Heart Surgery Forum 2024; 27(3): E315–E325
doi: 10.59958/hsf.7177

Review

3-Dimensional Printing in Transcatheter Aortic Valve Replacement: Periprocedural Value and Training Applications

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Submitted: 24 December 2023 Revised: 17 February 2024 Accepted: 27 February 2024 Published: 21 March 2024

Abstract

Transcatheter aortic valve replacement (TAVR) is a rapidly developing, cutting-edge technology. The skills to perform such procedures are difficult to acquire, and the learning curve is steep. In recent years, structural heart diseases, particularly valvular disease, have become one of the main areas to which 3-dimensional (3D) printing has been applied because it facilitates visualization and exploration of complex cardiovascular anatomical structures. 3D printing also addresses some of the challenges of these interventions, such as patient selection, prosthesis sizing, and of course, teaching and training. 3D printing can provide a valuable resource for teaching and training because it can produce educational models for all types of valvular diseases. A pulsatile platform for the simulation of TAVR with 3D printed models could be used for comprehensive training of young clinicians as part of the overall TAVR teaching and training program. In this review, we introduced the 3D printed model and TAVR simulator, illustrate its training applications in morphology teaching, surgical simulations and preprocedural planning. Additionally, we reviewed studies on 3D printing in predicting periprocedural complications of TAVR, discussed the current limitations and prospected future directions of 3D printing.

Keywords

transcatheter aortic valve replacement; 3D printing; models; teaching; training

Introduction

After twenty years of development, a large amount of evidence-based research has reinforced the idea that transcatheter aortic valve replacement (TAVR), as a leading and revolutionary technology, is changing the treatment strategy and direction of aortic valve diseases, which leads to less trauma, lower risk, faster recovery speed and better prognosis in patients [1–3]. However, the difference between TAVR and surgical aortic valve replacement (SAVR) lies in the fact that it is difficult to look directly at the full view of the aortic root, let alone to open the heart to observe the internal anatomic structures [4]. With the continuous development of medical visualization, digital modeling is required to be increasingly accurate, and the requirement of precision is particularly important in cardiovascular diseases [5]. Advances in 3-dimensional (3D) printing have proven its value and potential in many fields, in particular by opening up new approaches for the diagnosis and treatment of many complex cardiovascular diseases. Clinicians who specialize in diagnostic and interventional radiology could use imaging data to complete 3D reconstructions and models and to provide the surgeons with clear models of the individualized anatomical structures [6–8]. These clinicians collect the patients' preprocedural computed tomography angiography (CTA) imaging data to reconstruct 3D models and use the 3D printer to create individualized models [9,10]. The models provide clinicians with intuitive anatomical structures to assist with surgical training, preprocedural planning, and intraprocedural guidance and also play an integral role in medical education and training [11,12].

Furthermore, 3D printed models are already available for various applications, especially for training purposes. Studies have demonstrated the importance of hands-on participation and instruction in stimulating the interest of medical students in becoming surgeons [13–16]. This trend is driven by the desire to improve the quality of patient care and ensure patient safety [17]. A major advantage of simulation is that it creates a valuable practice environment for students [17]. The combination of 3D printing and transcatheter aortic valve replacement (TAVR) allows doctors to view the anatomical structures directly through the 3D printed models, which may also improve the communication between doctors and patients and train young clinicians and medical students as well [18,19]. Although the simulation-based mode has been widely accepted, it has not been applied in many areas of medicine in which educational needs exist. Therefore, in this review, we discussed recent advances and specific applications, especially training applications, of 3D printing in TAVR from a technical perspective.

3-Dimensional Aortic Valve Printed Model and Simulator

The process of creating an individualized 3D printed model is completed in 4 steps: (1) Clinical imaging: the medical image data are acquired; (2) image segmentation: the region of interest is extracted, reconstructed, and then printed; (3) data transformation: the volumetric data are transformed into a model recognizable for 3D printing; (4) model printing: the digital model is imported into a 3D printer for printing. Post-processing procedures, such as removal of support structures, grinding, clarifying, and polishing, produce an exquisite, colorful multimaterial 3D model for clinical use.

