3D Printing in Congenital Heart Disease

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Introduction

Medical 3D printing is an exciting technology that is improving the lives of children and adults with congenital heart disease. Congenital heart disease (CHD) affects nearly 1% of all infants born in the United States, or 40,000 patients a year (1,2). Of these, 25% have critical CHD requiring surgery or procedures during the first year of life (3). Although results have improved with the new era, recent data still reveals one-year mortality rates of patients with critical CHD to be as high as 20%. Perfect surgical repairs are required on hearts that may only be the size of a strawberry, include up to 7-8 defects at once, and must be performed within the very limited time the heart can be safely stopped.

A patient-specific approach is required in treating each child and adult with CHD. Although CHD is diagnosed primarily using two-dimensional imaging modalities, this approach limits the ability to develop an understanding of the 3D spatial relationships necessary to address complex CHD. Combinations of coexisting cardiac lesions and subtleties within a single heart lesion can fundamentally alter patient management and surgical approaches. Pediatric cardiothoracic surgeons and interventional cardiologists have a very challenging task: first "translating two-dimensional images into a three-dimensional figure, and then mentally planning how to change the heart structure," says Dr. Charles Huddleston, a pediatric cardiothoracic surgeon at SSM Cardinal Glennon Hospital and SLUCare. "Having a 3D model changes the game."

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Creating an exact physical replica of a patient's heart has become possible with medical 3D printing. Models can be created at resolutions as high as 200 microns. The latest 3D printing technology allows heart models to be created with multiple colors, multiple flexibilities, and allows for sterilization for intraoperative use. Medical 3D printing is creating the new paradigm where science of anatomy is certain. One can, thus, focus on the art and practice of medicine.

Technique

Image Acquisition

Construction of a 3D printed heart model begins with obtaining high quality 3D imaging datasets. CT angiography and MRI are standard methods, although rotational angiography and 3D ultrasound can also be used. Sufficient signal and contrast are required to highlight the cardiac structures. CT and rotational angiography require intravenous contrast agents to delineate the blood pool. MRI benefits from utilization of intravenous contrast agents, although contrast-free 3D whole-heart pulse sequences can be sufficient. Ideally, the image resolution should be at least 1 mm^3 with isotropic voxels to maintain accuracy and prevent step artifact. Maintaining sufficient temporal resolution is important to freeze cardiac motion and prevent image blurring. Generally, temporal blurring may be minimized if images are acquired during end-diastole when the heart rate is lower than 80 bpm and end-systole if the heart rate is higher than 80 bpm.

Building the CAD File

The image data is then exported into DICOM format and loaded into software that can convert the image to a CAD file. This is done through highlighting the structures of interest using automated and manual segmentation methods. The software can then build a CAD file from the defined geometry.

Postprocessing the CAD file

The CAD file can be postprocessed using engineering or modeling software to isolate the area of interest. Hollow heart models, heart models showing the myocardial wall, and multicolored heart models can be created using postprocessing techniques. Defects in the CAD file, such as non-water-tight meshes, can be repaired using postprocessing software.

3D Printing

The CAD file is loaded onto the 3D printer for fabrication. With PolyJet™ printers, each model within an assembly can be assigned a different material where both color and flexibility can be modified.

Postprocessing

3D prints are taken off the printer. Support material is physically removed using a waterjet or chemically removed using a solution in an ultrasonic tank. After cleaning, the 3D printed heart is ready for use.

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Congenital Heart Surgery

Case I

A 10-year-old patient adopted from a foreign country with Tetralogy of Fallot and pulmonary atresia had undergone single ventricle palliation with a Glenn shunt presented with increasing cyanosis. A surgery needed to be performed to provide his body with more oxygenated blood. While completion of single ventricle palliation with a Fontan procedure would be the safest intervention in the short-run, single ventricle physiology has long-term limitations. Performing a biventricular repair may ultimately have the best prognosis long-term, but if the left heart is too small, the patient may develop irreversible pulmonary hypertension and be at high risk for mortality in the short-term. Multimodality imaging was performed including cardiac catheterization, echocardiography, and cardiac MRI.

