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2018

## 3D printing is a transformative technology in congenital heart disease

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### Recommended Citation

Anwar, Shafkat; Singh, Gautam K.; Miller, Jacob; Sharma, Monica; Manning, Peter; Billadello, Joseph J.; Eghtesady, Pirooz; and Woodard, Pamela K., "3D printing is a transformative technology in congenital heart disease." *JACC: Basic to Translational Science*. 3, 2. 294-312. (2018).  
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STATE-OF-THE-ART REVIEW

# 3D Printing is a Transformative Technology in Congenital Heart Disease



Shafkat Anwar, MD,<sup>a</sup> Gautam K. Singh, MD,<sup>a</sup> Jacob Miller, MD,<sup>b</sup> Monica Sharma, MS,<sup>a</sup> Peter Manning, MD,<sup>b</sup> Joseph J. Billadello, MD,<sup>c</sup> Pirooz Eghtesady, MD, PhD,<sup>b</sup> Pamela K. Woodard, MD<sup>d</sup>

## SUMMARY

Survival in congenital heart disease has steadily improved since 1938, when Dr. Robert Gross successfully ligated for the first time a patent ductus arteriosus in a 7-year-old child. To continue the gains made over the past 80 years, transformative changes with broad impact are needed in management of congenital heart disease. Three-dimensional printing is an emerging technology that is fundamentally affecting patient care, research, trainee education, and interactions among medical teams, patients, and caregivers. This paper first reviews key clinical cases where the technology has affected patient care. It then discusses 3-dimensional printing in trainee education. Thereafter, the role of this technology in communication with multidisciplinary teams, patients, and caregivers is described. Finally, the paper reviews translational technologies on the horizon that promise to take this nascent field even further. (J Am Coll Cardiol Basic Trans Science 2018;3:294–312) © 2018 The Authors. Published by Elsevier on behalf of the American College of Cardiology Foundation. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Three-dimensional (3D) printing is an additive manufacturing technique with increasing use in health care. As a fabrication technique 3D printing was recently listed by the McKinsey Global Institute as a “disruptive technology that will transform life, business and the global economy,” with a potential economic impact of \$200 billion to \$600 billion between 2013 and 2025 (1). In health care, adoption of this technology has been a relatively recent phenomenon. A recent review found just 2 papers (excluding case studies and abstracts) in medical publications before 2000, and that number grew to 189 between 2011 and 2015 (2). Use within cardiology has followed a similar trend, with growth mainly in the past decade (3). Vukicevic et al. (4) recently published an excellent

review of cardiac 3D printing focusing primarily on acquired structural heart disease. In this paper, we review the transformative role of 3D printing in congenital heart disease (CHD) (Central Illustration).

## SCOPE OF CONGENITAL HEART DISEASE AND THE NEED FOR TRANSFORMATIVE CARE

The prevalence of CHD is approximately 9 in 1,000 live births (5,6). Survival rates vary by disease complexity, with long-term survival (>20 years) at approximately 95% for simple CHD, 90% for moderate complexity, and 80% for severe, complex CHD (7). Overall survival rates have steadily increased for even the most complex CHD (8–11), although survival alone

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All authors attest they are in compliance with human studies committees and animal welfare regulations of the authors' institutions and Food and Drug Administration guidelines, including patient consent where appropriate. For more information, visit the JACC: Basic to Translational Science [author instructions page](#).

Manuscript received July 4, 2017; revised manuscript received October 8, 2017, accepted October 11, 2017.

is not a sufficient outcome measure in the current era. Other important metrics include the following: long-term morbidity; reintervention rates; length of hospitalization; neurodevelopmental outcomes; cost to the health care system; and patient or caregiver satisfaction. Obtaining the best outcomes requires an impact at multiple levels, including patients and caregivers, individual clinicians, the medical team and the health care system. 3D printing is a disruptive technology that is affecting each of these key areas in CHD.

The earliest papers on cardiovascular 3D printing were published in the early 2000s. Binder et al. (12) showed feasibility from echocardiographic data in 2000, and Pentacost et al. (13) produced 3D models replicating cardiac embryology from photomicrographic data in 2001. Soon thereafter, datasets from computed tomography (CT) or magnetic resonance imaging (MRI) were used to produce 3D cardiac models of increasing complexity (14–16), with a steady rise in publications in the past decade (3). **Figure 1** shows the applications of 3D printing in medicine, broadly categorized as surgical planning, education, and manufacturing of custom parts (17). Given that a 3D model is a replica of a patient's anatomy, models may be used for precise pre-surgical planning and simulation (18–21). Patient-specific pre-surgical planning may potentially reduce time spent in the operating room (OR) and result in fewer complications. In turn, this may lead to shorter post-operative stays, decreased reintervention rates, and lower health care costs. Given the relatively recent use of 3D printing in CHD, there are currently no data supporting these presumed outcomes. Most of the evidence in published reports is qualitative, through case reports and series. Emerging reports from other surgical subspecialties appear promising. Recent data from craniofacial reports suggest that 3D printing can improve outcomes, including saving time in the OR and thus translating to direct cost savings (22,23).

### 3D PRINTING TECHNOLOGY AND OPTIONS FOR CARDIOVASCULAR PRINTING

Several recent publications have described the process of medical 3D printing (3,4,24–27), summarized as these key steps:

1. *Acquisition* of a high-resolution 3D imaging dataset
2. *Segmentation* of the anatomy using specialized post-processing software
3. *Computer-aided design* to refine the design, add cut-planes, or include elements required for model stability

4. *Creation of a 3D file* in a format recognized by the 3D printer, usually in the Surface Tessellation Language or stereolithography (STL) file format
5. *Printing of the physical model*

3D printing technologies may be categorized as *photopolymeric* (the use of light to harden a deposited photopolymer), *thermoplastic* (extruding melted thermoplastics in layers to build up a model), or *powder fusion* (a process that fuses ceramic or metal powder by using an adhesive or laser beam to create a 3D object) (4,24). Printer resolution for higher-end medical-grade printers is in the order of micrometers, well within the resolution needed to print cardiac structures. **Figure 2** shows these technologies in detail (28).

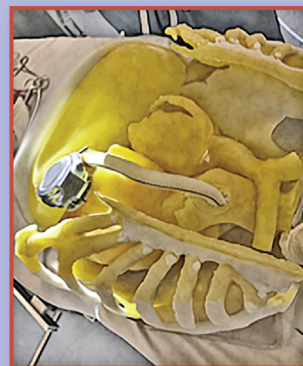
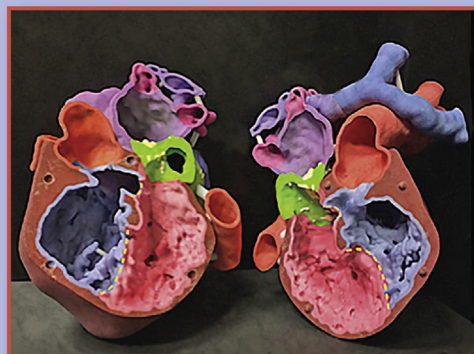
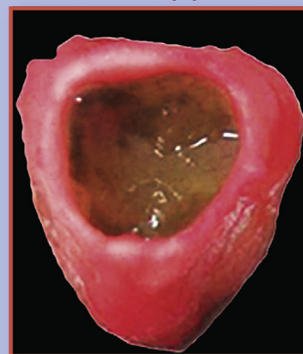
Principally, there are 2 main types of cardiac models: “blood-pool” and “hollow” models. Blood pool models are solid 3D representations of the blood pool within the cardiac chambers and vessels (**Figure 3**). They are created by segmenting the blood pool signal, usually from contrast-enhanced CT or MRI, after which the 3D object is printed. Non-cardiovascular structures such as airways or soft tissue may also be included for printing. These models provide excellent visualization of the great vessels, extracardiac vasculature, and surrounding structures such as airways or the esophagus. The drawback of these types of models is their limited views of intracardiac anatomy.

Hollow models are created by applying a mesh representing myocardium and vessel walls around the blood pool signal and then digitally removing the blood pool signal to show the intracardiac cavities. The end result is a hollow model showing the intracardiac anatomy in detail. These models are usually sectioned along a pre-determined cut-plane with 2 or more sections showing the intracardiac anatomy, as shown in **Figure 4**.

