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3D Printed Models of Complex Anatomy in Cardiovascular Disease

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ABSTRACT

Three-dimensional (3D) printing technology has undergone rapid developments over the last decades. The application of 3D printing has reached beyond the engineering field to medicine, with research showing many applications in cardiovascular disease. Due to the complexity of the cardiovascular system, application of 3D printing technology has shown potential value to benefit patients with cardiovascular disease. This mini-review provides an overview of applications of 3D printing in cardiovascular disease, with evidence of some of examples using patient-specific 3D printed models in the two common cardiovascular diseases, aortic dissection and abdominal aortic aneurysm.

KEYWORDS: 3D printing; Cardiovascular disease; Abdominal aortic aneurysm; Aortic dissection; Model.

ABBREVIATIONS: 3D: Three-dimensional; RP: Rapid Prototyping; CT: Computed Tomography; MRI: Magnetic Resonance Imaging; MSCT: Multislice CT; CAD: Computer Aided Design; STL: Standard Tesselation Language; AAA: Abdominal Aortic Aneurysm.

INTRODUCTION

The recent growth and development of three-dimensional (3D) printing has enabled the generation of 3D models of complex anatomy with high resolution and accuracy of depicting cardiovascular disease.[1-3] The concept of 3D printing was first introduced in the late 19th century, and then further advanced in 1980's.[4] 3D printing is a common term for Rapid Prototyping (RP), which is commonly used in the engineering and industry field to generate prototype models. 3D printing provides several significant advantages over traditional manufacturing, which include increased rapidity and removing the use of molds or production line. In recent years, this technology has been increasingly used in the medical field, with benefits of RP technology demonstrated in assisting clinical diagnosis, pre-surgical planning and surgical guidance.[5-9]

The expanded applications of this technology to cardiovascular disease allow for rapid generation of 3D complex anatomical structures from medical imaging datasets such as echocardiography, Computed Tomography (CT) or Magnetic Resonance Imaging (MRI) data of patients. This editorial provides an overview of current applications of 3D printing in cardiovascular disease.

IMAGING POST-PROCESSING OF 2D IMAGES OF CARDIOVAS-CULAR SYSTEM TO 3D MODELS

Although, 3D reconstructed visualizations from CT and MRI data are widely available, images are still presented on a computer screen, which impedes comprehensive understanding and interpretation of pathologies due to the differences between actual anatomical structures and reconstructed 3D images.[10] This limitation can be overcome with the development of RP technology through replication of the cardiovascular system. The procedure of creating 3D printed models consists of steps from image acquisition, image post-processing and 3D printing.

Acquisition of high resolution images is a very important step in generation of 3D objects as the quality of the object for 3D printing is determined by the quality of the original data. Superior resolution images (350-400 microns) can be achieved with modern CT or MRI scanners.[11,12] In most cases, slice thickness of submillimeter is required for generation of isotropic voxels to minimize the partial volume artifacts during image post-processing.[13] Currently, Multislice CT (MSCT) imaging is more commonly used for rapid prototyping than MRI due to the wide availability of MSCT scanners, excellent spatial resolution and less complexity of image post-processing for cardiac MSCT data.[14] Regardless of imaging modality used for image acquisi-

tion, the acquire data is saved in the Digital Imaging and Communications in Medicine (DICOM) for post-processing.

3D post-processing of DICOM images is performed on high performance workstations equipped with post-processing tools and software packages, which allow for image segmentation, semi-automatically or automatically. A variety of visualization tools are used during this process, such as multiplanar reformation, surface or volume rendering and maximum-intensity projection. Figure 1A is an example of 3D surface rendered visualization of a patient with aortic dissection with both contrast-enhanced arteries and bony structures displayed, while Figure 1B shows image post-processing of removing the bony structures. Figure 1C indicates the visualization of only vascular details for 3D models. Image post-processing can be enhanced with use of Computer Aided Design (CAD) software which enables automatic optimization of the geometry. Finally, the data is saved as Standard Tesselation Language (STL) file format which is commonly used for 3D printing.

