Three-dimensional printing in congenital cardiac surgery—Now and the future

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Feature Editor’s Note—Dr Van Arsdell and colleagues have presented an excellent feature article on 3-dimensional (3D) printing. They have very nicely summarized the history of 3D printing and given us a succinct timeline of the evolution of 3D print types available. They emphasize the role of 3D printing specifically for training congenital heart surgeons.

There are some key phrases within this article that I believe truly emphasize the importance and role for 3D printing. The first is, “the surgeon can decide the surgical plan much as is achieved with intracardiac exploration.” The days of the surgeon having to open up the heart and make an on-the-spot decision as to what type of repair to perform are rapidly fading. Now (like musicians) the surgeon (or trainee) can practice beforehand and have a definite plan for the operation.

“The time for learning curves on patients has passed.” In the current era of transparency and public reporting along with our obligation to provide the best-possible patient care, this statement is extremely important. The illustration of the “well-coached” versus “non-coached” Norwood arch reconstruction is a dramatic example. The residents can obtain their learning curve on 3D models, not patients.

“No professional musical performance is staged unless the music can be flawlessly executed.” This statement speaks for itself. Flawless surgical repairs are facilitated by careful preoperative practice/planning.

Finally, the authors pique our interest with the potential ability for the emergence of valve printing which will assist in our ability to provide improved outcomes in patients with atrioventricular septal defects where repair of the atrioventricular valves remains an Achilles’ heel for outcomes. Congratulations to Dr Van Arsdell and colleagues for this excellent contribution to where we should be now and the possible future of training congenital heart surgeons.

Three-dimensional (3D) printing is being used in the industrial supply chain for creating “just-in-time” unique parts. Formula 1 racing teams print auto parts to update car performance between races. In the medical world, proof-of-concept printing of blood vessel networks has led to visions of printing off-the-shelf replacement organs.1 Bio-printed liver organelles are currently being used for drug toxicity studies, and personalized orthotics are being printed and used for bodily injury.2,3 While there is medical promise for tomorrow, today 3D-printed cardiac models enhance surgical planning for complex intracardiac repair and aneurysm surgery.4,5 With the development of soft pliable models, complex anatomy learning and surgical rehearsal is emerging and is being incorporated into the training of current and future congenital heart surgeons.6-8 Commercially, this field is being developed as “biomimics.”

MODELS IN YOUR HANDS

3D printers became commercially available in the 1980s, with market application increasing exponentially in the 1990s and 2000s. Medical applications for 3D printing were reported at least as early as 1990.6,10 Stereolithographic
modeling of cardiac structures was described by Binder in 2000. In 2007, Greil and colleagues reported stereolithographic modeling for congenital cardiac morphology, which demonstrated the potential utility of printed models for diagnostics and surgical planning. Datasets derived from computed tomography and magnetic resonance images have subsequently been used to explore 3D printing of cardiac and other organ models.

PATIENT-SPECIFIC SURGICAL PLANNING FOR INTRACARDIAC TUNNEL REPAIR

Early print material had a firm porcelain-like quality and was advantageous for accurate anatomical demonstrations. In our practice, 3D-printed porcelain-like models were initiated in 2009 as a means to assist in operative planning for complex intracardiac tunnels seen in double-outlet right ventricle (DORV) and various forms of associated ventricular septal defects (VSDs). Preoperative decision-making based on 2-dimensional images can be problematic for both experienced surgeons and echocardiographers. Translating 2-dimensional images into a 3D format in one’s mind is not always readily achieved and may take years to develop for inexperienced clinicians. As such, for many intracardiac tunnel repair cases, the surgical decision is not clear until there is exploration of the arrested heart. These can be complex intraoperative judgment decisions consisting of (1) a simple tunnel repair, (2) arterial switch and tunnel repair, (3) aortic root translocation and tunnel repair, or (4) single ventricle repair. The model’s visualization of the pathway options and potential issues of inlet or outlet obstruction allows for easy understanding of the appropriate plan preoperatively. Figure 1 shows an example of the utility of a 3D model for surgical planning in a DORV with a subpulmonary VSD and subaortic stenosis (transposition of the great arteries type or Taussig–Bing anomaly) with side-by-side great arteries and an interrupted aortic arch.

Current 3D models provide spatial relationships between great vessels, VSDs, inlet orific, and each ventricle. Corresponding sizes are also represented. Limitations with data acquisition preclude printing representations of the patients’ valves meaning that echocardiography remains an important adjunct for surgical planning. Despite these limitations, with the models in hand, the surgeon can decide the surgical plan much as is achieved with intracardiac exploration. At the time of operation, they simply need to confirm the model validity and then execute the planned operation.

Biomimics

The second generation of print materials are pliable, being made from photopolymer resin with physical properties much closer to human soft tissue. This advancement galvanized the development of new models for surgical rehearsal and hands-on training. With the encouragement of then-AATS (American Association for Thoracic Surgery) president, Pedro del Nido and the AATS congenital skills course director Erle Austin, Shi-Joon Yoo developed, and with the assistance of Glen Van Arsdell, refined, models of hypoplastic left heart syndrome and 200% DORV with a subaortic VSD. The technical refinements allowed for realistic surgical rehearsal of operative repair. The Seattle AATS congenital skills course of 2015 featured these models. It was led by Erle Austin and formally supported by Shi-Joon Yoo and Glen Van Arsdell.