Echocardiography and MRI volumetric analysis suggested that the left atrial and left ventricular size may be too small (Figure 1). A 3D printed model was created which was able to demonstrate the size of the ventricles in true scale and how structures critical to the repair were related to one another in a very intuitive manner (Figure 2). After reviewing the clinical information as well as the 3D model in conference, the cardiologists and cardiovascular surgeons concluded that biventricular repair could be safely performed. The Glenn shunt was taken down, and the patient underwent biventricular repair with a VSD patch and right ventricle to pulmonary artery conduit. He did extremely well post-operatively and was discharged to home after a two-week hospitalization with normal oxygen saturations, normal pulmonary pressures, and excellent biventricular function. The 3D printed heart model was instrumental in determining which surgery to perform, a critical decision with life-changing implications.

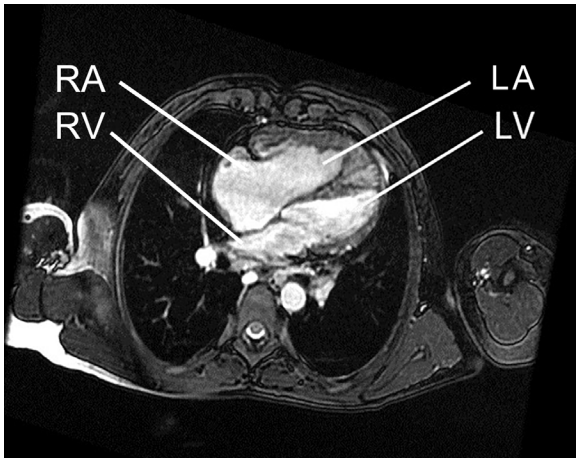

Figure 1. MRI – 10-year-old patient with Tetralogy of Fallot with pulmonary atresia s/p Glenn shunt showing a small left ventricle and a dilated right ventricle. (LA – left atrium, LV – left ventricle, RA – right atrium, RV – right ventricle).

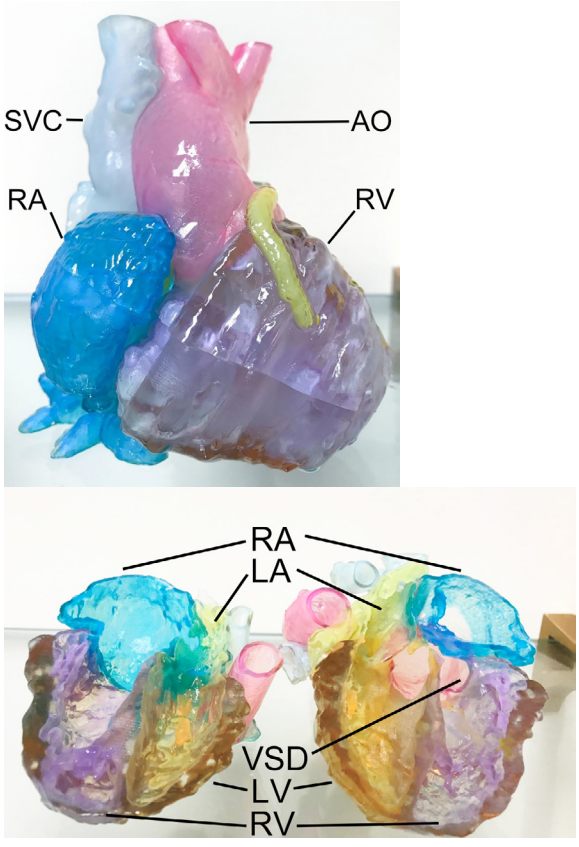

Figure 2. 3D printed model of Tetralogy of Fallot with pulmonary atresia s/p Glenn procedure. (RA – right atrium, RV – right ventricle, LA – left atrium, LV – left ventricle, SVC – superior vena cava, AO – aorta, VSD – ventricular septal defect.)

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Case II

A 6-month-old patient with heterotaxy with dextrocardia, double outlet right ventricle with a perimembranous VSD and subpulmonary stenosis and side-by-side transposed great vessels had presented from an outside institution after a pulmonary artery band placement. Surgical options even after reviewing echocardiography, cardiac catheterization, and CT were unclear (Figure 3). Pulmonary arterial pressures were too high to continue with single ventricle palliation, so two biventricular techniques were considered: a complex intracardiac baffle or an arterial switch with a VSD repair. All options were considered extremely high risk. A 3D model was created and showed that an intracardiac baffle from the left ventricle across the VSD to the aorta was much too long; however, arterial switch with VSD closure was the better option despite the size mismatch of the great vessels (Figure 4). In effect, the 3D printed model was able to integrate very complicated 3D anatomy that was difficult to understand using tomographic slices or even computer reconstructions into a single model that allowed the surgeon to quickly understand extremely complex anatomy and develop a surgical plan for repair. The VSD closure and arterial switch operation was performed, and the patient did extremely well and was discharged in less than two weeks. The 3D printed model was critical in determining which surgery to perform. She continues to do well three years after her surgery.

