Editorial

Three-dimensional printing in cardiovascular surgery: logical next step after three-dimensional imaging

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Kommerell diverticulum (KD) is an aneurysmal dilation at the origin of an aberrantly-arising subclavian artery. This congenital malformation is relatively uncommon with a prevalence of 0.04% to 0.4% and also exists with a right aortic arch configuration (1,2). Patients may be asymptomatic or may present with dysphagia and tracheal compression and the rate of rupture and dissection is 15–53% (1,2). For the majority of cardiovascular surgeons, it is a pathology that they may see once in their career, if ever. Consequently, when taking these patients to surgery they may find themselves in somewhat unfamiliar territory, especially in the presence of a right aortic arch. In this edition of the *Journal of Thoracic Disease*, Chen and co-authors describe their use of three-dimensional (3D) printing to guide and facilitate surgical treatment of KD associated with right aortic arch (3).

3D reconstruction of cross-sectional imaging has become mainstream in cardiovascular medicine to assist in diagnosis and evaluation of disease as well as planning and execution of treatment. The two-dimensional images produced by cross-sectional imaging require mental manipulation to understand the 3D structures they represent. The creation of 3D reconstructions from computed tomographic angiography (CTA) and magnetic resonance imaging (MRI) data using post-processing software obviates these mental acrobatics. There are a number of relatively affordable software packages available for use. The capacity to create digital 3D reconstructions is almost ubiquitous in modern hospitals and is increasingly available to non-radiologists. In echocardiography, real-time 3D imaging capabilities have become standard on new machines and require minimal additional manipulation to create the 3D images. One of the principal advantages over two-dimensional echocardiography is the ability to graphically represent the dynamic 3D structure and motion of the heart valves and in facilitating understanding of the abnormality leading to valve dysfunction and its repair (4). Digital 3D reconstructions can be used in planning complex aortic surgery (5) as well as planning the best minimally invasive approach for a specific patient's anatomy (6). In our recent paper (7), 3D reconstruction of CTA images improved our understanding of the anatomy in a patient with right aortic arch, aberrant left subclavian artery, and KD. It was apparent that due to a gothic arch and close spacing of the left and right carotid and right subclavian arteries, a zone 0 proximal landing zone and head vessel debranching would be necessary in conjunction with thoracic endovascular aortic repair.

3D printing can be seen as the next step in imaging, whereby the digital 3D model is transformed into a physical object. This manufacturing technique builds structures by depositing successive thin layers of material onto each other to create a physical model of the digital 3D object. While this technology has existed for over 30 years, it is in the last decade that 3D printing has gained used in the clinical realm (8). Briefly, the process begins with the acquisition of high-quality volumetric images, typically from CTA. Using post-processing software, the region of interest undergoes segmentation and conversion into a file format, usually the standard tessellation language (STL) format, which the 3D printer can interpret. Currently, four different printing technologies are used to create the models, which may be made of a number of different materials that possess different properties, can be made transparent or in different colors, and can even be made to be sterilizable (8). Most applications of this technique in cardiovascular medicine have been in congenital heart disease, valvular pathology, and pathologies of the great vessels. Patient-specific 3D-printed have been used in several ways, for education and communication; visualization and diagnosis; research; and planning and simulation of interventions (8). 3D-printed models can help in the understanding of medical trainees of complex anatomy and the relationship of defects with neighboring structures. Printed 3D models authentically depicting normal and abnormal patient anatomy can be much more readily available and portable than cadaveric models and may be easier for trainees to understand than virtual 3D models. They can also assist in communication with and education of patients and families about the condition in question. For many patients, their cardiovascular abnormality can seem quite abstract and having a 3D model demonstrating their particular anatomy improves engagement with the physician, their understanding of their condition, and can aid in the consent process (8). Additionally, cardiovascular surgery trainees that have not been exposed to certain uncommon pathologies could compensate for those missed opportunities using printed models.

Creation of 3D printed models of cardiac anatomy affords the opportunity to replicate and test *in vitro* either fictitious or real patient anatomy. Using a set of idealized 3D-printed coronary arteries with systematically placed stenotic lesions, Kolli and coauthors were able to demonstrate that coronary fractional flow reserve varied with aortic pressure (9). Such flow models can replicate cardiovascular physiology *in vitro*. Functional flow models employing 3D printed models of severely stenotic aortic valves, with its fairly static valve position, can allow the quantification of flow during various loading conditions (10). Finally, the ability to use 3D printed models of various cardiac pathologies facilitates testing of novel structural heart repair devices in conditions that more closely resemble their ultimate destined used, potentially replacing human cadaveric models which cannot replicate patient-specific anatomy and animal models which often lack certain characteristics of human cardiovascular disease or have a size mismatch.

It is particularly in congenital heart disease where this technique has been employed the most. Use of 3D printing patients gives treating physicians a better view of the complex and extremely variable anatomy found in these patients. The procedure can be planned and even practiced on the 3D model and troubleshooting can be done before proceeding to percutaneous or open intervention (8). This is true not only for congenital heart disease but can and has been extended to acquired valvular disease, aortic pathology, and even coronary intervention (10). Chen and co-authors used a 3D printed model of the heart, thoracic aorta, and head vessels to assist in planning complex aortic arch surgery in their patient with uncommon anatomy (3). Using the model, they were able to prepare for intraoperative exposure, determine the ideal aortic resection for their patient, and more easily measure the dimensions for the stent-graft to be used as a frozen elephant trunk before precisely executing the surgery.

With all its potential uses and advantages, 3D printing is still some years away from being as ubiquitous in cardiovascular medicine as digital 3D reconstructions are now. Currently, limitations include challenges in the generation of the data that the 3D printer needs to create the models, the availability of materials that can recreate the properties of most cardiovascular structures, the cost and complexity of workflow involved in generating the models, and lack of robust evidence as well as awareness that 3D printing can improve patient care (8). The process of segmentation depends on high-quality imaging as well as an operator that is trained and experienced in the manipulation of the data. Most materials currently used poorly emulate the characteristics of human tissue, particularly with regards to flexibility, elasticity, and tensile strength and generation of accurate models of small, thin-walled vessels is a challenge. Finally, until there is increased familiarity with 3D printing technology and more convincing evidence of its utility, the time and expense involved in acquiring the infrastructure and expertise required and in the generation of the 3D models themselves, will limit use of this technique. However, 3D reconstruction of cross-sectional imaging modalities faced many of these same financial and training obstacles over a decade ago and despite that, it is now almost universal; with time, the same will likely be true for 3D printing.

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Footnote

Conflicts of Interest: The authors have no conflicts of interest to declare.

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