The principle of RP in 3D printing is to use 3D computer models for the reconstruction of a 3D physical model through the additive manufacturing of material layers.[15] These layers correspond to the virtual cross-sectional slices from the 3D CAD model and are joined together to create the final shape
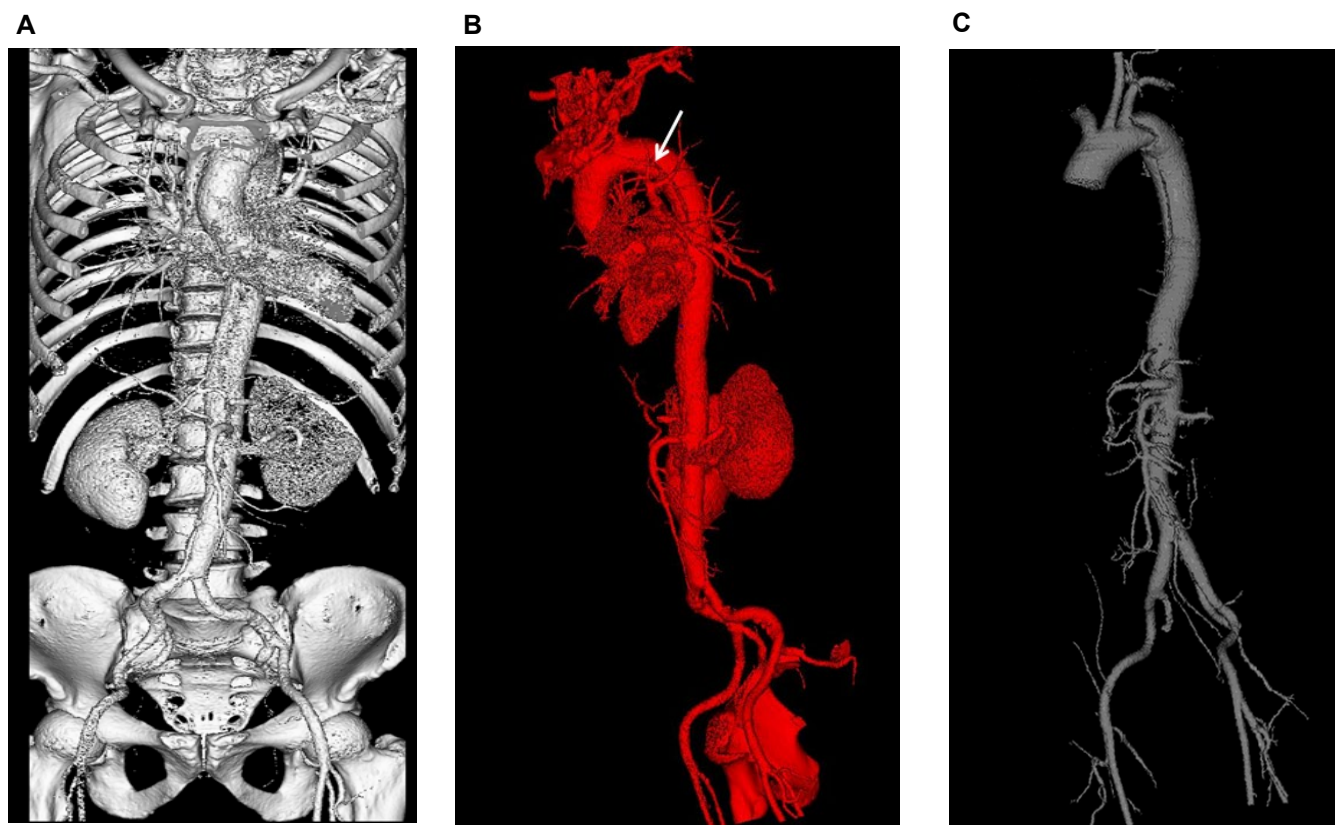

Figure 1: The process of using CT angiographic data for image post-processing, segmentation and generation of 3D aorta model. A: 3D surface rendering showing visualization of contrast-enhanced thoracic and abdominal aorta, as well as bony structures. B: Only anatomical vascular structures are displayed with most of the bony details removed through image post-processing. Arrow refers to the aortic dissection in the descending thoracic aorta. C: After image segmentation, only contrast-enhanced aorta and its branches are visualized for 3D models.

or geometric feature of the 3D printed models.

3D PRINTING MATERIALS

3D physical models may be printed in a variety of materials using different 3D printing technologies, depending on the application purposes, such as education or training, surgical planning, device sizing or diagnostic testing, etc. Each of these technologies has its own advantages and limitations.[14,16,17] Table 1 summarizes the currently available 3D printing technologies using different materials with corresponding clinical applications. The materials available from these technologies have different properties, minimum wall thicknesses and maximum part sizes, which also influences the material or technology selected for a particular purpose.

CLINICAL APPLICATIONS OF 3D PRINTING IN CARDIOVASCULAR DISEASE

3D printed models have been reported to benefit patients with cardiovascular disease in many different applications. Individualized or patient-specific 3D printed models have been shown to improve understanding of cardiovascular structure abnormalities, assist in predicting intraoperative complications, choose the best surgical procedures, improve the skills of young or junior surgeons with the use of 3D printed models for simulation training, and reduce operating times through efficient utilization of operating rooms.[1,10,18-20] Furthermore, 3D printing technology enables the manufacture of personalized cardiac stents to reduce the rate of in-stent restenosis,[1] optimize designs of biological scaffolds for tissue engineering of cardiac valves for valve replacement,[21,22] and fabrication of human microvasculature for organ transplantation.[23,24] We will present our preliminary experience of using 3D printed models in the two common cardiovascular diseases: abdominal aortic aneurysm and aortic dissection.