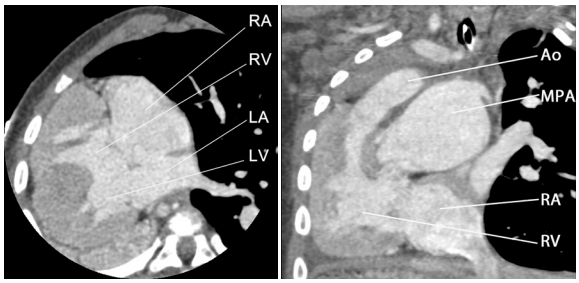

Figure 3. CT scan of 6-month old with Dextrocardia, Double Outlet Right Ventricle with atrioventricular canal and transposed great vessels s/p pulmonary arterial band (AO – Aorta, LA – left atrium, MPA – main pulmonary artery, LV – left ventricle, RA – right atrium, RV – right ventricle).

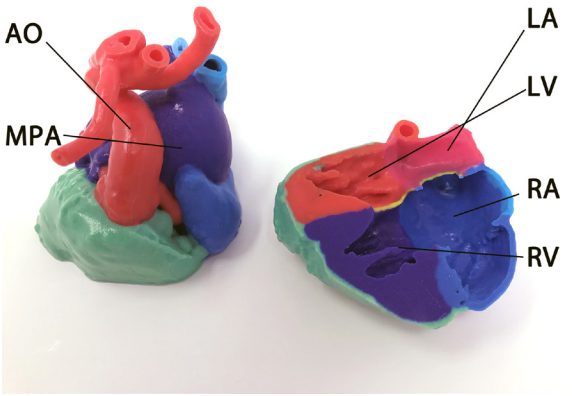

Figure 4. 3D model of 6-month old with Dextrocardia, Double Outlet Right Ventricle with atrioventricular canal and transposed great vessels s/p pulmonary arterial band (AO – Aorta, LA – left atrium, MPA – main pulmonary artery, LV – left ventricle, RA – right atrium, RV – right ventricle).

3D printed heart models have been a game-changer for many extremely challenging surgical cases (4-13). 3D printed models have been invaluable in understanding extremely complex cardiac anatomy, such as those associated with heterotaxy in which there may be up to 7-8 separate cardiac lesions at once. This technology has provided us added confidence to undertake high risk operations, such as taking a single ventricle patient with a Glenn shunt to two ventricle repair.

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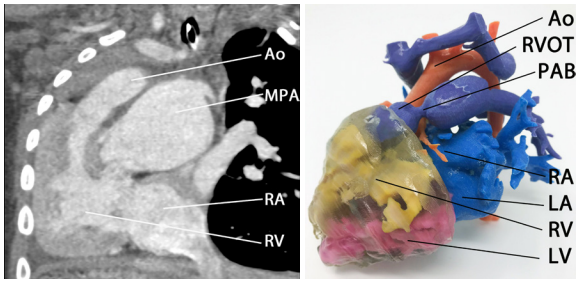

Figure 5. CT and 3D model of a 2-year-old with dextrocardia, double outlet right ventricle, atrioventricular canal, s/p pulmonary arterial banding and Glenn shunt (AO-Aorta, LA- left atrium, LV – left ventricle, MPA – main pulmonary artery, PAB – pulmonary artery band, RA – right atrium, RV – right ventricle, RVOT – right ventricular outflow tract).

It has also provided us the insight to decline other high-risk operations, such as creating intracardiac baffles in the double outlet right ventricle where the right ventricular volumes would become inadequate or tricuspid valve inflow would become obstructed (Figure 5) (14-18). When no data exists, 3D printed models have been extremely useful in proposing novel solutions, such as transplanting a normal heart into a chest that has mirror image reversed arterial and venous anatomy (Figure 6) (19). 3D printed heart models have helped us understand complex truncus arteriosus with interrupted aortic arch anatomy, conceptualize unifocalization of multiple aortopulmonary collaterals, and plan how to safely approach an atrial switch, VSD closure, and subaortic stenosis resection in a one-week-old child (Figure 7) (20). All of the preceding patients described underwent successful operations, and 3D printing technology played a critical role in their success.

