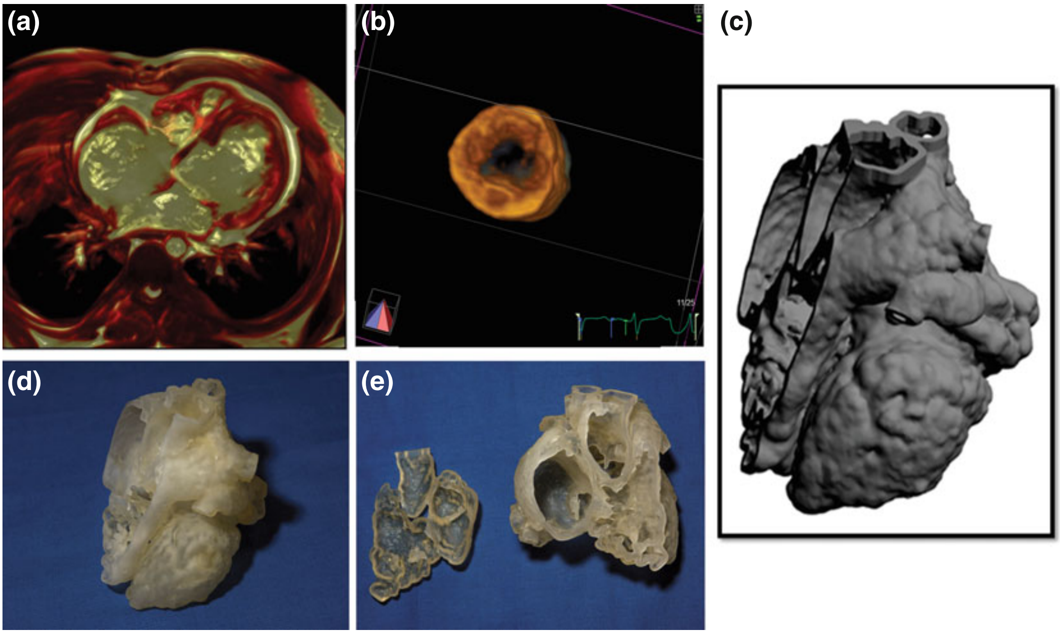


Fig. 2.5 **a** A 4-chamber view from CMR showing muscle bundles in the mid-right ventricle in a patient with pulmonary atresia intact ventricular septum palliated with a bidirectional Glenn anastomosis. **b** A 3D TEE showing the tricuspid valve. **c** A 3D rendering of the integrated CMR and 3D TEE datasets. **d** A hybrid 3D printed model showing the LV and the obstructing muscle bundles in the RV. **e** A hybrid 3D printed model corresponding to an echocardiographic apical 4-chamber view

Commitment of the VSD to one of the great vessels (pulmonary artery or aorta) is mandatory for successful biventricular repair. 3D printed models of the heart provide accurate visualization of the relationship of the VSD to the outflow tracts so that treatment decisions regarding routability can be made [23].

Considering the complications and late failure of the Fontan procedure, Fontan conversion or takedown may be considered in some cases [24]. Hybrid 3D printed models of these complex hearts provide excellent representation of the size and relationship of the chambers and the valvular anatomy. There are recent reports of the utility of 3D printed models of the RV outflow tract in the accurate selection of patients for pulmonary valve implantation [25]. It is critical to evaluate the size and orientation of the outflow tract and possibly test out the surgical intervention on a 3D printed model prior to undertaking such complex interventions. 3D printed models of the heart and the great vessels have been found to be useful in preoperative and pre-interventional planning of stent sizes in coarctation of aorta, branch pulmonary artery stenosis, and caval valve implantation techniques [16, 26]. Custom-sized patent ductus arteriosus stents in hybrid procedures for hypoplastic left heart syndrome may also be a potential application of 3D printing.