Abdominal Aortic Aneurysm (AAA) is a common vascular disease which most frequently involves abdominal aorta below the renal arteries. Once an aneurysm is detected by imaging studies (most commonly by ultrasound or CT), the risk of rupture is weighed against the risk of surgical repair for each individual patient.[25] The major determinant for risk of rupture is aneurysm diameter. The traditional approach of open surgery is less commonly performed due to its invasiveness and procedure-related complications, while endovascular stent graft repair is increasingly used as a minimally invasive technique with many advantages compared to open surgery.[25] The success of endovascular stent graft repair of AAA depends on imaging assessment, and currently computed tomography angiography has been confirmed as the best single imaging technique for both preoperative patient assessment and aortic stent-graft surveillance.[25-27] 2D and 3D reconstructions are routinely used to assist planning of endovascular repair by providing information about aneurysm extent and relationship between the aneurysm and the arterial branches. 3D printed models further enhance the role of CT angiography by demonstrating the patient-specific anatomical details of aortic aneurysm in relation to the surrounding structures (Figure 2).
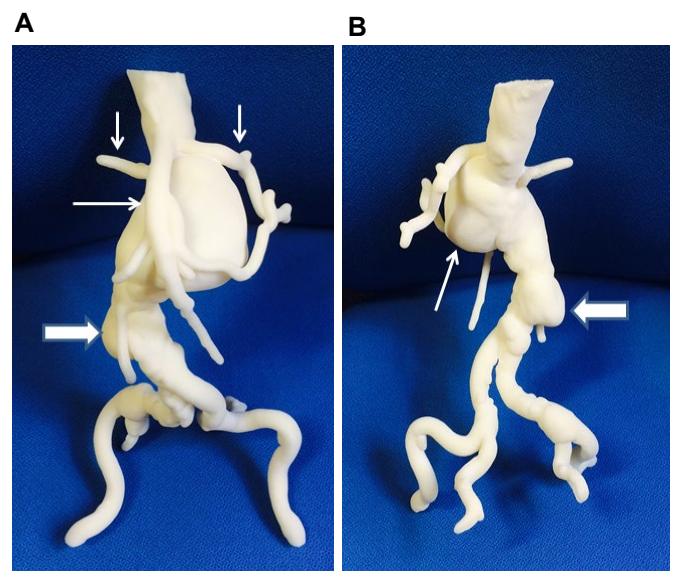
Figure 2: 3D printed aorta model of aortic aneurysm. A: anterior view of a full-sized 3D printed model in a patient with an infrarenal Abdominal Aortic Aneurysm (AAA). Arterial branches including superior mesenteric artery (long arrow), renal arteries (short arrows) are clearly visualized. Another small aneurysm (open arrow) is seen just above the common iliac arteries. B: posterior view of the 3D printed model. The long arrow refers to AAA.

Aortic dissection is a common vascular disease and it is the most frequent cause of aortic emergency. Aortic dissection can be a life-threatening event which is characterized by splitting of the aortic wall by high blood pressure entering the

Techniques	Materials	Advantages	Limitations
Stereolithography (SLA)	Photopolymers	High detail and precision, smooth surfaces	Moderate strength, high cost
Selective Laster Sintering (SLS)	Polymers, metals	High accuracy, good strength	High cost, powdery surface
Fused Deposition Modeling (FDM)	Thermoplastic materials or eutectic metals	Low cost, good strength	Low speed
Laminated Object Manufacturing (LOM)	Layers of paper or plastic films	Low cost, material stock easy to obtain	High material waste, slower printing
Inkjet printing techniques (such as ZPrinter 450, PolyJet and PolyJet Matrix)	Fine powers such as plaster or starch	Low cost, high speed, multiple materials	Moderate strength, fail to mimic true tissue properties

