

Echocardiography and Three-Dimensional Printing: Sound Ideas to Touch a Heart

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“If I could touch anything in the world right now, it would be your heart. I want to take that piece of you and keep it with me.”

—Jessica Verday, *The Haunted*

The technology of three-dimensional (3D) printing, also referred to as “rapid prototyping,” “additive manufacturing,” and “stereolithography,” refers to the process of converting a 3D computerized model into an actual physical object. This technology became a reality in 1986 as a result of the innovative thinking of inventor Charles Hull (US patent no. 4575330). Currently the “entry-level” 3D printing machines on the market can lay down layers of material (plastic, metal, etc) onto a platform until a 3D model is complete. More advanced algorithms can use a laser as the power source to bind powdered materials, ranging from nylon to steel, to create a solid structure. Inkjet technology has also revolutionized 3D printing; materials are jetted through print heads while being cured by an ultraviolet light into a 3D object. Three-dimensional printing has been successfully used in medicine to make prosthetic limbs, custom hearing aids, and dental fixtures¹⁻³ and is now being used to create more complex structures, such as cardiac models in patients with congenital heart disease. In this issue of *JASE*, Olivieri *et al.*⁴ describe their experience with creating 3D printed models from echocardiographic volumetric data sets in a series of nine patients, eight with ventricular septal defects (VSDs) and one with periprosthetic valvular leaks. In this editorial, we offer an overview of how technological explorations in 3D printing as carried out by Olivieri *et al.* will be fundamental to our understanding of the third dimension, elevating our impressions from textured flat-panel colored perspectives to real-time exploration of complex cardiac surface architecture, with the potential to guide personalized care of patients with structural heart disease.

WHY IS THREE-DIMENSIONAL PRINTING SUPERIOR TO VIEWING THREE-DIMENSIONAL IMAGES ON A TWO-DIMENSIONAL FLAT SCREEN?

Although multiple different 3D imaging modalities are currently available, one must question the effectiveness of most of these techniques, which project a 3D structure on a two-dimensional (2D) screen. Three-dimensional echocardiography, for example, allows us to create a volumetric data set and then manipulate and crop it from different perspectives to focus on the area of interest. Can one truly

consider such a structure to be effectively communicating to the observer in three dimensions? Previous research into the ability of “mental rotation,” or visualizing a 3D structure and then being able to imagine it from different perspectives, tells us that the answer is probably no.^{5,6} It has been demonstrated that examining a 3D structure in an actual 3D format, which can be held, is more useful in relating anatomy than simply trying to understand the structure from 2D images.⁷ In addition, individuals vary in the strength of their visuospatial skills, so that 2D images presented to a group of colleagues may not be interpreted in the same way by all.⁸ The use of 3D printed cardiac models eliminates this possibility and leaves no aspect of the spatial relationships to the imagination, which can be invaluable in patients with complex anatomy.

THREE-DIMENSIONAL PRINTING OF CARDIAC MODELS: WILL IT BE FOR EVERYONE?

The majority of work pertaining to creating cardiac models using 3D printing involves computed tomographic (CT) or magnetic resonance imaging (MRI) source data sets. The ability to create models from echocardiographic data brings forth a new level of accessibility. The steps in creating a 3D virtual model for the purpose of rapid prototyping start with the acquisition of the 3D imaging data set. Ideally, there is good blood pool to myocardial contrast. Olivieri *et al.*⁴ optimized their 3D echocardiographic images before processing, which is a critical step in both decreasing the time required to create a 3D virtual model and increasing its quality. Segmentation, the process by which we designate the range of gray values that highlights our area of interest, becomes much faster with such a set of images. The designation of the anatomy of interest to be printed is relatively simple and can be easily done either by pediatric cardiologists or sonographers. Although echocardiographic data do not allow us to visualize or print the whole heart in three dimensions, focusing on one part simplifies the process and makes it less time consuming and labor intensive. Once the area of interest is highlighted, the image-processing software creates a 3D structure that can be saved and then printed on a 3D printer to create a physical cardiac replica. Such a work flow brings us closer to the reality of a scenario in which we acquire images in a patient with newly diagnosed congenital heart disease on one day, with the physical replica in hand in time for discussion at a surgical conference the next day.