It is important to have proper guidelines for the effective use of this technology when it is integrated into routine clinical practice. The time and risk involved in obtaining the necessary images, performing segmentation, and the cost for printing must be taken into account. Patients with simple heart defects wherein the routine imaging modalities provide a straightforward diagnosis, and appropriate treatment strategies do not require 3D printed heart models, although models of these defects may still be useful for educational purposes. These include simple atrial and ventricular septal defects, tetralogy of Fallot without associated defects, and simple transposition of the great arteries.

Image acquisition is the most important step in the process of creating a virtual model to be used to print a physical model. A significant determinant in patient selection for 3D printing is the availability of high-quality images. Currently, the imaging modalities used to derive 3D printed models include cardiac CT, CMR, and both 3D TEE and TTE. Each imaging modality has different strengths and weaknesses that impact the quality and accuracy of the 3D printed model [9]. The visualization of extracardiac anatomy and "blood pool" imaging is enhanced by CT [27]. However, nephrotoxic intravenous contrast is often required for acquisition of cardiac CT imaging datasets and exposes patients to ionizing radiation. Cumulative medical radiation is of concern and can have important health implications for young patients [28, 29]. CMR is superior to other imaging modalities for the quantification of ventricular volumes and myocardial architecture [4]. For CMR, intubation and general anesthesia are often necessary in pediatric patients. Gadolinium-based contrast may also be required for acquisition of high-resolution imaging datasets. Scanning is not possible in patients with implanted devices that are incompatible with CMR. In contrast, 3D echocardiography is a bedside tool, which is safe for severely ill patients as they do not require transportation or positioning in a scanner. Intubation and sedation are also not required except when 3D TEE is utilized or if the patient's age makes it difficult for them to lie still for a prolonged period of time [30]. The best visualization of cardiac valve morphology is provided by 3D echocardiography when compared to other imaging modalities [31]. However, there are several limiting factors that may affect valve visualization by 3D echocardiography. Image acquisition focuses on one aspect of the anatomy, and a whole heart image dataset cannot be acquired. Technical settings including frame rate, gain, compression, and depth must be set by the echocardiographer to clearly define the blood–tissue border and to distinguish valve anatomy from artifact. Furthermore, hardware and software limitations in current ultrasound systems, specifically those affecting temporal and spatial resolutions, may not provide sufficient image quality for a 3D printed model. These limitations affect both 3D TTE and 3D TEE imaging. Availability of appropriate sized probes for TEE may be a limiting factor in young patients with complex congenital heart disease. However, 3D TEE has better image resolution and frame rates [20] and is preferable as a source dataset for 3D printing. Image acquisition is discussed in detail in subsequent chapters.

Post-processing to Virtual Model

A factor that significantly impacts the accuracy of 3D printed models is post-processing, the quality of which may vary among cardiologists and sonographers [20]. For this reason, there is a need for a unified protocol. The images from cardiac CT, CMR, and 3D ultrasound are usually acquired in the Cartesian digital imaging and communications in medicine (DICOM) format. As traditional 3D echocardiogram post-processing elements cannot be exported from segmentation software, image acquisition settings play an important role in determining the quality of ultrasound datasets. A frame rate of 30 frames per second (fps) is more than adequate for 3D echocardiography datasets. If there is no fusion artifact, 4 cardiac cycles provide optimal data for post-processing. The gain and compression settings must be optimized to get adequate visualization of the tissue–blood separation point. Visualization of the blood-tissue interface is also dependent on the patient's size and the frequency setting of the ultrasound probe. A frequency of 5–7 MHz is usually adequate for acquisition of 3D TTE datasets for 3D printing in children.

After assessing the data for quality and clarity and filtering for noise reduction, it is imported into the segmentation software. We utilized Mimics® Innovation Suite and 3-matic® (Materialise, Leuven, Belgium), a commercially available post-processing software. Thresholding and other interactive editing operations are then performed using automatic, semiautomatic, and hand segmentation methods. Thresholding is used to isolate tissue with a specific signal intensity in different regions of the image dataset to create anatomy-specific masks. In ultrasound datasets, thresholding helps to identify the blood–tissue border based on the intensity of the cardiac structures' echogenicity (echodensity). For CMR and CT data, segmentation is used to create a mask of the blood pool which is subsequently hollowed out to represent the intracardiac anatomy and orientation. For example, a 2–4 mm thickness may be provided to the model at all blood–tissue interfaces to depict cardiac/vessel walls in the rendered model.