A subtype of the hollow models consists of intact hollow models. These models also show the intracardiac anatomy but are printed intact (i.e., without a cut-plane), thereby resulting in the most accurate representation of the heart as it sits in the chest. When printed in a flexible material, these models allow cardiothoracic surgeons to use standard surgical approaches and see the anatomy from a “surgeon's perspective,” as they would for the actual case (**Figures 5A and 5B**). Thus, these models are ideal for surgical simulation, especially when they are printed in materials that can be cut, can hold suture,

### ABBREVIATIONS AND ACRONYMS

- 3D** = three-dimensional
- ACHD** = adults with congenital heart disease
- APC** = aortopulmonary collaterals
- ASD** = atrial septal defect
- CHD** = congenital heart disease
- CT** = computed tomography
- DORV** = double outlet right ventricle
- MAPCAs** = multiple aortopulmonary collaterals
- MRI** = magnetic resonance imaging
- OR** = operating room
- VSD** = ventricular septal defect

**CENTRAL ILLUSTRATION Applications of 3D Printing in Congenital Heart Disease****3D Printing in  
Congenital Heart Disease****Surgical Planning****Simulation  
and Education****Patient and Caregiver Counseling****Advanced Applications**

Anwar, S. et al. *J Am Coll Cardiol Basic Trans Science*. 2018;3(2):294-312.

and can allow engraftment of foreign materials (e.g., patch, cannula).

#### APPLICATIONS OF 3D PRINTING IN CHD

Several publications have described the use of 3D printing in CHD, spanning the spectrum from atrial or ventricular septal defects (ASDs, VSDs) (29,30) to the most complex cardiac lesions (18,21,25,31-36). Published reports have been summarized in a recent textbook on cardiac 3D printing (24).

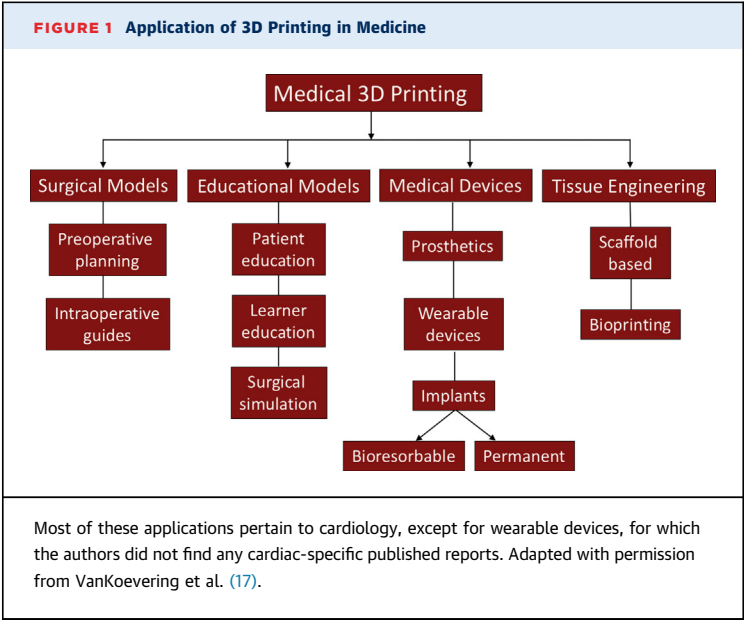
A selection of cases is now reviewed to show the main applications of 3D printing in CHD. These cases

were selected from a cohort of pediatric and adult patients with CHD at our institution who underwent 3D printing. For the complete list of cases, please refer to [Supplemental Table 1](#). Most of these cases were printed for surgical planning and simulation; others with unique or rare anatomy were printed for trainee education. The majority of cases had complex CHD, with a median complexity score of 3 (simple = 1, moderate = 2, great = 3) (37). Most of the cases printed for surgical planning were high-risk surgical candidates, and the median Society of Thoracic Surgeons-European Association for Cardio-Thoracic Surgery mortality category (1 to 5) was 4.

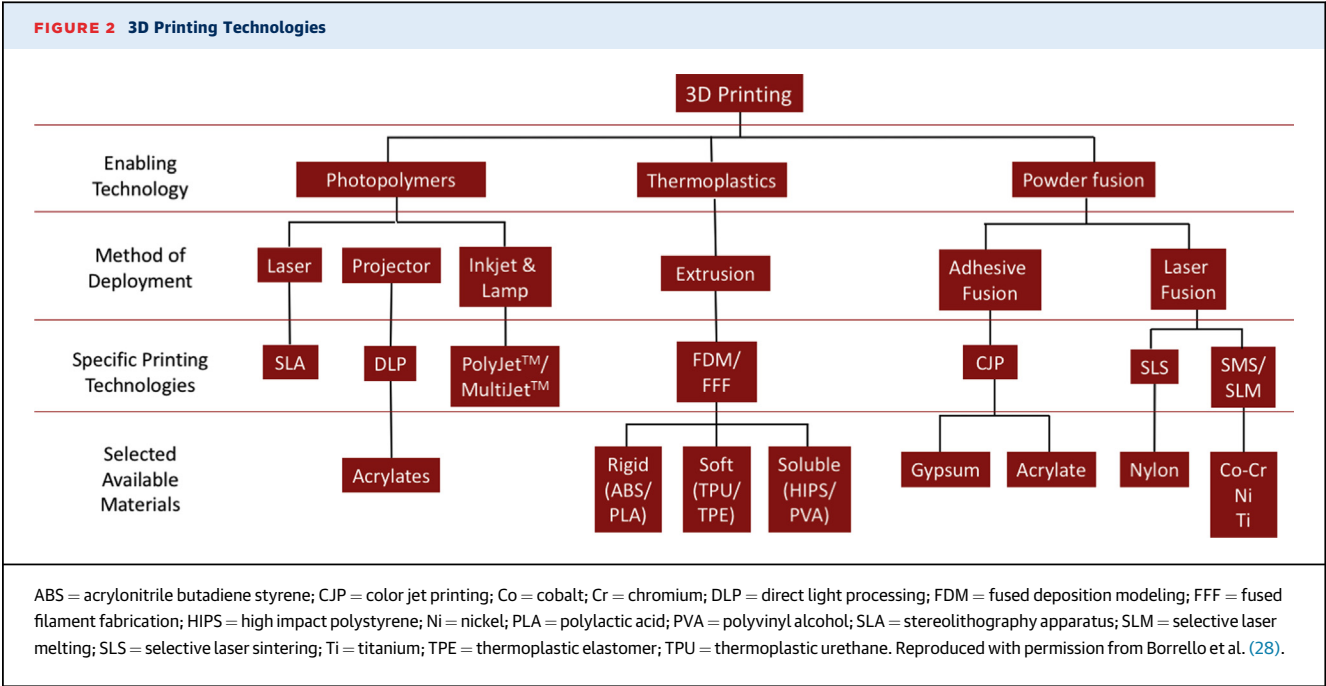
PLANNING COMPLEX INTRACARDIAC REPAIR.

Three of 1,000 patients born with CHD require catheter-based or surgical intervention early in life (38). Outcomes are significantly affected by the complexity of the underlying anatomy and perioperative factors, including cardiopulmonary bypass time, ischemic time, or circulatory arrest time (39-43). 3D models allow the visualization and understanding of complex spatial relationships and enable precise pre-surgical planning. A common application in CHD is planning repair of a double-outlet right ventricle (DORV) requiring a complex intracardiac baffle. This is typically a high-risk operation, Society of Thoracic Surgeons-European Association for Cardio-Thoracic Surgery category 4 (44). Figure 6 shows this application in an 8-month-old (8 kg) patient with a complex DORV, previously reported by our group (18). The patient had viscerotransposition, dextrocardia, and a DORV with levomalposed great arteries. The model in Figure 6 demonstrates the key anatomy to plan a 2-ventricle repair. The patient had a successful 2-ventricle repair consistent with the model-guided pre-surgical plan. Several other groups have reported the use of 3D printing to plan complex intracardiac repairs in patients with multiple VSDs or DORV (30-32,36).