There are certainly challenges in making this technology accessible to all programs that would like to use it. The ideal scenario would involve predefined protocols for image acquisition, automated post-processing, and subsequent creation of a 3D physical model on a cost- and time-efficient printer. Currently and unfortunately, there are no published recommendations on parameters that should be used during 3D image acquisition, for any modality. In addition, thin mobile structures, such as valves and the subvalvar apparatus, continue to be challenging to recreate. For patients with congenital heart disease, the automation of the segmentation process promises to be a challenge. With such a wide variation in cardiac anatomy for each lesion, it seems almost impossible for software to identify relevant structures for surgical planning, assign appropriate values

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Table 1 Applications of 3D printing in cardiology for preprocedural planning

Study	Purpose	Subjects	Principal findings
Binder <i>et al.</i> ¹³	To assess feasibility, accuracy, and clinical potential of creating hard stereolithographic models from echocardiographic data	Patients with mitral valve disease (stenosis, prolapse, annular dilation, leaflet restriction) and phantoms to test accuracy	Stereolithographic modeling of echocardiographic images is feasible and provides tangible polyacrylic models that are true to scale, shape, and volume.
Gilon <i>et al.</i> ¹⁴	To study the hemodynamic impact of the valve geometry in aortic stenosis using 3D stereolithographic physical models	Patients with aortic stenosis	Three-dimensional valve shape is an important determinant of pressure loss in patients with aortic stenosis, with smaller effective areas and higher pressure gradients for flatter valves.
Sodian <i>et al.</i> ¹⁵	To explore the use of RP for surgical planning and intraoperative orientation	Patients requiring re-sternotomy for aortic valve replacement with previous CABG	These replicas are helpful in choosing treatment strategies and for intraoperative orientation in patients with previous CABG.
Sodian <i>et al.</i> ¹⁶	To demonstrate the use of a 3D printed aortic arch model for planning and simulation of occlusion of a pseudoaneurysm	Patient with prior ascending aorta and arch replacement with an aortic arch pseudoaneurysm	The printed model allowed fabrication of an occluder device in a patient with a pseudoaneurysm.
Schmauss <i>et al.</i> ¹⁷	To evaluate the potential effects of 3D models for surgical planning and simulation of transcatheter intervention	Patient with aortic stenosis and porcelain aorta	The model was useful to demonstrate to the authors that a transcatheter valve should be positioned deep into the aortic annulus.
Schmauss <i>et al.</i> ¹⁸	To explore using RP for surgical planning, decision making and intraoperative orientation	Patient with a right ventricular primary cardiac tumor	The models allowed identification of the position and expansion of the tumor and to plan surgical intervention.

CABG, Coronary artery bypass graft; RP, rapid prototyping.

for segmentation, and crop the virtual 3D model in a manner to best display the anatomy of interest. In their “Conclusions” section, Olivieri *et al.*⁴ refer to the technology used to create these models as “highly accessible.” It is difficult at this stage for this technology to be considered readily available. The cost of both the image postprocessing software and the 3D printer put the process even further from the reach of every program that may wish to use it. In addition, it remains unclear which patient populations will benefit most from these models. Although the report by Olivieri *et al.* includes mainly cases of patients with VSDs, it may be more intuitive to study patients with more complex intracardiac anatomy, in whom the models would add more spatial information. Nevertheless, the report by Olivieri *et al.* should be considered symbolic of the progress and burgeoning interest in creating 3D cardiac models from routine echocardiographic data sets.

TOUCHING THREE DIMENSIONS TO EXPLORE STRUCTURAL HEART DISEASE

The utility of this technology in multiple areas of medicine is increasingly being noted in the literature.⁹⁻¹² The prospects for applications in transcatheter interventional procedures and presurgical planning for complex cardiac cases are particularly exciting¹³⁻¹⁸ (Table 1). One of the earliest works, by Binder *et al.*,¹³ used a multiplane transesophageal echocardiographic probe to recreate 3D echocardiographic data sets at a time when the process was far from automated. Subsequent work by Gilon *et al.*,¹⁴ also using echocardiographic data sets and stereolithographic technology, demonstrated

that the 3D aortic valve shape in aortic stenosis contributes to the lesions’ hemodynamic effects in addition to the limiting valve orifice.

