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EDITORIAL

Three-dimensional models for coronary artery fistulas: to print, or not to print—that is the question

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3D printing in cardiovascular medicine

The integration of advanced technologies into modern medicine has ushered in transformative approaches to diagnosis and treatment. Among these, three-dimensional (3D) printing has emerged as a promising tool with applications spanning various medical domains.[1] In the cardiovascular field, this technology has been considered of great potential to revolutionize diagnostic accuracy, enhance surgical/interventional planning, and facilitate patient education.[2,3] The creation of patient-specific cardiac models, based on data derived from patient's cardiac imaging data i.e. 3D datasets from, commonly, computed tomography (CT) or cardiac magnetic resonance imaging, has made the spatial visualization and thus assessment of complex congenital anomalies, valvular lesions, and vascular pathologies much easier.[4,5] Specifically, the ability to visualize complex lesions in three dimensions relative to its surrounding anatomical structures aids not only in deciphering the anatomical complexity of specific lesions but also helps in the identification of the potential challenges associated with intervention. This in turn allows for better planning and optimization of interventional/surgical approaches. The utility and application of this technology has had the largest impact in the area of paediatric and adult congenital heart disease.[6,7]

3D printing in coronary artery fistulas

Andersen *et al*.[8] presented two interesting cases whereby the utilization of 3D-printed models played a crucial role in influencing management. Both cases featured middle-aged, patients with complex left circumflex artery-to-coronary sinus fistulae who were initially asymptomatic, hence had not had surgical correction of their congenital coronary artery defects despite diagnosis of these congenital lesions. Both patients subsequently developed progressive symptoms with associated interval enlargement of their fistulae and resultant shunting that prompted re-evaluation of their management. Using 3D datasets from cardiac CT angiography, 3D models of the heart and the fistulas were constructed and printed using material jetting technique, which produced detailed reconstruction of the anatomical relationships of the fistulas relative to its surrounding anatomical structures providing a better appreciation of the impact of the defect on cardiac physiology and the reported symptoms. This was particularly helpful in the decision-making process with the multidisciplinary Heart team recommending a decision for surgical correction of the defect in both cases. The 3D models were also useful in the pre-operative planning and simulation of the planned surgical approach, resulting in successful treatment and good outcomes for both cases featured.

3D printing in congenital heart disease

These cases highlight the value of 3D-printed models in specific congenital defects such as coronary artery fistulas, which can often have complex anatomical make-up.[9,10] The diagnosis of coronary artery fistulas and their management have historically been complicated by intricate anatomical variations with connections between various coronary arteries and cardiac chambers or major vessels, and diverse clinical presentations.[11] These rare congenital anomalies often pose challenges that necessitate an accurate spatial appreciation of the anatomical complexity to allow for effective management.[12] Standard imaging approaches including invasive coronary angiography may not always allow for a full appreciation of the complexity of the lesion to both treating physicians and patients. This technology overcomes the limitations of traditional two-dimensional representations, providing novel insights into complex anatomical structures. Three-dimensional-printed models serve as an augmentation of the available imaging data by providing an accurate

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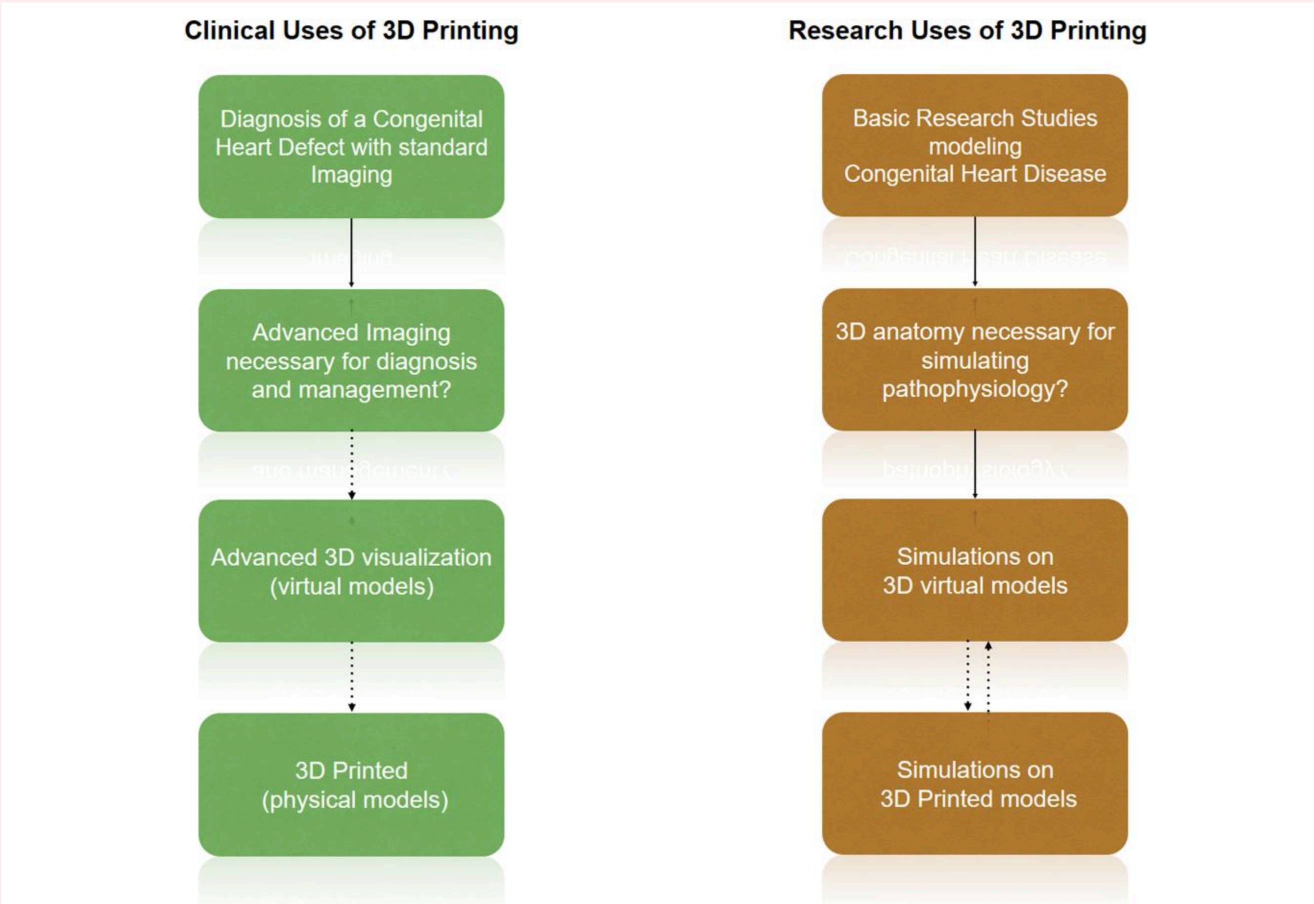