Table 1: Overview of 3D printing techniques and medical applications.[14,16]

media through an intimomedial entrance tear.[28] Multislice CT angiography is the preferred method for diagnosis of aortic dissection with a sensitivity and specificity of nearly 100%.[29-31] CT angiography has been shown to be more sensitive than invasive angiography for diagnosis of aortic dissection. The 3D aortic arch is difficult to assess on an axial CT plane. Although, 3D reconstructions serve as valuable tools for more accurate assessment of aortic dissection,[30,31] the complex anatomical structures of thoracic aorta, in particular when dissection involving aortic arch present a challenge to decision-making process (Figure 3). The 3D printed models overcome these limitations by providing the exact individual anatomy of the cardiovascular pathology in each patient. Figure 4 is an example of 3D printed model of thoracic aorta based on CT angiographic images (Figure 1) of a patient with Stanford type B aortic dissection. The model was evaluated with measurement of certain anatomical structures of the model comparable to the data from CT angiography (Table 2). The differences in dimensions are due to the process of preparing the digital model to make it suitable for 3D printing, e.g. wall thickening to meet the material's minimum thickness. However, these will be more fully investigated with the intention to match dimensions much more closely and reliably.

Anatomic structure	CT measurements (mm)	3D printed model (mm)
Ascending aorta	40	38
Aortic arch	36	38
Brachiocephalic artery	17	16
Left common carotid artery	13	14
Left subclavian artery	15	15.5
Descending aorta	36	35

Table 2: Correlation of CT angiography and 3D printed model.

SUMMARY AND CONCLUDING REMARKS

3D printing is an emerging and promising technique with many applications in cardiovascular disease with a focus on surgical training and device design. High resolution images, especially from cardiac CT make the use of 3D printing technology become a reality to assist patients with cardiovascular disease. Development of materials used for rapid prototyping is a key area to guarantee successful implementation of 3D printing technology. Another limitation lies within the time and cost spent in generation of 3D printed models. Further studies with inclusion of more patients and more data are needed to confirm
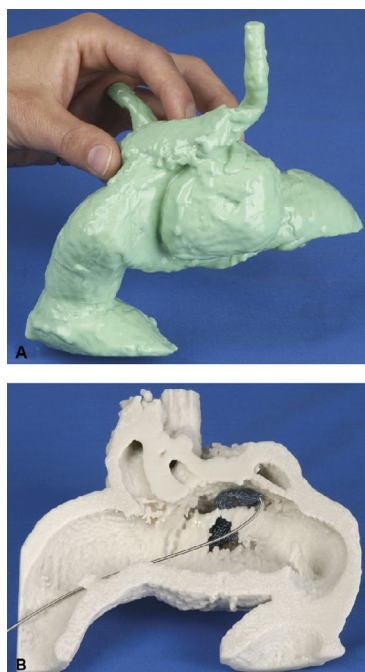

Figure 3: 3D printed model of aortic aneurysm in aortic arch. A: Stereolithographic model of the aortic arch (outside view) and the aneurysm. B: Stereolithographic model of the aortic arch (inside view) and preoperative testing of the interventional procedure with the custom-made occlude device.[19]
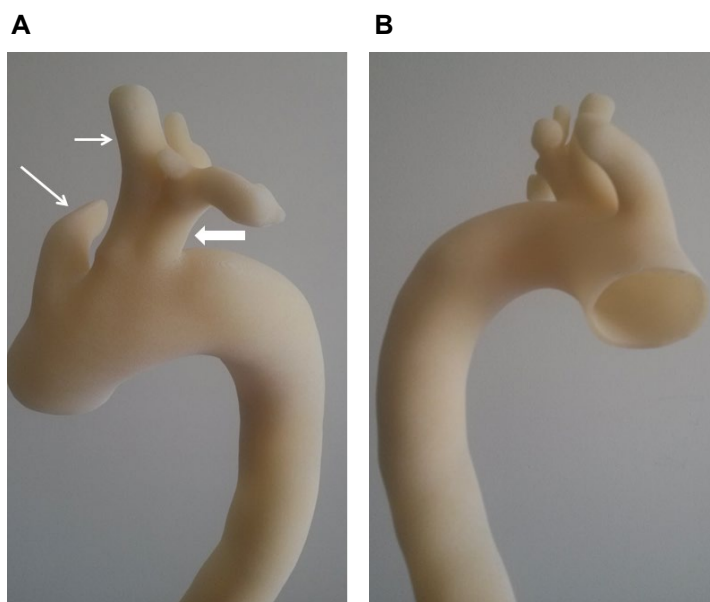

Figure 4: 3D printed model of aortic dissection. A: anterior view of a patient-specific 3D printed model based on CT angiographic images of aortic dissection (Figure 1). Aortic branches consisting of brachiocephalic artery, left common carotid and left subclavian arteries (long, short and open arrows, respectively) are seen arising from the aortic arch. B: posterior view of 3D printed model. Note that the intimal flap that separates the aortic dissection was not printed in the 3D model due to removal of the thin fibrous membrane of the flap during image post-processing.

its clinical value of using preoperative 3D printed models for reduction of perioperative/postoperative mortality.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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