In patients with complex congenital heart disease and complex intracardiac relationships (Table 2), 3D printing removes the potential for misinterpretation that may occur between the presentation of images in two dimensions and the mental reconstruction that is undertaken to understand the relationships in three dimensions.¹⁹⁻³¹ For example, 3D printing has been used to demonstrate the location of major aortopulmonary collateral arteries in patients with tetralogy of Fallot and pulmonary atresia^{19,30} and to guide sternotomy in adults who have undergone coronary bypass surgery and subsequently required aortic valve replacement at a later date.¹⁵ These two scenarios, in addition to the patient cases presented by Olivieri *et al.*,⁴ demonstrate the use of 3D models for the purpose of directly visualizing anatomic relationships in a physical replica.

This technique can also aid in comprehension of the intracardiac anatomy to help guide presurgical planning. One condition for which such detail is critical is double-outlet right ventricle. In more straightforward cases of double-outlet right ventricle, in which the VSD is related closely to the aorta, the left ventricle can be surgically “baffled” via the VSD to the aorta. In more complex cases, the relation of the VSD to the aorta is not so clear, so cardiac CT imaging or MRI may be performed in addition to echocardiography. Despite the acquisition of these additional imaging studies, however, the 3D anatomic arrangements of interest cannot be simultaneously demonstrated, and one is forced to imagine the 3D relationships on the basis of 2D imaging data. This gap may become nonexistent with the use of 3D printing. The potential baffle pathways transition from ambiguous to readily apparent anatomical connections.

Table 2 Applications of 3D printing in congenital heart disease for preprocedural planning

Study	Purpose	Subjects	Principal findings
Ngan <i>et al.</i> ¹⁹	To assess utility and accuracy of solid anatomic models for surgical planning	Patients with pulmonary atresia, VSD, and MAPCAs	Three-dimensional printed anatomic models of the pulmonary vasculature from CTA data accurately represented MAPCAs and were found by the surgeons to be very useful in visualizing the vascular anatomy.
Noecker <i>et al.</i> ²⁰	To demonstrate the utility of 3D cardiac modeling for medical device development	Pediatric patients with and without CHD	Three-dimensional models of pediatric cardiac and chest anatomy provided enhanced understanding and tactile representation of complex anatomy, which was found to be particularly useful during the development and placement of medical devices.
Sodian <i>et al.</i> ²¹	To explore the impact of using RP techniques for surgical planning and intraoperative orientation	Patients with complex congenital heart disease	Stereolithographic replicas are helpful for choosing treatment strategies, surgical planning of corrections, and intraoperative orientation, as demonstrated in a patient with aberrant retroesophageal left subclavian artery and right aortic arch and a patient with a VSD.
Schievano <i>et al.</i> ²²	To determine if MRI data could be used to create rigid models which accurately represent the right ventricular outflow tract and pulmonary trunk for PPVI	Patients requiring PPVI	Using 3D RP models resulted in more accurate selection of patients for PPVI than did using magnetic resonance images.
Greil <i>et al.</i> ²³	To demonstrate the creation of 3D physical models using high-resolution MDCT and MRI	Patients with congenital heart disease including tetralogy of Fallot, D-TGA, and DORV	High-resolution MDCT or MRI 3D data sets can be accurately reconstructed using laser sinter technique. Teaching, research, and preoperative planning may be facilitated in the future using this technique.
Jacobs <i>et al.</i> ²⁴	To create anatomically correct RP models to facilitate planning and execution of the surgery	Patients with complex congenital heart disease and altered geometry of the atria and ventricles	The use of the 3D rapid prototyping model during resection of ventricular aneurysm and malignant cardiac tumors may facilitate the surgical procedure because of better planning and improved orientation.
Mottl-Link <i>et al.</i> ²⁵	To improve spatial imagination for planning of surgical intervention	Patient with L-TGA, pulmonary atresia, atrial and VSDs, and dextrocardia	A 3D printed model in a patient with transposition of the great arteries, pulmonary atresia, atrial septal defect, and VSD were helpful in preoperative in surgical planning.
Vranicar <i>et al.</i> ²⁶	To assess accuracy of 3D stereolithographic models created in patients with great vessels anomalies including coarctation of the aorta and vascular rings	Patients with anomalies of the great vessels	Three-dimensional printed models for patients with aortic coarctation and vascular rings were useful in planning transcatheter and surgical interventions.
Sodian <i>et al.</i> ²⁷	To demonstrate the utility of 3D physical replicas in presurgical planning	Single-ventricle patients with failing ventricles requiring transplantation	Three-dimensional printed models were useful for perioperative planning and intraoperative visualization in patients with failing single ventricles undergoing cardiac transplantation.

