Rev Esp Cardiol. 2017;xx(x):xxx–xxx

Review article

Three-dimensional Printed Cardiac Models: Applications in the Field of Medical Education, Cardiovascular Surgery, and Structural Heart Interventions

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Keywords:
Three-dimensional printing
Congenital heart disease
Structural heart disease

ABSTRACT

In recent years, three-dimensional (3D) printed models have been incorporated into cardiology because of their potential usefulness in enhancing understanding of congenital heart disease, surgical planning, and simulation of structural percutaneous interventions. This review provides an introduction to 3D printing technology and identifies the elements needed to construct a 3D model: the types of imaging modalities that can be used, their minimum quality requirements, and the kinds of 3D printers available. The review also assesses the usefulness of 3D printed models in medical education, specialist physician training, and patient communication. We also review the most recent applications of 3D models in surgical planning and simulation of percutaneous structural heart interventions. Finally, the current limitations of 3D printing and its future directions are discussed to explore potential new applications in this exciting medical field.
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Impresión tridimensional de modelos cardiacos: aplicaciones en el campo de la educación médica, la cirugía cardiaca y el intervencionismo estructural

Palabras clave:
Impresión tridimensional
Cardiopatías congénitas
Cardiopatía estructural

RESUMEN

Durante los últimos años, la impresión tridimensional (3D) ha dado el salto al campo de la cardiología gracias a su potencial para mejorar la comprensión de las cardiopatías congénitas, la planificación de la cirugía y la simulación del intervencionismo en cardiopatía estructural. En este artículo se introduce al lector en la tecnología de la impresión 3D con el objetivo de conocer qué es lo que se necesita para obtener un modelo 3D: cuáles son las imágenes radiológicas que se pueden utilizar, los requisitos mínimos de calidad que deben cumplir y qué tipos de impresión 3D hay disponibles. También se evalúa la utilidad de los modelos cardiovasculares 3D en el campo de la educación, la formación de médicos especialistas y la comunicación con los pacientes. Se revisan las publicaciones más relevantes sobre la aplicación para la planificación de la cirugía cardiaca y la simulación del intervencionismo percutáneo estructural. Finalmente se analizan las limitaciones actuales de la impresión 3D y las perspectivas futuras con el objetivo de fomentar el espíritu crítico ante esta nueva tecnología y sobre todo despertar el interés para desarrollar nuevas aplicaciones en este apasionante campo de la cardiología.
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INTRODUCTION

The diagnosis and treatment of structural and congenital heart disease has traditionally relied on the analysis of images obtained by echocardiography, angiography, computed tomography (CT), and magnetic resonance imaging (MRI). To fully appreciate the complexity of the conditions they treat, clinical cardiologists, cardiac catheterization specialists, and surgeons depend on skills, acquired through years of experience, in mentally assembling the anatomical topology of the heart from these 2-dimensional images, as if they were solving a 3-dimensional (3D) puzzle. To make their task even more challenging, these images are usually reproduced as enlarged projections on a flat screen and thus do not represent structures at their real size. Virtual 3D projections offer

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http://dx.doi.org/10.1016/j.rec.2017.01.012
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Please cite this article in press as: Valverde I. Three-dimensional Printed Cardiac Models: Applications in the Field of Medical Education, Cardiovascular Surgery, and Structural Heart Interventions. *Rev Esp Cardiol.* 2017. http://dx.doi.org/10.1016/j.rec.2017.01.012

Abbreviations

3D: three-dimensional
MRI: magnetic resonance imaging
CT: computed tomography

some appreciation of topology, but these images cannot be held and give an imprecise impression of structural depth and the proximity of structures in distinct spatial planes.

Resolving these limitations has recently become a realistic prospect with the advent of 3D printing, a technology originating in engineering and the aeronautical industry that has begun to find applications in the world of medicine. The aim of this review is to introduce readers to 3D printing technology and to provide an overview of the imaging requirements for generating a 3D model. We review current scientific evidence on the usefulnessof 3D cardiovascular models for medical education, patient communication, specialist physician training, and the applications of 3D printing in cardiovascular surgery and percutaneous structural heart interventions.

INTRODUCTION TO THE TECHNOLOGY

Generating a 3D model is a complex process requiring a multidisciplinary team of radiologists, cardiologists, pediatricians, and engineers. These specialists need to work together on each of the following steps: medical image acquisition, segmentation, computer-assisted design, and finally 3D printing (Figure 1).