**SURGICAL SIMULATION.** The ultimate in pre-surgical planning using 3D models is one in which a “simulated surgery” is performed, as illustrated by the next case. The patient was a 3 1/2-year-old male child with

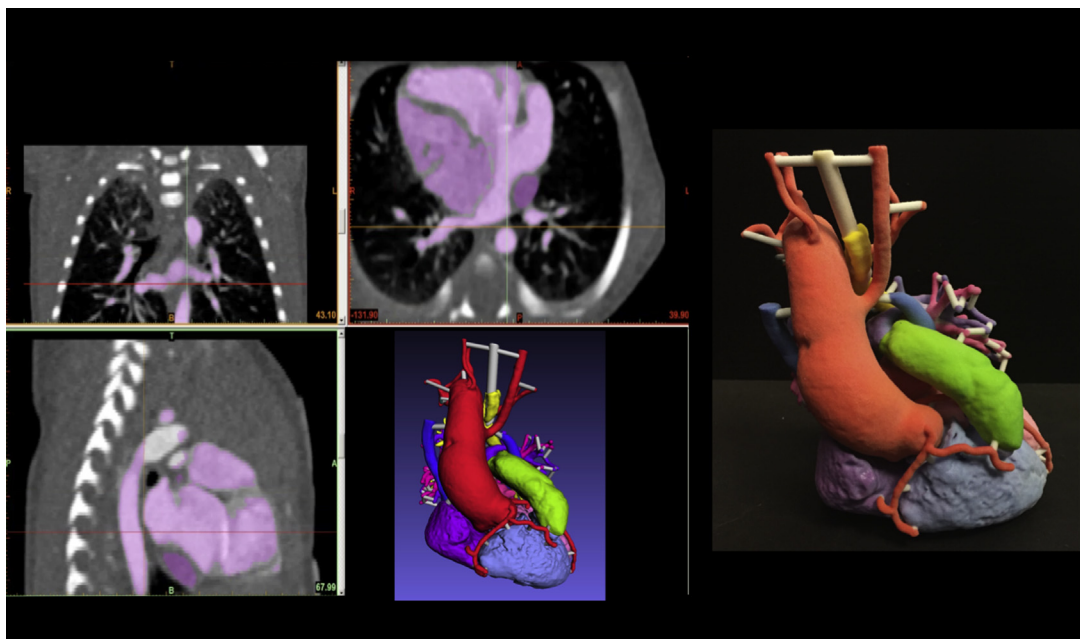


heterotaxy, asplenia syndrome with complex single ventricle anatomy, and abnormal systemic and pulmonary venous connections (Figure 7). He had previously undergone bilateral bidirectional superior cavopulmonary connections (bilateral Glenn procedure) as part of single ventricle palliation. 3D printing was performed to plan his next surgery, a total cavopulmonary connection (aka Fontan). Two 3D models were printed; 1 multicolor with an axial cut-plane and





**FIGURE 3** Blood Pool Cardiac 3D Model

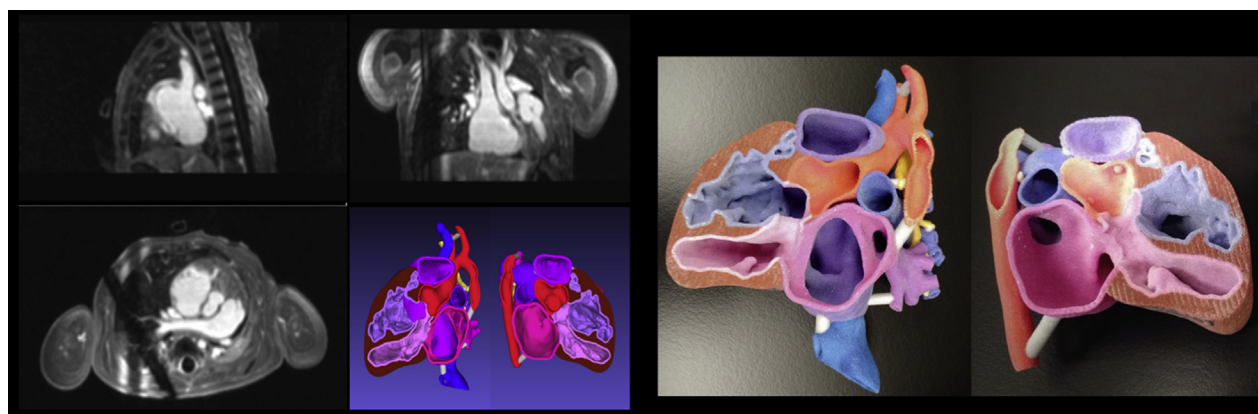


Source images on the **left** show the segmented blood pool signal. The model is shown on the **right**.

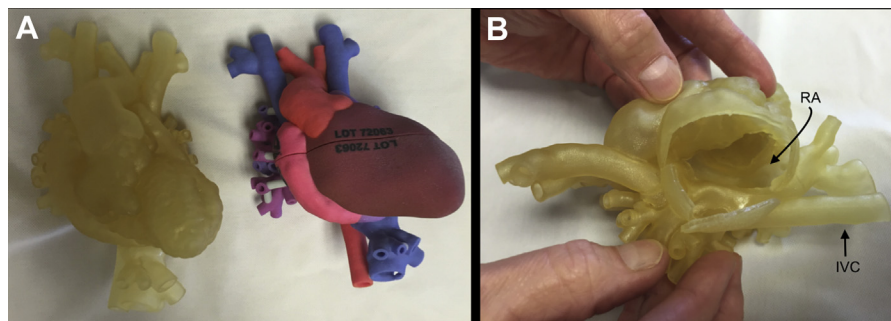
a second flexible intact-heart model (no cut-plane) for surgical simulation. The internal anatomy of both models was identical. By using the models, detailed pre-surgical planning was performed. Specifically, the models were used to plan placement of the Fontan conduit (intracardiac or extracardiac) and to evaluate its relationship with systemic veins and impact on pulmonary veins. The model was also used to

simulate “plan A,” “plan B,” or “bailout” scenarios, each with a unique surgical plan. This level of detailed surgical simulation is not feasible with current standard of care (e.g., 3D volumetric rendering), and it shows the added value of 3D printed models. [Supplemental Video 1 \(Figure 7\)](#) shows the pre-surgical planning session for this case with the cardiothoracic surgeon and cardiologists.

**FIGURE 4** Hollow Cardiac 3D Model Showing Intracardiac Anatomy



**FIGURE 5 Models for Surgical Planning**

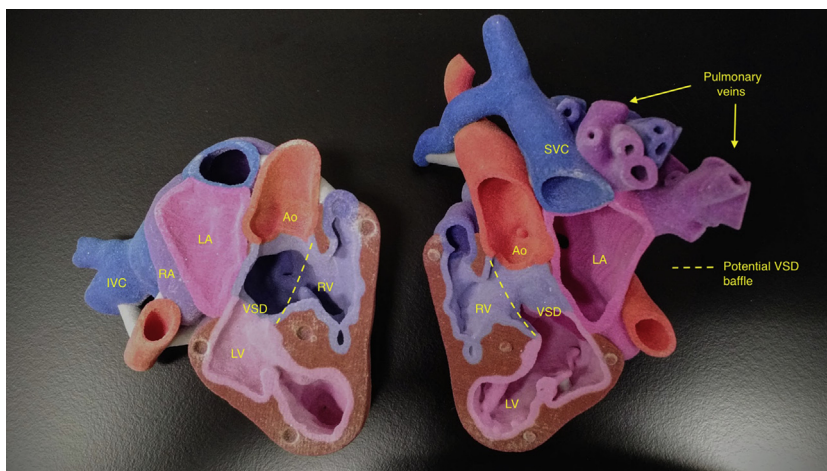


**(A)** Flexible hollow model printed intact with corresponding rigid multicolor model. **(B)** The “surgeon’s view” through a right atriotomy. IVC = inferior vena cava; RA = right atrium.

**EXTRACARDIAC AND VASCULAR SURGERY.** 3D printing can be a valuable tool to plan extracardiac and vascular surgery in patients with CHD. 3D models are helpful for planning high-risk unifocalization surgery, as illustrated by the following case. **Figures 8A to 8E** show a case of tetralogy of Fallot, pulmonary atresia, and MAPCAs in a patient with 22q11 deletion (DiGeorge syndrome), with repair undertaken in 3 stages because of high pre-surgical morbidity in this patient. We previously reported the first stage of this operation done at 10 months of age (18). **Figure 8** shows all 3 stages. The 3D models show spatial relationships among the aorta,