(Continued)

Table 2 (Continued)

Study	Purpose	Subjects	Principal findings
Shiraishi <i>et al.</i> ²⁸	To assess if a stereolithographic modelling technique can be applied for anatomical diagnosis and surgical simulation	Patients with complex congenital heart disease	Rubber-like urethane cardiac biomodels allowed surgeons to practice and actually suture and cut the flexible material.
Schmauss <i>et al.</i> ²⁹	To present a single-center experience with a wide variety of cases using this technology in complex pediatric and adult cardiac cases	Patients with congenital heart disease and adults with structural heart disease	This group demonstrated its center's experience and the feasibility of creating 3D models in a series of patients with congenital and structural heart defects in preparation for either surgical or transcatheter interventions.
Ryan <i>et al.</i> ³⁰	To demonstrate a new approach to identify location of MAPCAs using RP that may preclude cardiac catheterization	Patient with tetralogy of Fallot, pulmonary atresia, and MAPCAs	Use of a 3D printed model allowed preoperative planning in a patient with tetralogy of Fallot, pulmonary atresia, and MAPCAs without cardiac catheterization.
Olivieri <i>et al.</i> ³¹	To demonstrate utility of a 3D printed model to assist in presurgical and interventional planning	Patient with D-TGA who had undergone a Mustard repair	The insight provided by 3D modeling may help increase procedural efficiency, decrease radiation exposure, and mitigate procedural complications.

CHD, Congenital heart disease; CTA, computed tomographic angiography; D-TGA, D-transposition of the great arteries; DORV, double-outlet right ventricle; L-TGA, L-transposition of the great arteries; MAPCA, major aortopulmonary collateral artery; MDCT, multidetector computed tomography; PPVI, percutaneous pulmonary valve implantation; RP, rapid prototyping.

STATIC VERSUS DYNAMIC MODELING USING THREE-DIMENSIONAL PRINTING

Because of the dynamic nature of the heart, one may question the reliability of planning surgical repairs on a model that is static. Ideally, a printed model would be able to somehow mimic the anatomic and potentially physiologic changes that occur during the cardiac cycle. A brief report by Maragiannis *et al.*³² hints that we are moving in the right direction. Their group was able to print a flexible left ventricular outflow tract in a patient with severe aortic stenosis and then replicate the hemodynamics by attaching the printed aorta to a pulsatile flow imaging circuit. The circuit was able to duplicate the extent of obstruction, as confirmed by catheter measurement and Doppler assessment. Echocardiography may offer an advantage over cardiac CT imaging and MRI in the demonstration of anatomy in different phases of cardiac cycle. However, CT imaging and MRI offer better blood pool to myocardium contrast than ultrasound. Olivieri *et al.*⁴ addressed this issue by performing postprocessing of 3D echocardiographic images to increase contrast between the tissue planes and to remove potential artifact in the blood cavity. Although previous reports described stereolithographic 3D models' being created from an echocardiographic data set, none described such image postprocessing and optimization.^{13,14} The current report should encourage the development of optimal segmentation and image postprocessing schemes for all imaging modalities.