Following the initial enthusiasm for the congenital practice models, Dr Yoo created models of tetralogy of Fallot, Taussig–Bing anomaly, transposition with the usual coronary arrangement and with coronary variations, coarctation,
interrupted aortic arch complex, and common arterial trunk. All have been used in subsequent surgical training courses internationally.6

A difficult lesion for new surgeons to learn is the atrioventricular septal defect (AVSD) repair. To overcome this difficulty, Dr Yoo graphically designed leaflets to mimic actual valves, including the subvalvular apparatus (Figure 2). With this advance, a realistic model of an AVSD was created for surgical rehearsal. Today, congenital cardiac surgical fellows are training on these simulated AVSD models in preparation for reality. Surveys following training on multiple 3D models suggests that they realistically assist in learning the operation for surgeons.6 It is noted that the 3D model material feels different than patient tissue, but that the difference does not detract from the value of the training tool. In time, advances in printing techniques and printing material (such as adding small fibers) should lead to improved model handling characteristics.

**SHOULD THERE BE MANDATORY LEARNING ON MODELS?**

As was suggested by Burkhart14 in the previous commentary on 3D model training, we would advocate that surgical training on congenital models should be a required element of formal congenital heart surgeon training. The ability to learn operative sequencing, body and hand positioning, patch-cutting skills, and accurate anastomosis skills can only similarly be found in actual patients. The time for learning curves on patients has passed.14,15 Figure 3 illustrates a well-coached versus noncoached Norwood arch reconstruction in a 3D model.

Published data on the utility of enhanced learning through 3D models with cleft palate surgery are documented.16 Our experience from observing trainees learn complex congenital operations would suggest it is the same in this field.

Multiple arterial switch, or Norwood operation rehearsals, under the guidance of a staff surgeon, will allow
for progression to the patient when technical proficiency is demonstrated. Staff confidence in the trainees’ ability to perform the procedure will be enhanced. The result will be increased patient safety. This method of augmenting current resident/fellowship training is starting to be introduced in some centers.

WHAT PREVENTS MANDATORY TRAINING ON MODELS?

The technology for model training and multiple rehearsals exist. The barriers are simply that our training standards need to reflect such a requirement with a move toward competency-based education paradigms. A secondary barrier that needs to be overcome is the relative expense. At an estimated cost of $300 to $400 to produce a model, it is a vital element for readily achieving multiple rehearsals for a given procedure. Nevertheless, one can envision surgical rehearsal much as a musician would rehearse a piece of music prior to a performance. No professional music performance is staged unless the music can flawlessly be executed at the right rhythm. Much should be the same for professional surgical performance.

INSTITUTIONAL OR OUTSOURCED PRINTING

Printing accurate models requires image data cleaning through a time-consuming process known as segmentation. Segmentation allows printing that reflects only the areas of interest. Expertise for segmentation, in others besides physicians, will need to be developed much as cardiac sonographers have become expert at acquiring echocardiographic images. In some institutions, this role has been undertaken by professionals with a background in biomechanical engineering, under the guidance and supervision of an experienced clinician.

The best economic model for 3D printing with high fidelity has not yet been clearly delineated. The cost of acquiring equipment, developing skills, and achieving strong segmentation data are significant. Funding printing is typically a challenge. The Walter Reed National Military Medical Center leads the way on in-house medical printing.17 Our own institution has developed an internal program. Other institutions have chosen to commercially outsource printing through companies such as Materialise (Leuven, Belgium) and Stratasys (Eden Prairie, Minn).

There may yet be another step change in cost. Today publications are starting to emerge demonstrating open source software and simple 3D desktop printers. This can be readily purchased by a consumer and provide meaningful clinical data at a fraction of the commercial quality cost.

THE FUTURE: FLATTENING THE WORLD FOR VALVE REPAIR OUTCOMES

As data acquisition for valve leaflets and their support structure improves, printed models will be able to represent leaflet and chordal pathology. Emergence of valve printing will likely lead to the same evolution found with models printed for congenital heart disease. First, diagnostic and operative planning will be readily ascertainable before opening the heart. From this advancement, operative rehearsal will become possible. This will increase the possibility of improving the quality of surgical care delivery, particularly when rehearsal of patient-specific valve repair becomes widely available. If indeed this becomes a reality, 3D-printed models will become far more ubiquitous. They will also be important for globally flattening valve repair quality. We would propose that valve repair will become much more commoditized with the evolution of 3D printing. Dr Yoo and his team are using high-resolution
computational tomography images and computer-aided design to develop accurate normal atrioventricular valve models including both valvar and subvalvular apparatus (Figure 4). Other institutions are developing similar models, suggesting that this possibility is on the horizon.

**Perspective**

What seems clear to these authors is that the utility of 3D models for diagnosis, surgical planning, surgical training, and surgical rehearsal is just beginning across multiple surgical disciplines. Each individual that holds a complex disease model in their hands and inspects the anatomic relationships inevitably has an “a-ha” moment. As this experience expands, demand for models will dramatically increase. With it, the possibility of improving quality and facility of surgical procedures will be enhanced.

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**References**