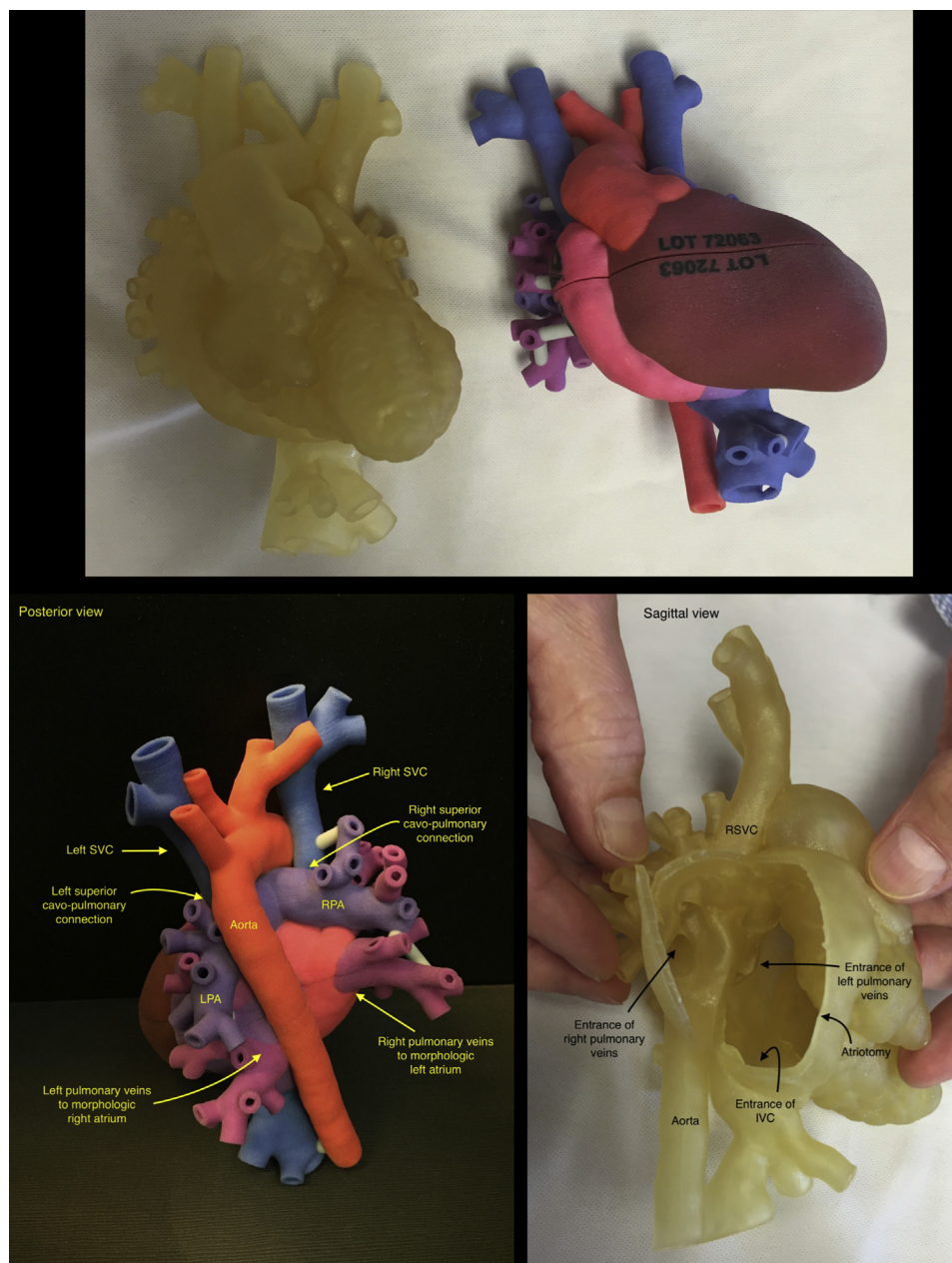
aortopulmonary collaterals (APCs), pulmonary veins, and airways that enabled detailed pre-surgical planning. Precise visualization of the complex relationships between APCs and surrounding structures enables easier identification and surgical manipulation during the case, thereby reducing operative time and potentially improving the surgical outcome. This patient underwent a right modified Blalock-Taussig-Thomas shunt to the right-sided APCs (**Figure 8B**), followed by a left modified Blalock-Taussig-Thomas shunt (**Figure 8D**) and, ultimately, successful unifocalization (**Figure 8E**). 3D printing for pulmonary atresia and MAPCAs offers significant benefits over

**FIGURE 6 3D Model of Double-Outlet RV Showing Relationships Among Ventricles, VSD, and Outflows**



The **dashed line** indicates the potential ventricular septal defect (VSD) baffle pathway to achieve a 2-ventricle repair. Ao = aorta; LA = left atrium; LV = left ventricle; RV = right ventricle; SVC = superior vena cava; other abbreviations as in **Figure 5**.



**FIGURE 7** Simulated Surgery for Complex Total Cavopulmonary Connection Planning Using Flexible, Intact-Heart Model

See Supplemental Video 1. LPA = left pulmonary artery; RPA = right pulmonary artery; RSVC = right superior vena cava; other abbreviations as in Figures 5 and 6.

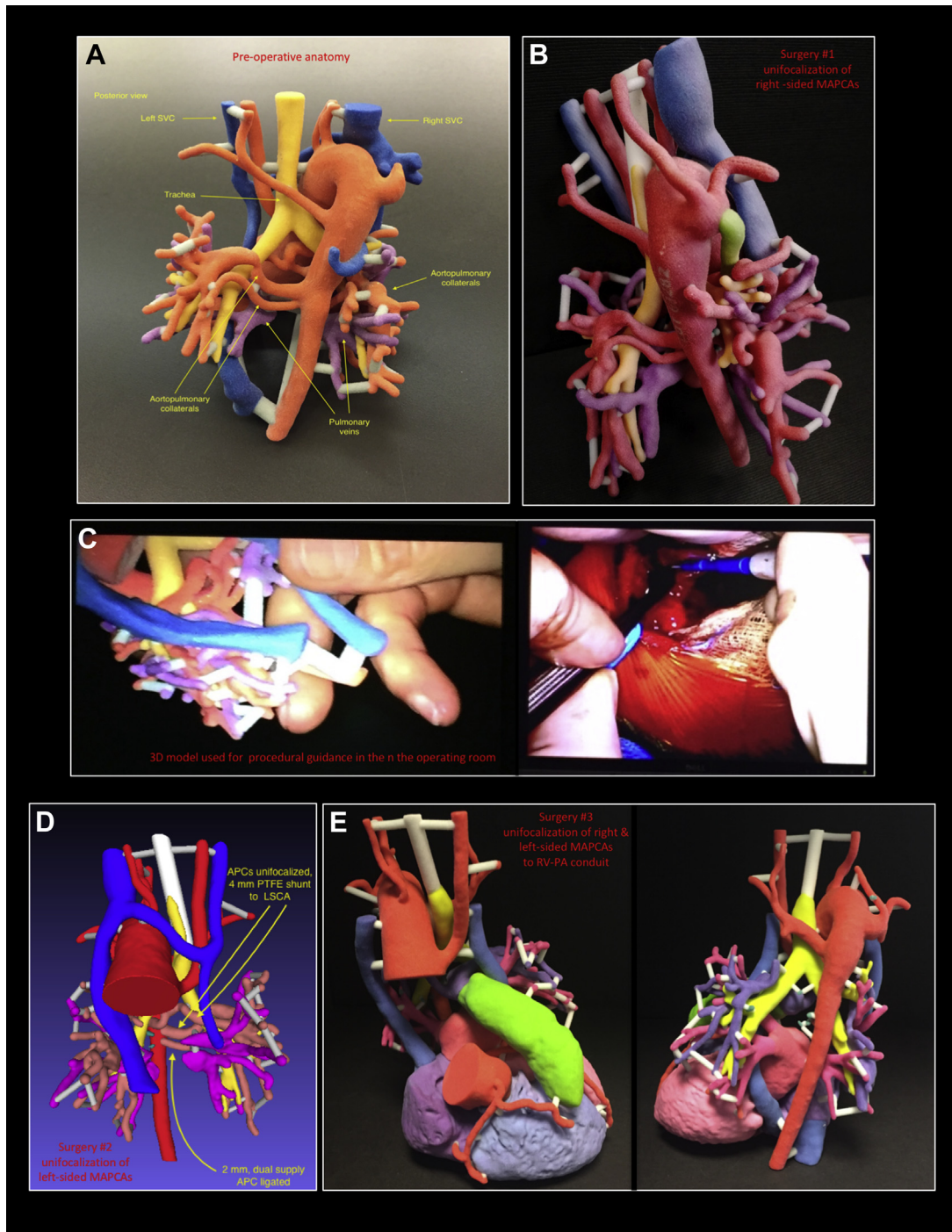
current standard of care, also described in prior publications (14,21).