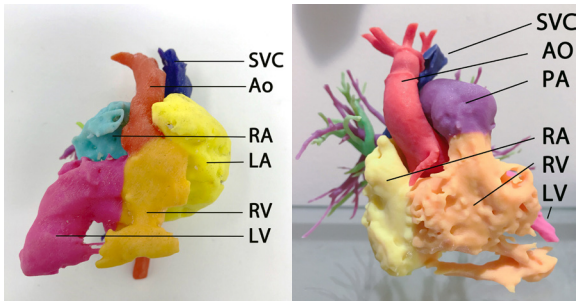

Figure 6. 3D print of infant with thoracic situs inversus with dextrocardia, double outlet right ventricle, and pulmonary atresia pre and post cardiac transplant (AO – aorta, LA – left atrium, LV – left ventricle, PA – pulmonary artery, RA – right atrium, RV – right ventricle, SVC – superior vena cava).

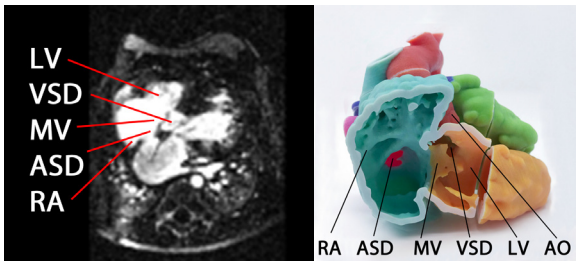

Figure 7. MRI and 3D model of a 5-day old infant with congenitally corrected transposition of the great arteries with a large ventricular septal defect and severe subaortic stenosis. (AO – aorta, ASD- atrial septal defect, RA – right atrium, LV – left ventricle, MV – mitral valve, VSD – ventricular septal defect).

Interventional Cardiology

Case III

A 26-year-old with repaired Tetralogy of Fallot presented with symptoms of fatigue. Echocardiography and MRI showed severe pulmonary insufficiency across a dilated native pulmonary valve. The diameter of the pulmonary artery was very dilated. The advantage of a transcatheter pulmonary valve replacement (TPVR) is that open heart surgery is not required, and the recovery is usually only a day. If the pulmonary artery is too large for the device, the valve may not be stable and can embolize. The pulmonary artery in this case was just at the limit of the largest transcatheter pulmonary valve available by MRI. A hollow compliant 3D model of the right heart was constructed using TangoPlus™ (Figure 8). The model was brought into the interventional catheterization suite. The diameter of the pulmonary valve was evaluated with sizing balloons

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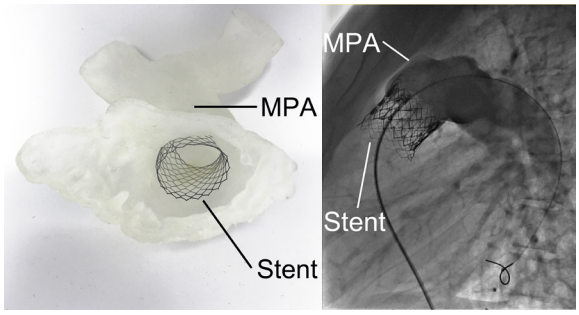

Figure 8. 3D model and fluoroscopy of an adult with Tetralogy of Fallot with a dilated main pulmonary artery with free pulmonary insufficiency. The 3D model was stented to simulate the actual procedure and assess suitability of device placement. Transcatheter pulmonary valve replacement was performed on the actual patient the following day. The 3D printed model predicted the actual pulmonary artery dimensions exactly (MPA – main pulmonary artery).

under fluoroscopy, and the dimension was 30 mm, just at the limit of the device. A stent was deployed within the model, which showed good position. The patient was brought in the next day, and the diameter of the patient's pulmonary artery under fluoroscopy was identical to the model. Subsequently, the stent was deployed, followed by the transcatheter pulmonary valve. TPVR was successful, and the patient was discharged the next day. Medical 3D printing had a significant impact in ascertaining the effectiveness of this complex and expensive procedure. It provided the interventional cardiology team with confidence that the TPVR procedure could be successfully undertaken without embolization.