For all three modalities, there are varying degrees of manual editing required for proper representation of cardiac morphology. Thin-walled structures such as the interatrial septum may result in "dropout" on a CT scan when other imaging datasets do not support the presence of a hole or defect. Careful attention must also be given to artifacts in ultrasound datasets to reduce similar errors in being represented in the 3D printed models. We have not yet reached the state of technological advancement required for fully automated segmentation. A sound knowledge of normal and abnormal intracardiac anatomy is essential for appropriate segmentation and accurate reproduction in the printed model. It is recommended that the caregivers managing the patient be involved in the segmentation process and be familiar with all available imaging information.

Upon the completion of segmentation, a 3D digital replica of the heart is rendered for visualization and measurements. The segmentation software is then utilized to prepare the digital model for printing and exporting in stereolithography (STL) format. Prior to conversion into STL file format, the 3D rendering is smoothed to reduce pixilation and improve the 3D file quality. The surface of the STL file is then prepped for printing by creating a surface mesh model (Fig. 2.6a, b). The STL file can then be printed on any 3D printer depending on the choice of model material and detail needed [9, 12, 13]. Prior to 3D printing, the reconstructed model can be dissected to display the region of specific interest [9–14]. This step also relies heavily on the contributions of the interventionalist or surgeon so that maximum information for procedure planning can be obtained from the model.

For hybrid 3D printing from two or more imaging modalities, the 3D rendering must be imported into dedicated post-processing software for additive manufacturing such as 3-matic® (Materialise). The datasets are imported into segmentation software and integrated after individual imaging segmentation has been performed. It is important to identify the targeted cardiac phases for rapid prototyping and ensure that each imaging modality is in the same phase prior to integration [9, 14]. After completion of segmentation of the individual imaging modalities as described above, the datasets can be merged manually in 3-matic by superimposing the datasets to create a composite mask (Fig. 2.7a–c). After confirming that the measurements of the virtual file correlate with the original dataset, the merged dataset is exported back into Mimics® Innovation Suite for optimization. The 3D rendering is (Fig. 2.7d) then converted to STL format for hybrid 3D printing (Fig. 2.7e–g).

More recently, CT and CMR data segmentation has become less labor-intensive due to automation of the segmentation function within the 3D segmentation software. Comparatively, 3D ultrasound data segmentation continues to be a long, manual editing process even for experienced individuals. The ideal personnel for processing data for 3D printing must be familiar with both the segmentation software and congenital heart disease. For hybrid 3D printing, additional time and experience is required for proper alignment of modality datasets. Ideally, anatomical markers such as a valve annulus can be identified on each modality to assist with hybrid model reconstruction.

Limitations of 3D Printing

A limitation of a 3D printed cardiac model is that it is a static model of a dynamic organ, making it difficult to deduce from it any hemodynamic information. The various changes that occur during the cardiac cycle are frozen in time and