#### VENTRICULAR ASSIST DEVICE AND HEART TRANSPLANT.

An endpoint of many patients with CHD is heart failure requiring a ventricular assist device or heart transplant. 3D printing can aid in ventricular assist

device placement and optimizing function in complex CHD, as recently described by Farooqi et al (20) and Saeed et al. (45). 3D printing can also assist with transplant planning for recipients with complex CHD, as in the following case. Figures 9A to 9C show a 22-year-old male patient with heterotaxy syndrome, unbalanced atrioventricular canal, L-looped

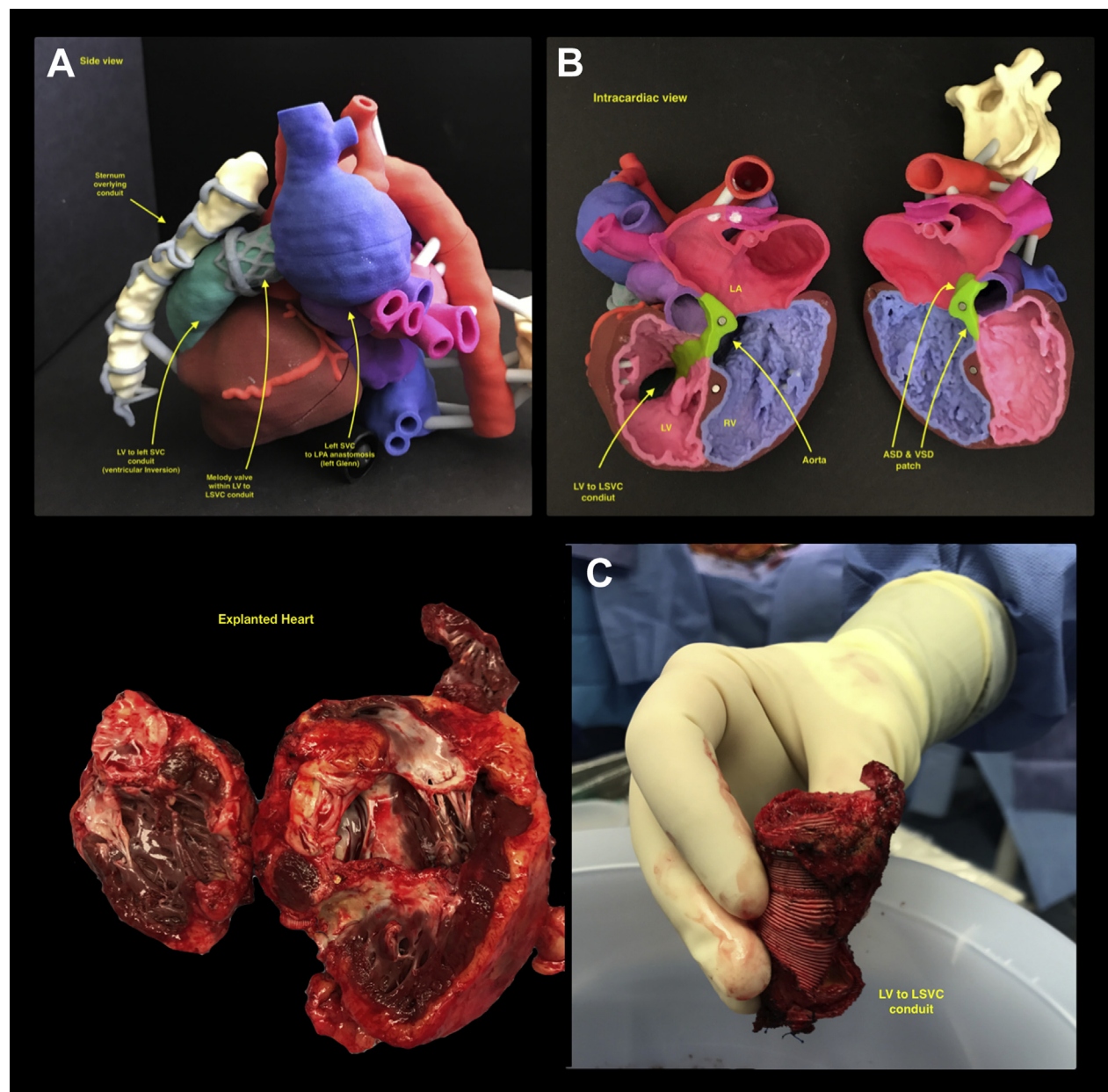
**FIGURE 8** Staged Repair of Tetralogy of Fallot, Pulmonary Atresia, and MAPCAs



(A) Pre-operative anatomy. (B) Unifocalization of right-sided major aortopulmonary collateral arteries (MAPCAs) and small right pulmonary artery (PA)-to-right modified Blalock-Taussig-Thomas shunt. (C) Use of 3D model in the operating room for procedural guidance. (D) Unifocalization of left-sided major aortopulmonary collateral arteries-to-left modified Blalock-Taussig-Thomas shunt. (E) Right ventricular (RV)-to-pulmonary artery conduit placement (green) to unifocalized major aortopulmonary collateral arteries and takedown of bilateral modified Blalock-Taussig-Thomas shunts. APC = aortopulmonary collateral; LSCA = left subclavian artery; PTFE = polytetrafluoroethylene; SVC = superior vena cava.



**FIGURE 9** Heterotaxy, Unbalanced Atrioventricular Canal, Ventricular Inversion, Modified Fontan



**(A)** 3D model showing a left ventricle (LV)-to-left superior vena cava (LSVC) conduit and left-sided Glenn procedure that complicates transplantation of a normal donor heart. **(B)** Intracardiac anatomy. **(C)** Intraoperative findings: explanted heart and a left ventricle-to-left superior vena cava conduit, showing accuracy of the 3D model. ASD = atrial septal defect; other abbreviations as in [Figures 6 and 7](#).

ventricles (ventricular inversion), and pulmonary atresia. He had undergone 6 prior sternotomies including ASD and VSD closure, culminating in a unique modified Fontan procedure with a left ventricular (pulmonic ventricle)-to-left superior vena cava conduit after thrombosis of his right-sided Glenn

procedure. More recently, a Melody valve was placed in a left ventricular-to-left superior vena cava conduit for conduit stenosis. He presented with severe protein-losing enteropathy and heart failure. Given the patient's debilitated state and multiple prior sternotomies, he was deemed a very high

surgical risk for cardiac transplantation. 3D printing was performed to plan key components of the transplant, including thoracic entry, cannulation options, conduct of bypass, and graft-donor connections. 3D printing for transplant planning has been previously described for patients with complex pre-transplant anatomy (46,47).

**AIRWAY ABNORMALITIES.** In CHD cases, the airways may be involved in the pathophysiology or need to be accounted for in surgical planning, as demonstrated earlier in the case with tetralogy of Fallot with pulmonary atresia and MAPCAs. In some CHD lesions, airways may be directly affected by the cardiovascular disease. Examples include vascular rings (Figure 10A), where aberrant vessels cause airway compression, or compression from dilated pulmonary arteries in tetralogy of Fallot with absent pulmonary valve (Figure 10B).

Airway compression or tracheobronchomalacia can significantly add to morbidity of patients with CHD from prolonged ventilator dependence. 3D printing recently led to a momentous breakthrough in the management of these patients with the use of 3D printed bioresorbable airway splints (48,49). Pilot data from 4 patients are shown in Figure 11. In this series 3D printed splints were implanted without complications and resulted in patency of the airway. If successful in larger cohorts, this application of 3D printing will dramatically change the management and outcomes for these challenging patients. Other applications of 3D printing in otolaryngology and airway abnormalities were recently reviewed by VanKoeveering et al. (17).

**CATHETER-BASED INTERVENTIONS.** 3D printing has been used for catheter-based interventions in CHD, although to a lesser degree compared with cardiothoracic surgery. Some noteworthy applications include the following: percutaneous pulmonary valve implantation, reported as early as 2007 (50); coarctation procedures (51); and stenting for aortic arch hypoplasia (52). Other reported applications include transcatheter ASD closure (29), double-lobed left atrial appendage closure (53), caval valve implantation (54), and stenting of Mustard baffle obstruction (55). 3D printing is of particular interest in noncongenital structural heart disease, including transcatheter mitral and aortic valve interventions (56–58). Potential benefits in interventional cardiology include visualization of complex anatomy that leads to decreased radiation and contrast from fluoroscopy and angiography and improved procedural outcome. Other benefits may include device development and testing in models that replicate abnormal anatomy (59). Finally, a key

benefit may be feasibility testing for complex or borderline cases, as in the case of this 15-year-old male patient from our institution with repaired tetralogy of Fallot who met the criteria for pulmonary valve replacement (Figure 12). MRI measurements indicated that his right ventricular outflow tract dimensions were borderline large for transcatheter pulmonary valve replacement; thus, a 3D model was made in flexible material to trial pre-stenting as a precursor to transcatheter pulmonary valve replacement. The 3D model showed feasibility of the catheter-based strategy, and the procedure was carried out, with subsequent successful implantation of a transcatheter pulmonary valve, thereby avoiding surgery.