Interventional cardiologists and electrophysiologists have used 3D printing for advanced visualization, planning, and simulation (1-24). As catheter-based control is fairly distant from the anatomy of interest and device sizes are limited, precise understanding of the cardiac anatomy becomes even more important. Transcatheter pulmonary valve deployment has been a key application. Current transcatheter pulmonary valve and deployment systems cost nearly $30,000 and are only available in limited sizes. 3D printed models have provided interventional cardiologists with a high degree of confidence with regard to whether the native pulmonary artery lumen is of adequate size or length, whether coronary arteries can be compressed with deployment of a stent, and whether or not adjacent structures such as the ascending aorta may be distorted (25-27). We have tested multiple patient-specific compliant models under fluoroscopy with no variance between the model and patients' pulmonary artery measurements. 3D printed models have also been used to plan difficult ASD device closures, as well as navigate complex congenital anatomy for diagnostic catheterization (28-30). 3D printing has also been useful in planning for complex congenital electrophysiology ablations for atrial arrhythmias. Patient-specific models provide the operator with significantly better understanding of complex congenital anatomy, particularly in reference to the likely areas of electrically inert tissue. Ablation lesions can be accurately planned to connect these structures and block formation of reentrant circuits.

Patient Education

Case IV

A five-day-old patient with a diagnosis of interrupted aortic arch and ventricular septal defect was scheduled for an open heart procedure to fix her aortic arch and ventricular septal defect. A 3D printed heart was provided to the family before the procedure (Figure 9). The anatomy was explained to the family, and the team discussed how the repair would be performed. The 3D printed model gave the family tremendous confidence in the medical team that the latest technology was being used to help their child. She did well with her procedure and was discharged in good condition.

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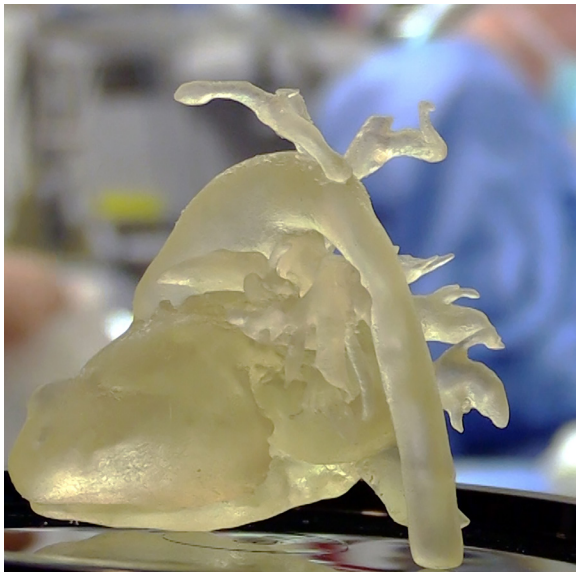

Figure 9. 3D model of infant heart with interrupted aortic arch type B with large outlet ventricular septal defect.

Families have been extremely appreciative of having 3D models to explain their child's condition (31, 32). There is an immediate connection when they see this is a model of their own child's heart. The model allows parents to better understand their child's condition and make informed decisions on their behalf. Effective comprehension permits authentic informed consent. 3D printing provides patients and families with the confidence that the medical and surgical teams are using the best techniques available to evaluate and treat their child.

Student Education

Case V

Explaining transposition of the great arteries and its subsequent surgical options are challenging for medical students, residents, and even fellows due to difficulties in understanding abnormal three-dimensional anatomy (Figure 10). A 3D model is extremely valuable to even explain basic congenital heart lesions such as atrial septal defects. It allows for conceptualization of anatomical subtleties that can result in divergent treatment options. (Figure 10, 11).