THREE-DIMENSIONAL PRINTING OF LIVE TISSUE AND ORGANS

The scenario of having patient-specific live tissue created on a 3D printer for use in medical interventions may have seemed like fiction a few decades ago but has certainly gained the potential to become

reality in the near future. Three-dimensional printing technology has found applicability in the fields of tissue engineering and regenerative medicine in the form of bioprinting. Bioprinting involves the process of laying down cells in a spatially controlled manner using 3D printing technology. The goal is to have the cells maintain their viability and specific function within this new atmosphere. Although bioprinting has gained significant media attention recently, with the potential for "organ printing" generating much excitement, the ability to actually create a full organ from scratch using 3D printing is still far from a reality. However, the field is progressing rapidly, with recent advances including success with rapid prototyping of blood vessels, including the aorta, and even heart valves.³³⁻³⁵ It is also tempting to imagine a time when drug testing on animals may become obsolete because of the accuracy and reliability of such testing on 3D printed tissues. To go even one step further, patient-specific tissue may one day become available for testing the individual effectiveness of therapeutic interventions.

A NEW ERA FOR PERSONALIZED APPROACHES

It is tempting to imagine the potentially limitless applications of rapid prototyping in moving the medical field toward an era of truly personalized medicine. To that end, funding for projects that explore such ventures is becoming more visible. The National Institutes of Health recently posted a request for applications for projects working toward the use of 3D printing to produce medical devices, specifically with the premature infant patient population in mind. The image that comes to mind is one of medical staff members' being able to enter a premature neonate's height and weight into a 3D printer to create a patient-specific medical device. Depending on the technology available at the time, the device may be ready for

use in a few hours or even a few minutes after pressing “start.” Even more exciting is the prospect of creating implantable tissue from scratch. In addition to simply visualizing the VSD anatomy, as described in the report by Olivieri *et al.*,⁴ we would be able to actually construct a patient-specific patch for repair. In patients with severe aortic stenosis, we can look forward to a time when a valve seeded with patient-specific cells was created decades previously, in anticipation of progression of this aortic pathology that plagues so many adults. These scenarios are a far cry from the cookie-cutter approaches currently used in these patients but at the same time may be within arm’s reach.

THREE-DIMENSIONAL PRINTING VERSUS HOLOGRAPHIC DISPLAY

Three-dimensional printing is not the only method by which structural anatomy can be visualized directly in three dimensions. The advent of holography also allows similar display and assessment of different cardiac structures. Its utility lies in removing the ambiguity present in visualizing 3D structures using 2D images, in much the same way as 3D printing.^{36,37} Holographic images have been used of the mitral valve, for example, allowing true assessment of mitral valve pathology in three dimensions before planning for an interventional procedure.³⁸ However, beyond just visualization of pathologic anatomy, 3D printing allows us to actually test an approach to repair. In a report by Shiraishi *et al.*,²⁸ the group highlighted this exact concept. Three-dimensional full hearts of patients with congenital heart disease, including hypoplastic left heart syndrome and total anomalous pulmonary venous return, were printed in a flexible material. This allowed the simulation of surgical repair, for example with a Norwood procedure in the patient with hypoplastic left heart syndrome. Another group used this method to allow operators to test and replicate the ideal positioning of a transcatheter valve in relation to the patient’s native valve in patients in need of aortic valve placement.¹⁷ The real-life clinical application is exciting in this regard, but so is the potential for education of residents and fellows using this technology.³⁹ In both surgical and interventional fields, lack of a specific type of pathology at a center can lead to inadequate hands-on experience for trainees. In this setting, multiple copies of the same model could be printed and distributed to trainees to practice the repair. In the cases reported by Olivieri *et al.*,⁴ patches for surgical repair of the VSDs could actually be sutured into the ventricular septum to simulate surgical repair.

In summary, the study by Olivieri *et al.*⁴ highlights the potential to use 3D echocardiographic data sets to create physical cardiac replicas using 3D printing. In the near future, one can expect the field of 3D printing to evolve for testing interventions, creating dynamic models throughout the cardiac cycle, and models made with live cells to create implantable tissue. There is little doubt that the field of 3D printing technology will continue to challenge our views of how to best use imaging modalities for patient care. The responsibility we have as noninvasive imagers is to communicate a patient’s relevant anatomy to our audience, with the least room left for interpretation as possible. Given this sizable task, to be clear, concise, and unambiguous in our delivery, there is no better method of communicating a patient’s cardiac anatomy than use of a 3D printed cardiac model. And yet there is so much more potential that this technology holds: it represents a shifting paradigm and promises to surprise us with each new and more innovative aspect of medicine that it infiltrates.

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