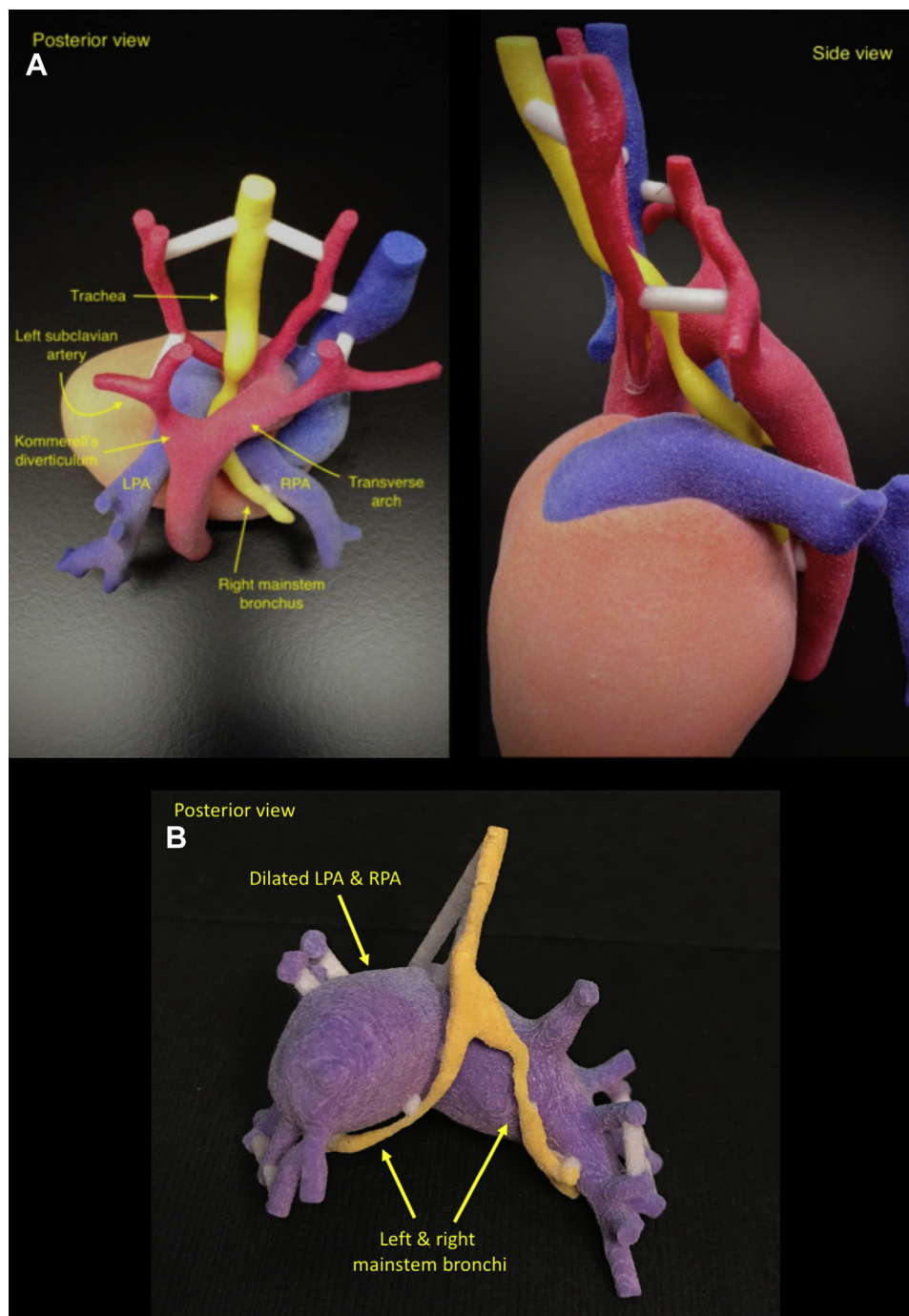
Impediments to greater use of 3D models in catheter-based procedures include tissue characteristics of the models that do not respond to balloons and stents in the same way as native tissue. Moreover, current models do not reflect the physiological environment encountered during catheterization, with nonpulsatility a major limitation of static models. Both these limitations may be overcome with future iterations of 3D models, as discussed later in this article.

#### ADULTS WITH CONGENITAL HEART DISEASE.

Approximately 85% of children with CHD now survive into adulthood (60), and adults with CHD (ACHD) now outnumber children (61). There are an estimated 5 million adult survivors in the United States alone (62,63). Over the past few decades the proportion of all deaths in patients with CHD has shifted from infants to the ACHD population (64). Similar to their pediatric counterparts, risk factors that worsen ACHD outcomes include complex anatomy, prior surgeries, and length of time spent on cardiopulmonary bypass (65–67). Although the challenges involving complex ACHD are considerable, 3D printing may help in their management by applications described in prior sections and in recent publications (20,25,26,68,69). Representative cases are shown in Figures 13A to 13D, as previously described (68).

#### ACCURACY AND QUALITY ASSURANCE IN CARDIAC 3D PRINTING

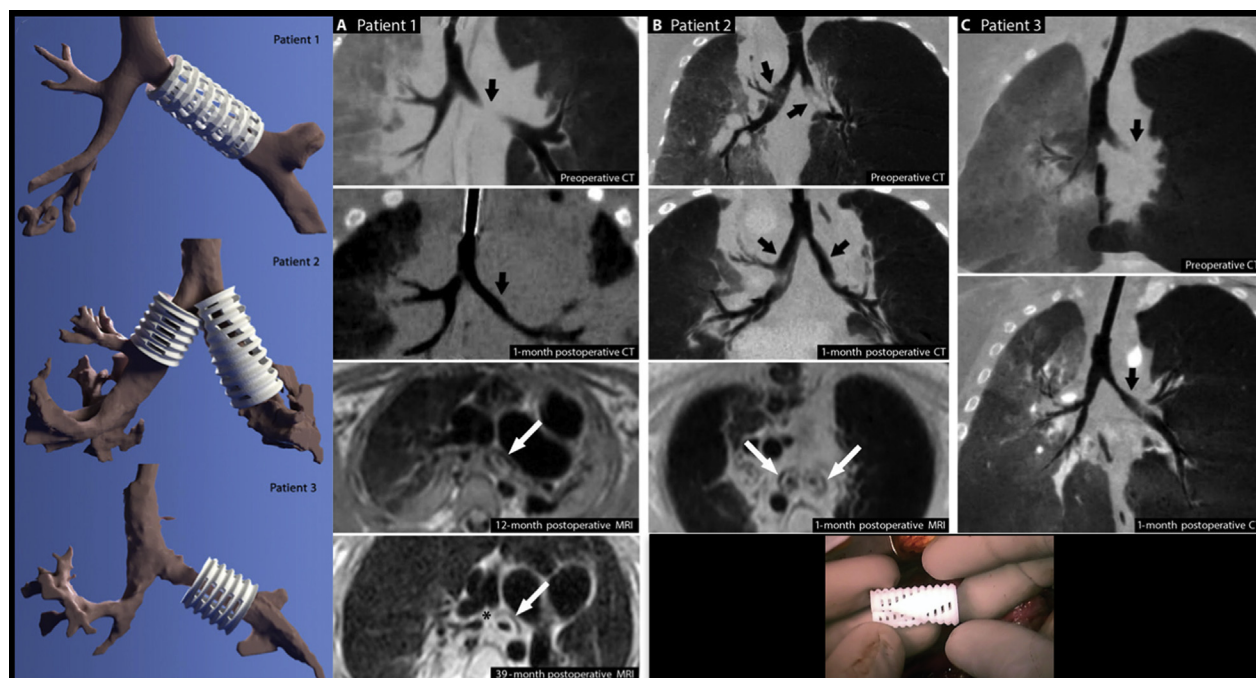
Accuracy in medical 3D printing is of paramount importance, although published reports on this topic are limited. Accuracy is defined by comparison with a gold standard, and in the case of 3D printed models, 1 metric of accuracy is comparison with operative findings. At our institution, the quality assurance process is driven by feedback from our surgical

**FIGURE 10** Airway Abnormalities in Congenital Heart Disease

(A) Vascular ring with posterior compression of trachea by a circumflex transverse arch coursing behind the aorta. (B) Severe branch pulmonary artery dilation in tetralogy of Fallot with absent pulmonary valve with compression and malacia of bilateral mainstem bronchi. Abbreviations as in [Figure 7](#).



**FIGURE 11** Bioresorbable Airway Splint Manufactured From Polycaprolactone With a Bellowed Design to Promote Expansion and Growth Over Time



Reproduced with permission from Morrison et al. (48).