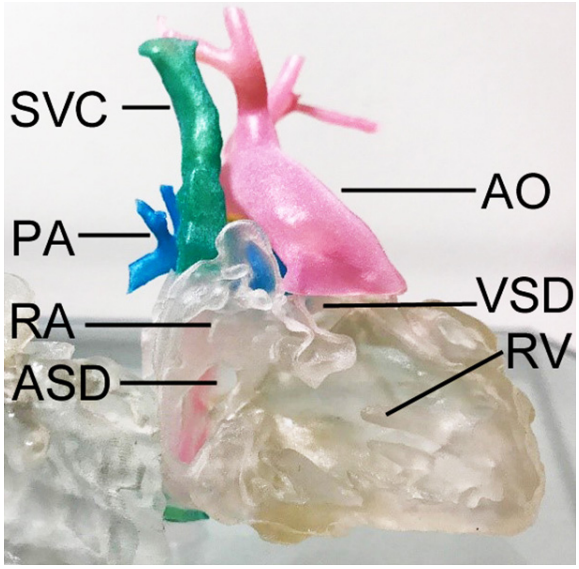

Figure 10. 3D model of infant with D-Transposition of the great arteries with large ventricular septal defect and hypoplastic pulmonary valve (AO – aorta, ASD – atrial septal defect, PA – pulmonary artery, RA – right atrium, RV – right ventricle, SVC – superior vena cava, VSD – ventricular septal defect).

After providing a clinical vignette, a model is handed to each student. They are given five minutes to study the anatomy, and each model is discussed as a group. This laboratory course engages visual, auditory, and tactile senses in a discussion format that facilitates their curiosity and enhances their knowledge.

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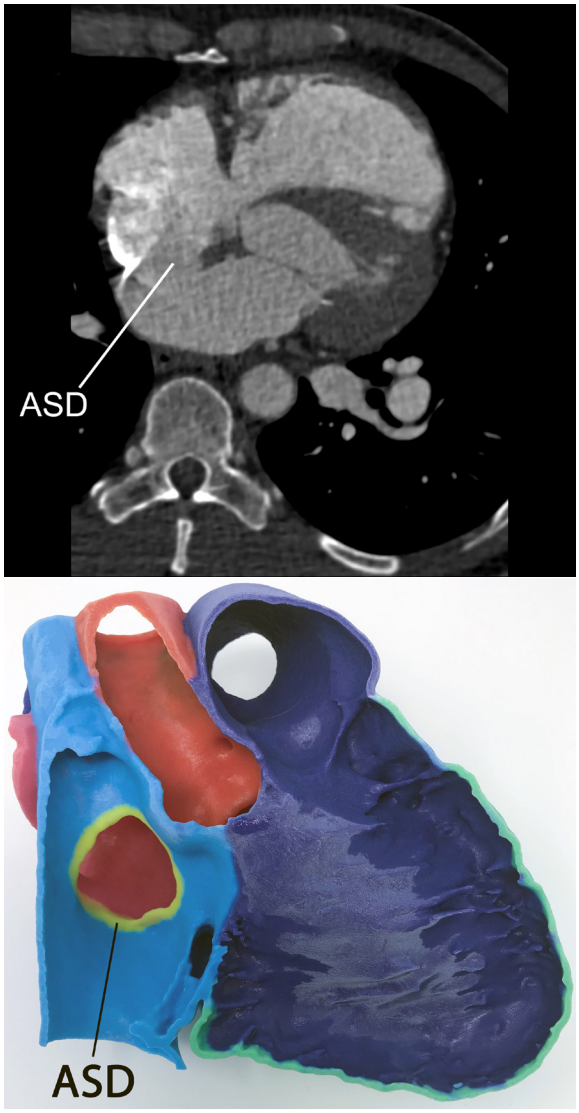

Figure 11. Adult with large secundum atrial septal defect with deficient posterior rim (ASD – atrial septal defect).

3D printing is a powerful method to teach trainees and staff about CHD (33-39). As outcomes for CHD have improved, less cardiac pathology specimens are available for study. Old pathology specimens degrade over time with handling year-to-year (40). We have developed a library of color-coded CHD models which has been very well received by medical students. Other groups have used 3D printed models of CHD to train cardiothoracic fellows how to perform complex repairs under the supervision of experienced professors (41). Simulation will continue to improve as more realistic materials are developed and imaging becomes even more precise.

Summary

3D printing has made a significant difference in the lives of many of our patients and families. It has allowed our physicians and families to make wiser decisions and allowed us to operate and perform procedures more effectively, more safely, at less cost. This new technology will provide patients and families greater understanding of their child's illness, and increased confidence in their treatment teams. 3D printing will help accelerate research and innovation in this field. We believe 3D printing will serve to inspire the next generation of physicians and providers to enter this fascinating field and develop novel approaches to treating patients with congenital heart disease.

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