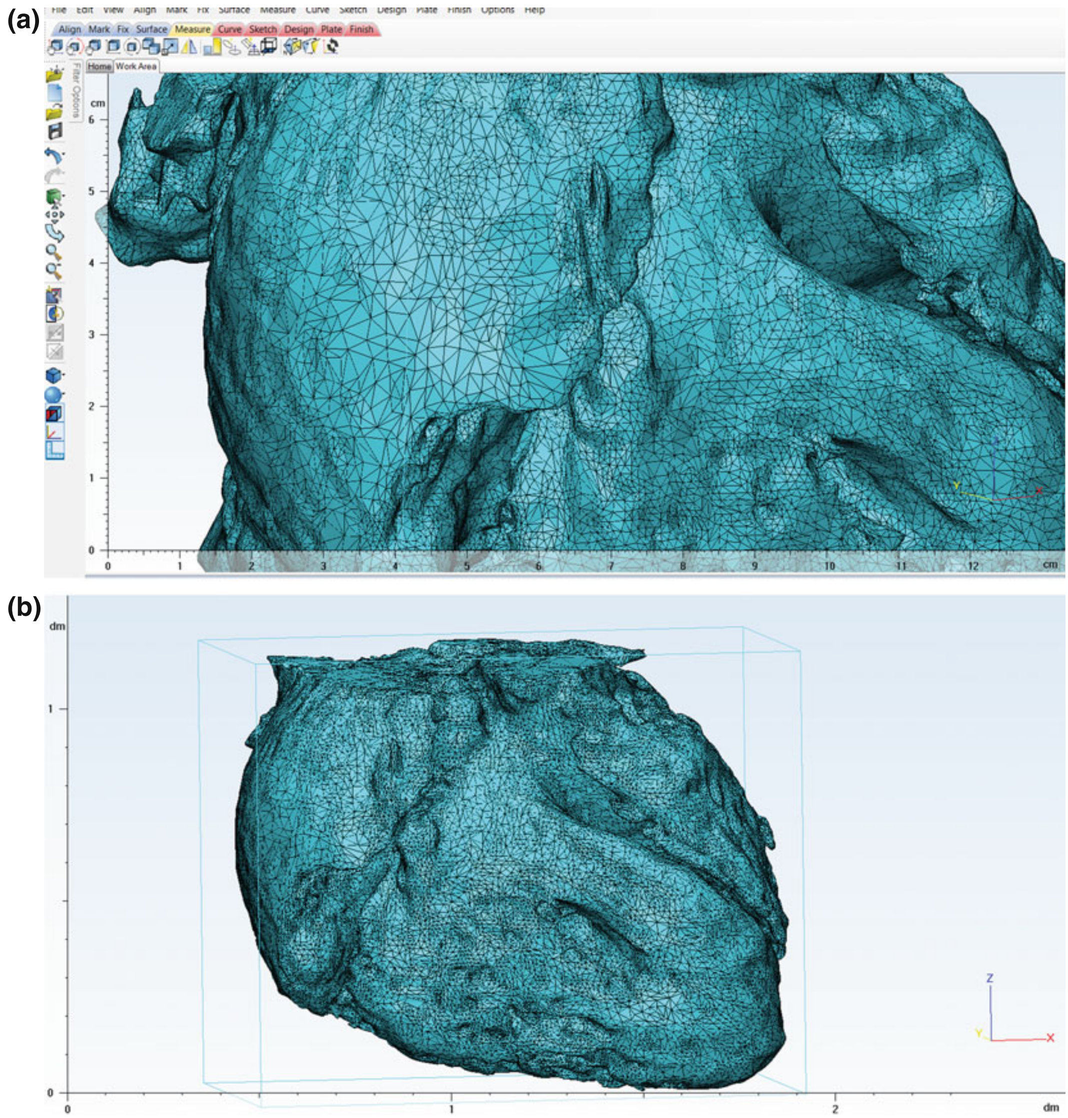