**FIGURE 12** 3D Printed Model in a Case of TOF With Borderline Large PA Measurements

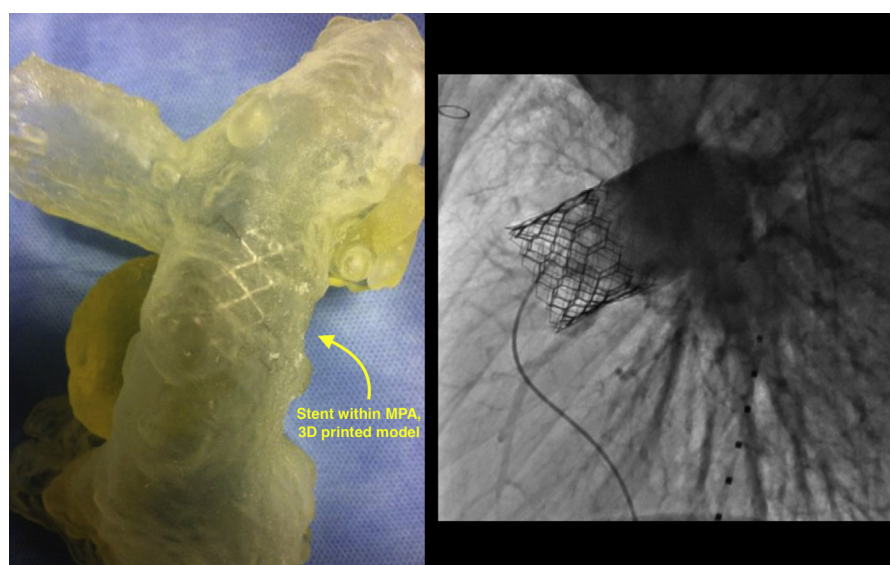
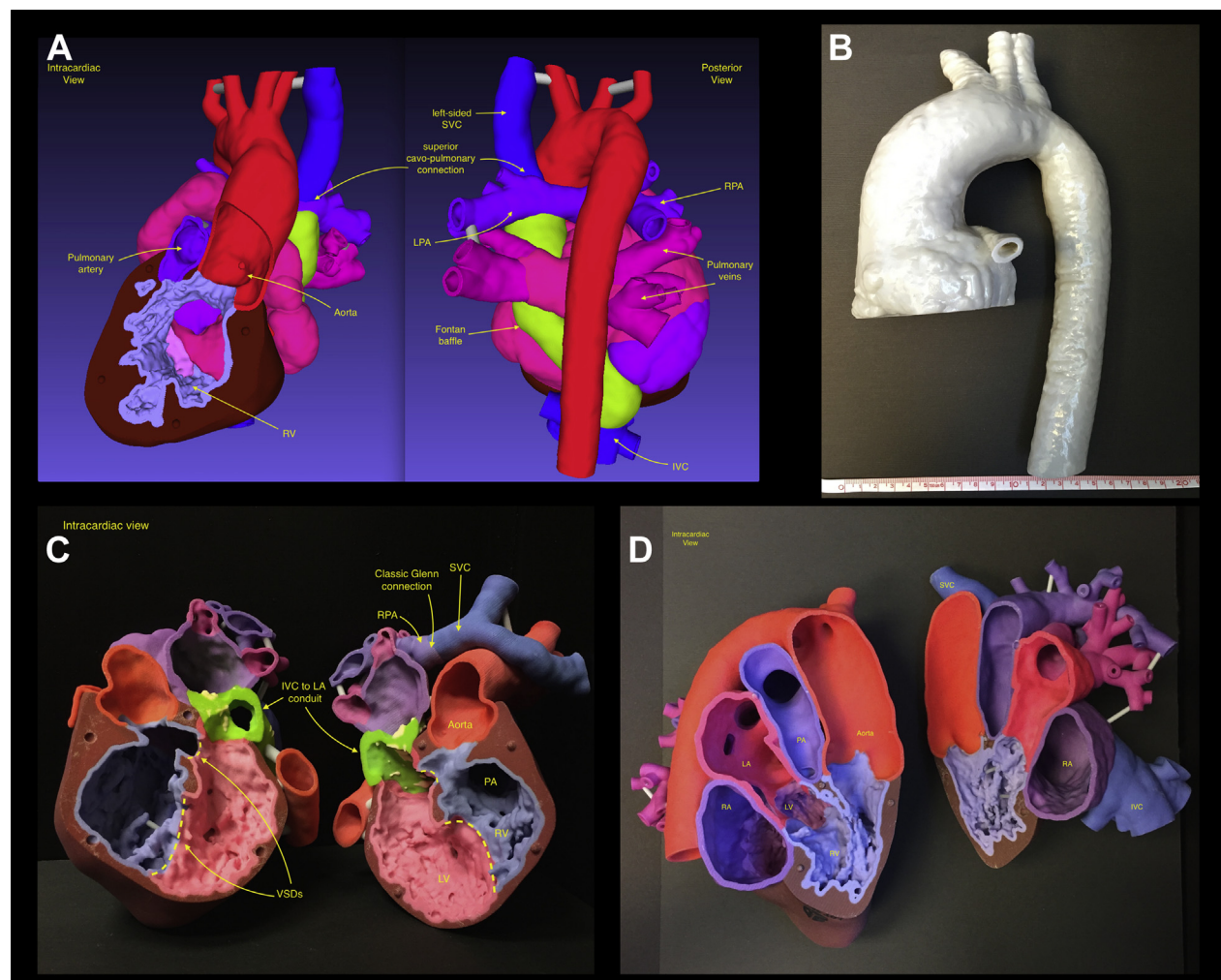


Image on the **left** shows a stent within main pulmonary artery (MPA). Image on the **right** is an angiogram taken after successful transcatheter implantation of pulmonary valve. PA = pulmonary artery; TOF = tetralogy of Fallot.

**FIGURE 13 3D Models of Adults With Congenital Heart Disease**



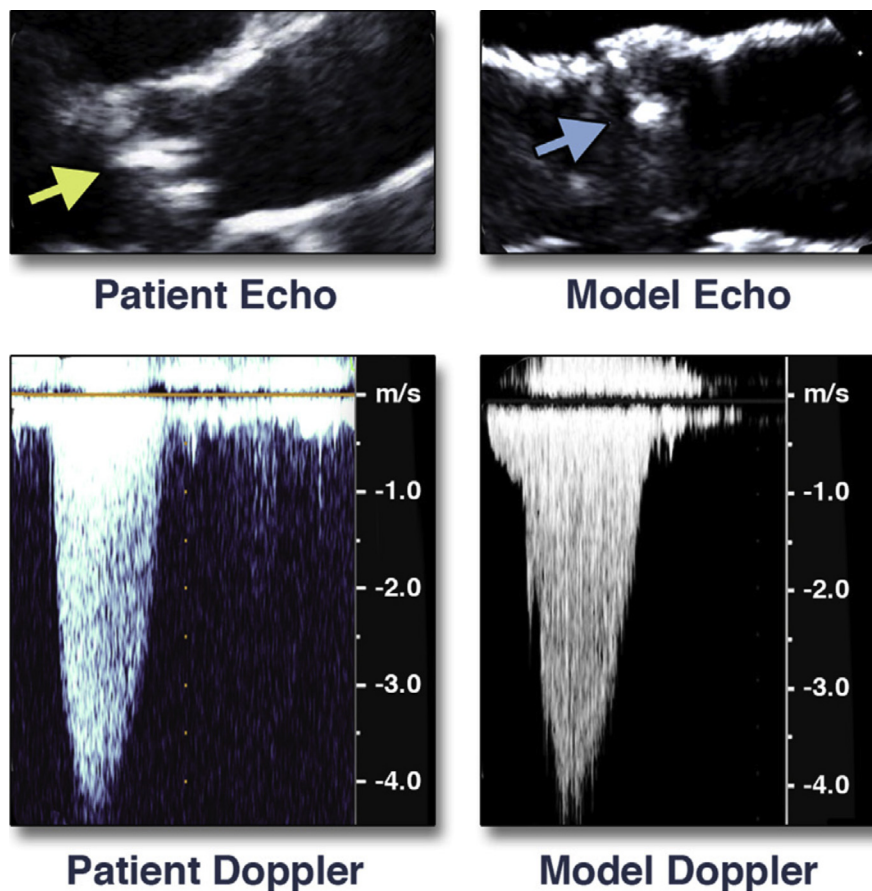
**(A)** A 31-year-old patient with dextrocardia, a double-outlet right ventricle (DORV), and a Fontan procedure. **(B)** A 19-year-old patient with a bicuspid aortic valve (not shown) and a severely dilated aortic root and ascending aorta. **(C)** A 40-year-old patient with a double-outlet right ventricle, 2 VSDs, and classic Glenn and modified Mustard procedures (conduit from inferior vena cava [IVC] to left atrium [LA], in green). **(D)** A 45-year-old patient with a left dominant unbalanced atrioventricular canal, a double-outlet right ventricle, and right ventricular outflow tract obstruction. Abbreviations as in [Figures 5 to 8](#). Reproduced with permission from Anwar et al. (68).

colleagues and findings in the OR. Between February 2015 and May 2017, the average accuracy score for 21 3D printed models at our institution was 4 of a possible 5 points when the surgeon compared model anatomy with findings in the OR. A similar quality assurance process was described by Hermesen et al. (70) for surgical models of hypertrophic obstructive cardiomyopathy. We have found that direct and ongoing communication among the imaging, modeling, and surgical teams is essential for maintaining high levels of accuracy. In addition, model accuracy may be diminished if there is a significant delay between acquisition of source images and time

of surgery. In infants and young children somatic growth and evolution of the pathophysiology can produce relatively large changes to the anatomy as time passes; thus, the pre-operative imaging and 3D modeling should be performed close to the time of anticipated surgery.