What Type of Medical Image Is Needed?

Medical images suitable for 3D printing must be isotropic, of high spatial resolution in order to provide rich detail, and of sufficiently high contrast to distinguish between adjacent structures. High resolution and contrast minimizes processing time and ensures an exact anatomical replica. Low resolution images or the presence of artifacts can give the appearance of continuity between neighboring structures such as the aorta and pulmonary artery; when transferred to the 3D model, these characteristics will produce a false diagnosis of an aortopulmonary window.

Each imaging methodology has its advantages and limitations. For printing 3D images of large vessels, heart chambers, and ventricular septal defects, the best options are CT[1–8] and MRI.[9–15] The desired isotropic resolution is 0.5 to 1.25 mm^3 for CT and 1.5 to 1.8 mm^3 for MRI. In contrast, echocardiography is the preferred imaging technique for 3D printing of heart valves, the subvalvular apparatus, and the interatrial septum.[16–21] As with clinical practice, multimodal evaluation is applicable to 3D printing, yielding 3D models with a high level of detail (Figure 2).[16] Another key factor in the choice of imaging modality for 3D printing is the center's level of expertise in different imaging modalities.

Tissue Segmentation

The next step is segmentation, the delineation of the cardiovascular structures of interest and exclusion of irrelevant noncardiac structures such as bone and lung. There are 2 basic segmentation strategies for heart modeling: blood pool segmentation to derive the chamber-wall structure (Figure 2A), or myocardium segmentation (Figure 2B). Models derived from blood pool segmenation provide a rapid understanding of the disease,[22] structural dimensions, the coronary arteries, and the great vessels; in contrast, 3D models of the myocardium are ideal for delineating ventricular septal defects and specimen dissection and therefore allow simulation of surgical strategies.[13] Available software for segmenation includes comprehensive commercial packages (Materialise, Leuven, Belgium) and freeware (ITK snap[23]), the latter being an attractive option for small centers taking their first steps in this technology. The various segmentation algorithms and methodologies are covered in depth in Suárez-Mejías et al.[24] and Byrne et al.[25]

Three-dimensional Printing

Three-dimensional printing is a form of additive manufacturing in which the 3D object is contructed by the layer-on-layer addition of new material to an existing surface. The most common printing methods are fused deposition modeling, selective laser sintering, and stereolithography. Other much more complex 3D printing methods used to print living tissues fall outside the scope of this review, but are described in detail elsewhere.[26,27]

APPLICATIONS OF 3-DIMENSIONAL PRINTING

Medical Education

Medical education is subject not only to economic limitations, but also to ethical, legal, and cultural concerns that restrict the availability of cadavers. Modern technology and 3D printing offer possible solutions in this area and have been used to model human anatomy in a variety of settings.[28] This application of 3D printing is especially relevant to the teaching of congenital heart disease because it can expose students to the full spectrum of malformations and the variability that may exist even within a single condition. Handling 3D models engages students' sight and touch to achieve rapid understanding of anatomical defects, including complex phenomena such as criss-cross atrioventricular connections (Figure 3). 3D models have been used to teach the morphological characteristics of tetralogy of Fallot. Classes that used the 3D models were more positively evaluated by students than those that did not, which was reflected in higher student satisfaction scores and higher retention rates.[29]

Moreover, the interconnectivity provided by the internet makes it easy to share digital files through online networks, allowing users to rapidly access and print 3D models of the disease of interest. Making 3D images available through online collections can provide hospitals and research centers with free access to a broad spectrum of heart conditions.[30]

Even more importantly, 3D models promise to transform teaching in ways that go beyond the lecture hall, and over the next few years are set to revolutionize medical training, especially in percutaneous interventions.[31] Acquiring the necessary skills in these procedures requires a major dedication of financial and human resources, is time consuming, and puts patients at risk. These concerns are behind current moves to make simulations a required element of cardiac catheterization training, part of a joint effort affecting the clinical practice guidelines of several international societies, including the Cardiovascular and Interventional Radiological Society of Europe, the Society for Cardiovascular Angiography and Interventions, the Society of Interventional Radiology, and the Radiological Society of North America.[31,32] Simulations involving 3D cardiac models allow trainees to practice with a diverse range of scenarios, repeat technical procedures, and learn from mistakes without putting patients at risk.[10] Simulations can be used to train specialists before they carry out their first

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