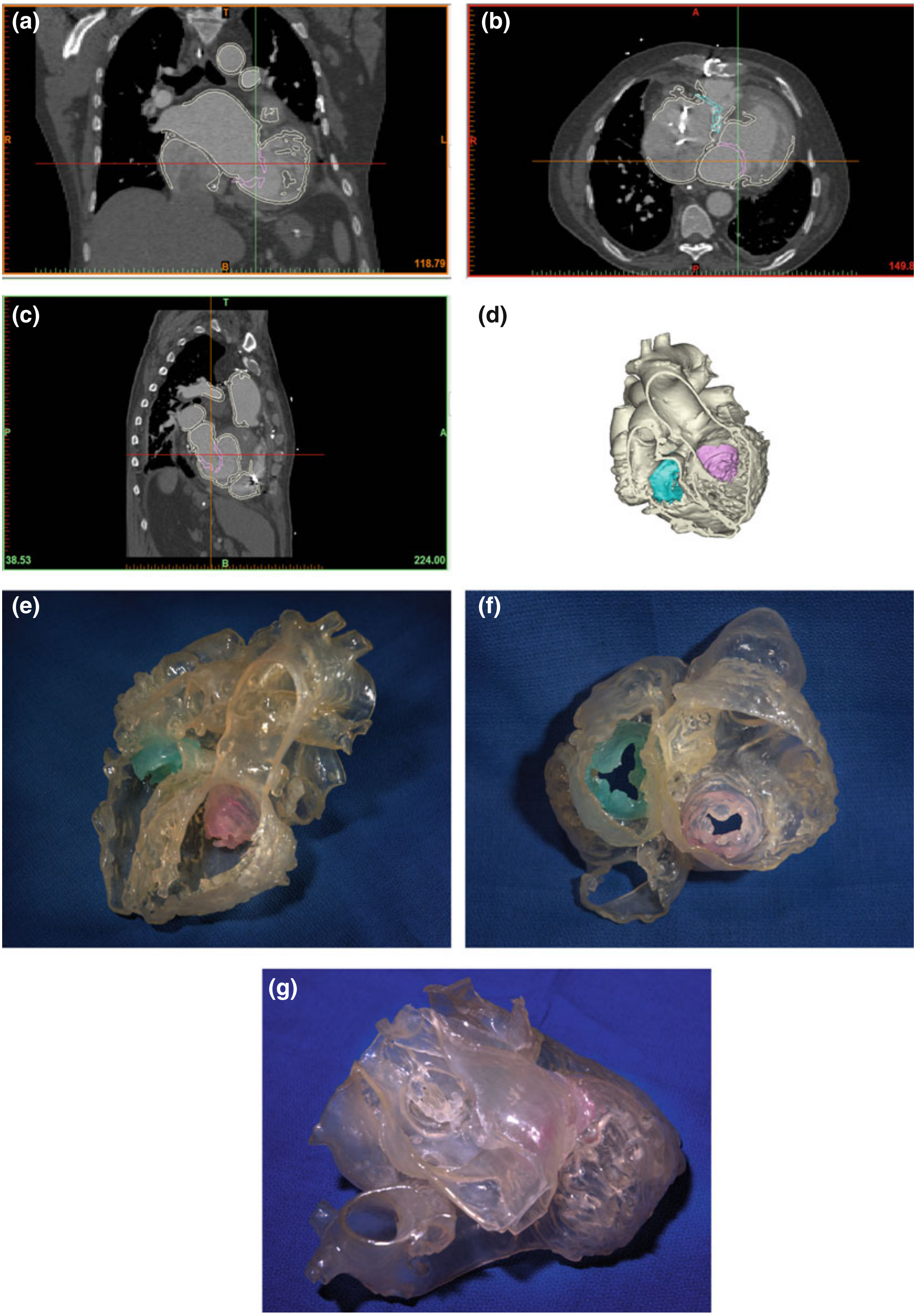


