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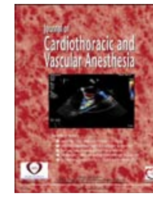

Review Article

Innovations in Preoperative Planning: Insights into Another Dimension Using 3D Printing for Cardiac Disease

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Two-dimensional visualization of complex congenital heart disease has limitations in that there is variation in the interpretation by different individuals. Three-dimensional printing technology has been in use for decades but is currently becoming more commonly used in the medical field. Congenital heart disease serves as an ideal pathology to employ this technology because of the variation of anatomy between patients. In this review, the authors aim to discuss basics of applicability of three-dimensional printing, the process involved in creating a model, as well as challenges with establishing utility and quality.

Keywords: Imaging; 3D modeling; 3D printing; preoperative planning; congenital heart disease

The role of the noninvasive imaging specialist caring for patients with congenital heart disease is to communicate, often complex, anatomy to colleagues. This is usually done in the setting of a surgical conference during which all members of the care team review the available imaging data and form a plan incorporating other relevant clinical information. In this setting, it is crucial that the information be communicated as clearly as possible. Three-dimensional (3D) printing technology has been around for quite some time but recently has gained more visibility. Use of this method of displaying a patients' cardiac anatomy removes ambiguity that can result from variations in interpretation of the presented imaging data. Although it is currently a relatively time-consuming technique to employ, as the cost of 3D printers decreases and the expertise of noninvasive imaging specialists increases, it will inevitably become more of a mainstay for treatment planning of complex cardiac lesions. This review will cover the basics of applicability of 3D printing, the process involved in creating a model, and challenges with establishing utility and quality. The authors focus specifically on the cardiovascular applications of 3D printing, with an emphasis on congenital heart disease given the complexity of the spatial intracardiac relationships, which are most accurately represented using a 3D physical model.

Congenital Heart Surgery: The Perfect Substrate

Congenital heart disease (CHD) is the most common type of birth defect.[1] Although patients with simpler defects may not need intervention, those with more severe lesions almost certainly will require intervention. The mainstay of diagnosis of CHD both pre- and postnatally include imaging studies. Echocardiography is the most commonly used of these

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imaging modalities. Postnatally, cardiac magnetic resonance imaging (CMR) or computed tomography (CT) often are used in patients with complex anatomy. Typically, once the imaging study is complete, the findings are discussed with the surgical and cardiac team to plan the best intervention for the patient. Usually done in the setting of a combined cardiology and cardiothoracic surgery conference, the imaging study is presented by an imaging specialist to the group. The audience typically consists of cardiologists, congenital cardiothoracic surgeons, cardiac anesthesiologists, trainees, and other members of the team who contribute to the patients' care. Given the variety of backgrounds of the audience, it is difficult to imagine that the imaging data, which are presented in two-dimensional (2D) form, are being interpreted in the exact same way by each person. The challenge lies in recreation of the 2D data in one's own mind in 3D. Most commonly, sequential 2D echo sweeps are presented to the audience as the ultrasound beam moves through the different planes of the patient's heart. At different points in the sweeps, the relevant parts of the anatomy are highlighted. For example, in the subcostal view, taken from the abdomen, the initial part of the sweep displays anatomy that is more posterior and inferiorly located. As the sonographer moves the probe anteriorly, the anatomy represented later in the sweep is more anterior and superior. Those more familiar with such sweeps are expected to be able to understand this progression and piece together the different spatial locations of anatomic structures.

Limitations of Current Imaging Strategies

Although the process of deducing 3D anatomy may seem intuitive to some, especially more experienced clinicians, individuals vary significantly in their ability to perform this task. The concept of mental rotation, involves viewing a 2D drawing of a 3D object and being able to imagine it from different perspectives. It has been shown that the ability to accurately accomplish this task is variable.[2,3] Given the lack of consistency in clinicians possessing the skill needed to recreate 3D structures mentally from 2D imaging data, it is hard to imagine that we communicate accurately all spatial cardiac anomalies to all members of the cardiac care conference all of the time. Although this may be of little consequence for simple congenital cardiac lesions, for those patients with more complex congenital abnormalities, ambiguity in the comprehension of spatial anatomy may lead to changes in surgical management. For such patients, advanced imaging techniques such as 3D echocardiography, CMR, or CT often are employed. Even when these modalities are used to depict anatomy in 3D, it is done on a 2D screen. The element of a true 3D representation of cardiac anatomy is not captured with any of these techniques.

What Is 3D Printing?

3D printing, also known as additive manufacturing (AM), is a method of creating a physical object by laying down numerous thin layers of a material, on top of one another, in a predefined pattern. Initially, a virtual computer-aided design (CAD) model is processed by a 3D printer, which will then proceed to stack each layer of model material on top of the next until the 3D object is created. Although 3D printing has gained more visibility in the last 5 years, the technology has been available since the 1980s. A pioneer in the field of additive manufacturing is Charles Hull, who developed the stereolithography apparatus, patented in 1986.[4] Since then, multiple other AM techniques have been invented including fused deposition modeling and polyjet technology. Initially used for industrial prototypes, additive manufacturing has become more recently a method of creating personalized medical models for patient care. Creation of models in the fields of orthopedics, otolaryngology, dentistry, neurosurgery, and cardiology are the most common applications and are being noted increasingly in literature.[5–10]

3D printers vary in the technique used to create each layer, the type of material used to create the object, as well as other characteristics such as build volume and layer resolution. More costly printers have more advanced capabilities such as multimaterial or multicolor printing within the same model.

The material that is used to create the physical object varies by the type of printer used. Two of the most common materials used for fusion deposition modeling (FDM) are acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA), both of which are hard plastics. In cases for which the flexibility of the printed material is not a relevant factor in planning, these models are reasonable options to represent intracardiac anatomy. Materials used to print flexible models vary in "stiffness" as defined by its Shore value. For example, Tango material from Stratasys (Eden Prairie, MN) includes a number of rubber-like photopolymers that vary in characteristics such as hardness, elongation, and tear resistance. Scenarios in which it is useful to print a cardiac model in a softer material include when the model is being used to simulate surgical procedures. Ideally, the consistency of printing material is similar to myocardium or a vessel wall so that a trainee is able to practice a surgical procedure on these structures.[11] Table 1 lists information on printing capabilities of various printers.

Steps in Creating a 3D Model

In patients for whom a 3D cardiac model is determined by the care team to be useful in pre-procedural planning, multiple steps precede the printing process. First, a 3D imaging source dataset must be acquired. Most commonly, CMR or CT is used. These modalities offer the advantage of providing 3D whole heart visualization, which can then be used to focus on the anatomy of interest. Disadvantages include long scan times with CMR and radiation exposure with CT. 3D echocardiography datasets also may be used and offer real-time imaging that can be done at bedside. Thin, mobile structures, such as valves, are represented better by echocardiography. Unfortunately, the field of view is limited in datasets acquired using