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iREVIEWS

STATE-OF-THE-ART PAPERS

Cardiac 3D Printing and its Future Directions

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ABSTRACT

Three-dimensional (3D) printing is at the crossroads of printer and materials engineering, noninvasive diagnostic imaging, computer-aided design, and structural heart intervention. Cardiovascular applications of this technology development include the use of patient-specific 3D models for medical teaching, exploration of valve and vessel function, surgical and catheter-based procedural planning, and early work in designing and refining the latest innovations in percutaneous structural devices. In this review, we discuss the methods and materials being used for 3D printing today. We discuss the basic principles of clinical image segmentation, including coregistration of multiple imaging datasets to create an anatomic model of interest. With applications in congenital heart disease, coronary artery disease, and surgical and catheter-based structural disease, 3D printing is a new tool that is challenging how we image, plan, and carry out cardiovascular interventions.
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Three-dimensional (3D) printing is a fabrication technique used to transform digital objects into physical models. Also known as additive manufacturing, the technique builds structures of arbitrary geometry by depositing material in successive layers on the basis of a specific digital design. Several different methods exist to accomplish this type of fabrication and many have recently been used to create specific cardiac structural pathologies. Although the use of 3D printing technology in cardiovascular medicine is still a relatively new development, advancement within this discipline is occurring at such a rapid rate that a contemporary review is warranted. In this review, we address the 3D printing technologies that are relevant to cardiovascular medicine and discuss the principles of clinical image segmentation. We also present several recently reported applications of 3D printing and discuss the unresolved issues and future directions of this emerging technology.

PRINTING TECHNOLOGY

The first 3D printing technology was introduced by Charles Hull in 1986 (1), and the industry has grown to now encompass many different manufacturing technologies. There are several 3D printing technologies with promising applications in medicine. *Stereolithography* fabricates a solid object from a photopolymeric resin using digitally guided ultraviolet laser light (some new versions use visible light) to harden the surface layer of the polymer liquid. *Fused deposition modeling* creates a 3D structure by extruding melted thermoplastic filaments layer by layer along with a physical support material that is later dissolved away. *Selective laser melting* creates strong parts of fused metal or ceramic powder using a high-power laser beam and is also preferred for building functional prototypes or medical implants, such as facial bone or sternal bone replacements (2,3). *PolyJet technology* creates 3D prints through a process of jetting

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ABBREVIATIONS AND ACRONYMS

AS = aortic stenosis

CAD = computer-aided design

CMR = cardiac magnetic resonance

DICOM = Digital Image and Communication in Medicine

LVOT = left ventricular outflow tract

MV = mitral valve

TAVR = transcatheter aortic valve replacement

TMVR = transcatheter mitral valve replacement

thin layers of liquid photopolymers that are instantly hardened using ultraviolet light and can incorporate multiple materials and colors simultaneously. PolyJet is capable of producing highly complex models with smooth surfaces and thin walls (down to a resolution of 0.016 mm) (4) and is a commonly used technique for the fabrication of flexible, patient-specific anatomical models that combine several different materials. For the creation of cardiovascular models, the 3D printing method of choice depends upon the required complexity, durability, and desired surface quality of the model.

The creation of a patient-specific 3D model begins with clinical imaging. An imaging dataset must be volumetric, which limits the modalities to electrocardiography-gated computer tomography (CT), volumetric 3D echocardiography, and cardiac magnetic resonance (CMR). Volumetric 3D echocardiography is an attractive data source because it is abundantly available, relatively low-cost, and lacks ionizing radiation. For models of clearly imaged cardiac structures, such as ventricular chambers and valve leaflets, a 3D transesophageal echocardiography (TEE) data source may be sufficient to create a 3D patient-specific model. However, ultrasound-based imaging is subject to artifact and unique limitations, such as anatomic data loss within an ultrasound "shadow." To date, CT has been the principle imaging modality for 3D printing, because CT imaging can provide submillimeter tissue resolution, can clearly identify bone and pathologic calcium deposition, and is a commonly acquired imaging method before surgical or other structural interventions. In addition to excellent spatial resolution, CT is able to image patients with pacemakers, pacemaker wires, and metal implants that are not compatible with CMR scanning. In contrast, CMR can acquire high-resolution images without ionizing radiation and distinguish tissue composition without iodinated contrast media. CMR images have been used for 3D print modeling of congenital heart chambers and vasculature and for the reconstructive modeling of intracardiac tumors. However, the spatial resolution of CMR is generally lower than CT, which limits its use for the evaluation of coronary arteries or the small morphological features within heart valve complexes.

IMAGE DATA SEGMENTATION

Image segmentation is the process of converting the 3D anatomical information obtained by CT, CMR, or 3D echocardiography volumetric imaging datasets into a 3D patient-specific digital model of the target anatomic structures. Increasing interest in anatomical modeling and the growing need for personalized structural heart interventions has encouraged the evolution of segmentation techniques. Initially, segmentation was on the basis of CT images only (5–9); however, more recently, CMR images have been utilized to replicate congenital heart and systemic vasculature disorders (10–14). The feasibility of reconstructing the mitral leaflets and annulus from 3D TEE images has been demonstrated by multiple investigators (1,15–20), and efforts to combine echocardiographic data acquired from multiple views or echocardiographic data combined with CT data have been reported (19,21).

Segmentation involves several steps, as illustrated in **Figure 1**. Prior to segmentation, the acquired imaging dataset is exported into a Digital Imaging and Communication in Medicine (DICOM) format (3D TEE images are converted into Cartesian DICOM format). From the DICOM dataset, the target anatomic geometry is identified and segmented on the basis of the threshold intensity of pixels in the grey-scale 2-dimensional (2D) image projections (axial, sagittal, and coronal). Segmentation masks are created such that pixels with the same intensity range are grouped and assigned to be printed using a single material (step 2). Segmentation masks are converted into 3D digital models (step 3) using rendering techniques, and these patient-specific 3D digital models are saved as a stereolithography file. Frequently, this 3D digital model may be further modified within computer-aided design (CAD) software, where adjustments can be made to reflect the purpose of the 3D-printed model (e.g., color coding a region of interest, texturing blended materials, or adding coupling components for evaluation of the 3D-printed model within a flow loop) (19). In general, the spatial resolution afforded by TEE is adequate for many 3D modeling purposes; however, the anatomic resolution can be further improved by combining ultrasound datasets acquired from different imaging perspectives. For example, a deep transgastric TEE image window of the mitral valve (MV) apparatus including the papillary muscles can be digitally combined with data from a midesophageal view of the mitral leaflets to create a more complete dataset of the entire MV complex (19). In addition, segmentation can be enhanced by the digital coregistration of DICOM data from complementary imaging modalities (e.g., TEE visualization of the chordae tendineae combined with CT delineation of the mitral annular calcification). The coregistration is on the basis of

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