Figure 1 Schematic representation of the potential clinical and research pathways whereby 3D printing might be a useful addition for congenital heart diseases. Solid lines represent a standardized mandatory course, whereas dashed lines a rather reasonable pathway that could be implemented but will not always be necessary.

spatial representation of the aberrant defects and its anatomical relationship with surrounding structures including other coronary arteries, and adjacent structures. This enhanced understanding can potentially impact clinical decision-making and allow for treatment strategies to be tailored to the precise anatomical context of each patient. The value of 3D reconstructed printed models also extends beyond diagnosis of complex lesions. The translation of complex imaging data into 3D-printed models plays a useful role in pre-procedural planning and allow interventionalists and surgeons to simulate complex procedures and refine techniques, thereby mitigating procedural risks and optimizing patient outcomes. Furthermore, these 3D-printed models help with patients' understanding of their pathology and serve as useful aids in medical education and training.

Limitations and challenges

While the advantages of 3D-printed models are clear, a number of barriers should be noted. Firstly, there is a significant financial cost associated with the necessary equipment i.e. 3D printers and specialized software. Secondly, the post-processing required to translate the raw imaging data to the final output of a 3D-printed model involves a multi-step complex process frequently necessitating the integration of multi-modality datasets and image segmentation (where specific structures of interest are selected from a specific phase of the cardiac cycle that defines the structure of interest to generate digital models) in order to generate an STL file for digital mesh construction. The constructed digital mesh has to then be further processed to eliminate unnecessary anatomy and further refined through surface conditioning (where an automated or semi-automated approach is adopted to subdivide images into regions sharing similar properties such as brightness, grey level, and texture) prior to the generation of the final model.[13–15] Furthermore, inherent issues associated with specific imaging modalities i.e. in the case of CT imaging inadequate opacification or blooming artefacts may potentially limit the utility of this technology in certain patients.[16] Despite the availability of commercial software packages and cloud-based services from vendors, the post-processing time and costs remain significant. Such financial implications of routine adoption in a centre with busy workflow can potentially be restrictive and influence resource allocation within healthcare systems. These barriers therefore limit the application of this technology to larger institutions with digital imaging centres and appropriately trained staff. Additionally, the ability of 3D software to authentically replicate *in vivo* conditions remains an area of ongoing research, and as such, a degree of caution is warranted in relying solely on anatomical-only 3D-printed models. Correlation to actual clinical scenarios is still necessary. Finally, the familiarization of the upcoming generation of interventionalists/surgeons with 3D images may potentially limit the value of 3D-printed models to only selected challenging cases. Perhaps utilization of 3D printing in congenital heart diseases might be more straightforward in the research field by enhancing simulations of pathophysiology in combination with virtual models (*Figure 1*).

Future directions of 3D printing

Three-dimensional-printed models are a valuable tool particularly for the diagnosis and management of congenital heart disease, with clear advantages in certain pathologies such as complex coronary vascular malformations. While 3D printing presents a tantalizing frontier given its potential to illuminate complex anatomical details, guide interventions, and inform patients, there are also inherent limitations to the widespread application of this technology. The merits and value of this technology will need to be balanced with the practical constraints such as availability and costs. This technology has been available since the end of the past century but hard data from multicentre-international prospective randomized trials on its added value are still lacking. Collaborations between clinicians, researchers, engineers, industry, and healthcare stakeholders will be crucial in unlocking the true potential of 3D printing and to define its ongoing role in the advancement of cardiovascular care.

Lead author biography

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Data availability

The data underlying this article will be shared on reasonable request to the corresponding author.

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