Fig. 2.6 **a**, **b** The surface mesh model utilized to fill in any signal dropouts or gaps in the 3D virtual model in preparation for 3D printing

Fig. 2.7 **a**–**c** The integration of CT and 3D TEE in a patient with congenitally corrected transposition of the great arteries for hybrid 3D printing. **d** A 3D rendering produced from integration of CT and 3D TEE in a patient with congenitally corrected transposition of the great arteries for hybrid 3D printing. **e** The HeartPrint® Flex hybrid 3D printed model. The translucent material depicts the extracardiac structures and the cardiac contour derived from CT with the right (*green*) and left (*pink*) atrioventricular valve morphology derived from 3D TEE. **f** 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 affected by interference from pacing wires. **g** The Amplatzer septal occluder device visualized in the atrial septum on the 3D printed model ►


(a)
T
R
L
B
118.79
(b)
A
R
P
149.8
(c)
T
P
A
B
38.53
224.00
(d)
(e)
(f)
(g)

space, lacking the function and hemodynamic changes related to the functional morphology of the heart.

Conclusion: Personalized Medicine in Congenital Heart Disease

A 3D printed model that would be able to replicate the anatomical and physiological changes that occur during the cardiac cycle would be invaluable for diagnosis and management of children and adults with complex congenital heart disease. Further advancements in cardiac imaging and computing power combined with miniaturization of processors promise a new era in advanced cardiac imaging. Visualization of 3D images in 3D media with augmented reality will define the future of personalized cardiac medicine.

References

1. Laschinger JC, Vannier MW, Gutierrez E, et al. Preoperative three-dimensional reconstruction of the heart and great vessels in patients with congenital heart disease. Technique and initial results. J Thorac Cardiovasc Surg. 1988;96(3):464–73.
2. Dekker DL, Piziali RL, Dong E Jr. A system for ultrasonically imaging the human heart in three dimensions. Comput Biomed Res. 1974;7(6):544–53. doi:10.1016/0010-4809(74)90031-7.
3. Farooqi KM, Sengupta PP. Echocardiography and three-dimensional printing: sound ideas to touch a heart. J Am Soc Echocardiogr. 2015;28(4):398–403. doi:10.1016/j.echo.2015.02.005.
4. Luijnenburg SE, Robbers-Visser D, Moekler A, et al. Intra-observer and interobserver variability of biventricular function, volumes and mass in patients with congenital heart disease measure by CMR imaging. Int J Cardiovasc Imaging. 2010;26(1):57–64. doi:10.1007/s10554-009-9501-y.
5. Guillot A, Champely S, Batier C, et al. Relationship between spatial abilities, mental rotation, and functional anatomy learning. Adv Health Sci Educ Theor Pract. 2007;12(4):491–507. doi:10.1007/s10459-006-9021-7.
6. Hoyek N, Collect C, Rastello O, et al. Enhancement of mental rotation abilities and its effect on anatomy learning. Teach Learn Med. 2009;21(3):201–6. doi:10.1080/10401330903014178.
7. Estevez ME, Lindgren KA, Bergethon PR. A novel three-dimensional tool for teaching human neuroanatomy. Anat Sci Edu. 2010;3(6):309–17. doi:10.1002/ase.186.
8. Greil GF, Wolf I, Kuettner A, et al. Stereolithographic reproduction of complex cardiac morphology based on high resolution imaging. Clin Res Cardiol. 2007;96(3):176–85. doi:10.1007/s00392-007-0482-3.
9. Kurup HKN, Samuel BP, Vettukattil JJ. Hybrid 3D printing: a game-changer in personalized cardiac medicine? Expert Rev Cardiovasc Ther. 2015. doi:10.1586/14779072.2015.1100076
10. Jacobs S, Grunert R, Mohr FW, et al. 3D-Imaging of cardiac structures using 3D heart models for planning in heart surgery: a preliminary study. Interact CardioVasc Thorac Surg. 2008;7(1):6–9. doi:10.1510/icvts.2007.156588.
11. Olivieri L, Krieger A, Chen MY, et al. 3D heart model guides complex stent angioplasty of pulmonary venous baffle obstruction in a mustard repair of D-TGA. Int J Cardiol. 2014;172(2):e297–8. doi:10.1016/j.ijcard.2013.12.192.
12. Samuel BP, Pinto C, Pietila T, et al. Ultrasound-derived three-dimensional printing in congenital heart disease. J Digit Imaging. 2015;28(4):459–61. doi:10.1007/s10278-014-9761-5.
13. Olivieri LJ, Krieger A, Loke YH. Three-dimensional printing of intracardiac defects from three-dimensional echocardiographic images: feasibility and relative accuracy. J Am Soc Echocardiogr. 2015;28(4):392–7. doi:10.1016/j.echo.2014.12.016.
14. Gosnell J, Pietila T, Samuel BP, et al. Integration of computed tomography and three-dimensional echocardiography for hybrid three-dimensional printing in congenital heart disease. J Digit Imaging. 2016. doi:10.1007/s10278-016-9879-8.
15. Kim MS, Hansgen AR, Wink O, et al. Rapid prototyping: a new tool in understanding and treating structural heart disease. Circulation. 2008;117(18):2388–94. doi:10.1161/CIRCULATIONAHA.107.740977.
16. Valverde I, Gomez G, Coserria JF, et al. 3D printed models for planning endovascular stenting in transverse aortic arch hypoplasia. Catheter Cardiovasc Interv. 2015;85(6):1006–12. doi:10.1002/ccd.25810.
17. Villafane J, Lantin-Hermoso MR, Bhatt AB, Tweddell JS, Geva T, Nathan M, et al. D-transposition of the great arteries: the current era of the arterial switch operation. J Am Coll Cardiol. 2014;64(5):498–511.
18. John AS. Fontan repair of single ventricle physiology: consequences of a unique physiology and possible treatment options. Cardiol Clin. 2015;33(4):559–69.
19. Anderson RH, Wessels A, Vettukattil JJ. Morphology and morphogenesis of atrioventricular septal defect with common atrioventricular junction. World J Pediatr Congenit Heart Surg. 2010;1(1):59–67.