Besides direct comparison with OR findings, other metrics of accuracy include comparison with source images and user feedback. Olivieri et al. (71) reported that 3D printed models from echocardiographic data were comparable in measurements of VSDs when compared with source images. Yoo et al. (72) reported data from 50 surgeons after undergoing a Hands-on

**FIGURE 14 Patient and Model Doppler Comparisons**



Doppler profile of a patient's echocardiogram on the left, compared with the Doppler image from the 3D printed model on the right. Arrows point towards the aortic valve from the patient's echocardiogram (left) and model (right). Adapted with permission from Vukicevic et al. (4).

Surgical Training course using 3D models. The majority of cardiothoracic surgeons reported that the 3D models were of “excellent” or “good” quality for surgical simulation (72). Finally, accuracy of 3D models may be judged in terms of their ability to recreate native physiology, not just anatomy. The innovative work of Vukicevic et al. (4) has shown the ability to recreate “hemodynamics” of abnormal aortic valves in 3D models, with Doppler characteristics nearly identical to those of the patient's own diseased valve (Figure 14).

### 3D PRINTING FOR TRAINEE EDUCATION AND SURGICAL SIMULATION

Another arena where 3D printing can bring about transformative change is in the education and training of the next generation of physicians. This is an

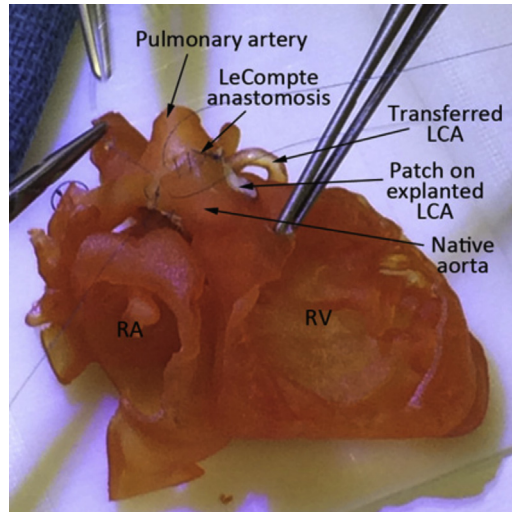
established practice in neurosurgery (73,74) and otolaryngology (17), with more recent application in cardiology (75-78). Although medical training has long followed the practice of “see 1, do 1, teach 1,” use of 3D models in education represents a paradigm shift from an apprenticeship model to a simulator-based learning method that complements traditional mentored training (79,80). 3D models in CHD can reduce the learning curve for cardiac trainees in 3 key areas:

1. Understanding complex 3D anatomy
2. High-fidelity simulation experiences
3. Exposure to rare cases

As a tool for surgical simulation, 3D printing has been applied toward septal myectomy for hypertrophic obstructive cardiomyopathy (70), vascular procedures (76,77,81), and complex congenital procedures, as described by Yoo et al. (72) (Figure 15).



**FIGURE 15** Simulated Arterial Switch Operation From a Hands-on Surgical Training Course for Cardiothoracic Surgeons



Reproduced with permission from Yoo et al. (72). See Supplemental Video 2. LCA = left coronary artery; other abbreviations as in Figures 5 and 6.

In addition to allowing practice on highly accurate simulators, the 3D models expose trainees to pathological features they may rarely encounter. This shifts the practice of surgery from an “opportunity-based” (26) to a “curriculum-based” experience. For experienced practitioners, models may be used for lifelong learning, for maintenance of certification, or for practice before challenging cases. Thus, a repository of 3D printed cardiovascular models with the spectrum of CHD would be an ideal educational resource (82,83). The 3D print Heart Library at the National Institutes of Health (84) is a good example of this concept. Electronic 3D models may supplement traditional learning methods, and an example is shown in Supplemental Video 2 (Figure 15). Finally, virtual reality displays may be used as complementary platforms to interact with electronic 3D models, with several robust options currently available (25,85).

### 3D PRINTING TO FACILITATE COMMUNICATION WITHIN THE MEDICAL TEAM AND FOR COUNSELING PATIENTS AND FAMILIES

Cardiac surgery and perioperative care are conducted in a multidisciplinary setting requiring highly skilled and specialized teams. Communication among specialists is essential for avoiding errors and optimizing

patient outcomes (86-88). 3D models provide clarity, and they are cornerstones around which multiple subspecialists can gather to discuss the pathological condition, surgical plan, anticipated outcomes, and perioperative care. In so doing, they may reduce medical errors, a postulate that deserves further investigation.

In addition to facilitating communication among medical team members, 3D models enable better communication between the medical team and patients or their caregivers (51,89,90). The models can help the patient or caregiver better understand the disease process, risks, benefits, and alternatives. Anecdotally, our institutional practice is to counsel patients and families by using 3D models if a model has been printed for a case. Eleven caregivers who completed a questionnaire for cardiac models between 2014 and 2017 reported that the models were “very helpful” (score 5 of 5) to improve understanding of the anatomy. Similarly, Biglino et al. (75) reported that 3D models could help improve the family’s experience with medical care when models were used for counseling. More data are needed on the potentially powerful impact of 3D printing in patient and family education and shared decision making.

### ADVANCED APPLICATIONS AND FUTURE DIRECTIONS

3D printing is rapidly evolving in medicine, with technical improvements in printers and software fueling new and exciting applications in patient care, innovation, and research. In cardiovascular medicine, a major limitation is high-resolution printing of structures currently not well resolved by CT or MRI, such as atrioventricular valves (91) or the atrial septum. 3D printing from 3D echocardiography could potentially overcome these limitations, with some promising early results (92-96). 3D printing from angiographic imaging could expand options, currently largely unexplored (97). The next evolution in 3D printing would be “multimodality” printing, with a model created by combining key elements of the anatomy from different imaging modalities. True co-registration of a highly accurate dataset is a technical challenge, and there are some early feasibility data (98,99).

In addition to advances in 3D dataset acquisition and post-processing, the next major step forward in 3D printing will likely be driven by improvements in printer technology and print materials. “Tissue mimicking” materials currently under development (100,101) would enable the creation of more life-like models that replicate the patient’s unique anatomy

and physiology. Currently there are highly accurate noninvasive methods to assess cardiac function and blood flow (102), including methods to assess 3D information over the cardiac cycle, thereby providing “4D” function and flow. These multivariate datasets could be integrated into 3D models to build holistic models to advance our understanding of cardiac disease. As 3D models achieve more realistic states, they may be used to study pathophysiology, predict long-term outcomes, and choose optimal treatment plans or surgical repairs (58,103–107). Recent studies have analyzed blood flow in deformable models (108,109), including flow characteristics in patients with hypoplastic left heart syndrome following Norwood arch reconstruction (75,110).

Finally, bioprinting offers the potential to make the leap from printing “life-like” to living tissue itself. This revolutionary technology is in its infancy; however, several techniques now exist that can deposit bioinks in precise locations to build up complex tissue constructs (111). Bioprinting has been applied to print anatomically shaped cartilage structures (112), skin (113,114), implants for bone growth (115), and even a 3D printed “bionic ear” (116). Within cardiology, researchers have reported techniques to print vasculature, myocardium, and valves (117–121). These applications and bioprinting techniques were recently reviewed by Duan. (111).

Although current and future applications of 3D printing are exciting and potentially game-changing, broad adoption is currently hampered by the costs of modeling and printing. The cost of a 3D printing center to a medical program is considerable, and at minimum it includes the cost of segmentation software, a medical-grade 3D printer, material costs, and personnel with 3D printing expertise. Some of the costs

may be lowered by printing off-site through commercial vendors, although with inherent trade-offs in long-term costs and turn-around time. These are evolving issues, and the ultimate viability of medical 3D printing will in large part depend on the impact it has on improving patient care.

## CONCLUSIONS

3D printing is a transformative technology that is affecting key aspects of CHD care. As a planning and simulation tool, it offers the promise of more precise surgery with fewer complications. For training, 3D models can reduce the learning curve and increase opportunities for procedural practice. The models can facilitate communication among multidisciplinary teams, thus potentially reducing medical errors. They can increase engagement of patients and families, thereby enhancing shared decision making. Finally, 3D models can lead to medical breakthroughs by enabling basic science, translational, and clinical investigations. More data are needed to quantify these potential benefits from 3D printing, and the early experience is promising.

**ACKNOWLEDGMENTS** The authors wish to acknowledge Benjamin Johnson and Joseph Fullerton at 3D Systems Healthcare as collaborators in the creation of some of the 3-dimensional models from Washington University School of Medicine and for review of technical details.

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**KEY WORDS** cardiac imaging, cardiothoracic surgery, congenital heart disease, simulation, 3D printing

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**APPENDIX** For a supplemental table and videos, please see the online version of this article.