20. Cohen MS, Spray TL. Surgical management of unbalanced atrioventricular canal defect. Semin Thorac Cardiovasc Surg Pediatr Card Surg Annu. 2005:135–44.
21. Loukas M, Housman B, Blaak C, Kralovic S, Tubbs RS, Anderson RH. Double-chambered right ventricle: a review. Cardiovasc Pathol. 2013;22(6): 417–23.
22. Haw MP, Gosnell JM, Samuel BP, Kurup H, Baliulis G, Hillman ND, Lacina SL, Vettukattil JJ. 147: hybrid 3D printing in congenital heart disease. Select abstracts from cardiology 2016: The 19th annual update on pediatric and congenital cardiovascular disease, Orlando, Florida, 24–28 Feb 2016. World J Pediatr Congenit Heart Surg. 2016;7(2):274–5. doi:10.1177/2150135115626922.
23. Farooqi KM, Uppu SC, Nguyen K, Srivastava S, Ko HH, Choueiter N, et al. Application of virtual three-dimensional models for simultaneous visualization of intracardiac anatomic relationships in double outlet right ventricle. Pediatr Cardiol. 2015.
24. Kottayil BP, Sunil GS, Kappanayil M, Mohanty SH, Francis E, Vaidyanathan B, et al. Two-ventricle repair for complex congenital heart defects palliated towards single-ventricle repair. Interact CardioVasc Thorac Surg. 2014;18(3):266–71.
25. Schievano S, Migliavacca F, Coats L, Khambadkone S, Carminati M, Wilson N, et al. Percutaneous pulmonary valve implantation based on rapid prototyping of right ventricular outflow tract and pulmonary trunk from MR data. Radiology. 2007;242(2): 490–7.
26. O'Neill B, Wang DD, Pantelic M, Song T, Guerrero M, Greenbaum A, et al. Transcatheter caval valve implantation using multimodality imaging: roles of TEE, CT, and 3D printing. JACC Cardiovasc Imaging. 2015;8(2):221–5.
27. Goitein O, Salem Y, Jacobson J, et al. The role of cardiac computed tomography in infants with congenital heart disease. Isr Med Assoc J. 2014;16(3): 147–52.
28. Glatz AC, Purrington KS, Klinger A, et al. Cumulative exposure to medical radiation for children requiring surgery for congenital heart disease.
29. Hoffman A, Engelfriet P, Mulder B. Radiation exposure during follow-up of adults with congenital heart disease. Int J Cardiol. 2007;118(2):151–3. doi:10.1016/j.ijcard.2006.07.012.
30. Vettukattil JJ. Three dimensional echocardiography in congenital heart disease. Heart 2012;98:79–88. doi:10.1136/heartjnl-2011-300488.
31. Black D, Vettukattil J. Advanced echocardiographic imaging of the congenitally malformed heart. Curr Cardiol Rev. 2013;9(3):241–52. doi:10.2174/1573403x11309030008.

http://www.springer.com/978-3-319-53522-7

Rapid Prototyping in Cardiac Disease
3D Printing the Heart
Farooqi, K.M. (Ed.)
2017, XIII, 198 p. 74 illus., 64 illus. in color., Hardcover
ISBN: 978-3-319-53522-7