3-Dimensional Printed Models Generated by Multimodality Imaging

CTA is commonly used in cardiovascular diseases to provide high-quality images through angiography and is the preferred data source for 3D printing of cardiac anatomical structures. Computed magnetic resonance (CMR) has certain advantages over CTA in the display of valves and adjacent tissues, but the application is somewhat limited because it is time-consuming. With the development of echocardiography, the spatial and temporal resolution of images has increased significantly and could also be used for 3D reconstructions. These acquired images are then converted to the standard format for Digital Imaging and Communications in Medicine for storage.

First, the patient's computed tomography (CT) data are imported into Materialise Mimics version 21.0 software (Materialise, Leuven, Belgium). Three orthogonal sections (coronal, sagittal, and cross-sectional) are created by using interactive multiplanar imaging reconstruction. After comparison and confirmation of the 3D reconstruction, the outlined area is reconstructed to obtain the initial 3D model of the aortic root. Second, Materialise 3-matic software (Materialise, Leuven, Belgium) is used to fully reconstruct the morphology of the aortic root and the distribution of the calcified areas. Different colors are used to differentiate the parts in the digital model that exemplify the multidimensional structural information, such as the morphology, distribution, and junctions of each part. The digital model is then exported into Standard Tessellation Language format. Finally, the Standard Tessellation Language files are imported into a Polyjet 850 multimaterial full-color 3D printer (Stratasys, Inc., Eden Prairie, MN, USA). Different materials are selected to represent the different tissues [20–22] (Fig. 1).

Pulsatile Platform for the Simulation of Transcatheter Aortic Valve Replacement

Conventional *in vitro* tests rely on static models that do not truly reflect the pathophysiological characteristics of the heart. By assembling a pulsatile platform for simulation, the individual 3D printed models of the aortic root and adjacent tissues are used to simulate cardiac motion in the diseased structures [23,24]. The 3D printed models, such as those for aortic stenosis with calcification and aortic valve prolapse with regurgitation, closely simulate the actual physiological environment. At the same time, measurements are taken using high-speed cameras, X-ray equipment, and echocardiography to simulate TAVR and to obtain data similar to the clinical data. Data analysis and comparisons may optimize all aspects of the TAVR procedure, including the hemodynamic characteristics of the aortic valve (e.g., incomplete valve expansion due to valve calcification), further improving the efficacy and reliability of the operation. The platform may help young clinicians develop an intuitive understanding of TAVR, rapidly improve their learning curves, and avoid the occurrence of future complications [25–27] (Fig. 2 and **Supplementary Video 1**).

Current Teaching and Training Applications in Transcatheter Aortic Valve Replacement

3D printed models of different types of aortic valve diseases are used to educate and train young clinicians and medical students to fully appreciate the reconstructed anatomical structures of the aortic root prior to the procedure and to practice procedural simulations using the models. Applying 3D printing in TAVR for the evaluation of complications is a new concept [28,29]. It is of great significance in helping young clinicians and medical students understand the structural changes that can occur in various types of aortic valve diseases and to deepen their knowledge of the anatomical and pathophysiological characteristics of diseases. In addition, it contributes to reducing the use of experimental animals and improving animal welfare.

Morphology Teaching

An accurate understanding of aortic valve diseases is essential for diagnosis and treatment. The teaching of valve morphology has traditionally relied mainly on the observation of pathological specimens removed from deceased patients or of heart transplants. Although the surgical outcomes continue to improve, sources of new specimens are becoming increasingly rare due to the ethical and legal issues associated with retaining human or body parts for educational purposes [30]. Unlike actual specimens that can be cut into a limited number of dissections, the 3D printed models can be replicated in any number of dissections to fully demonstrate the complex anatomical structures and

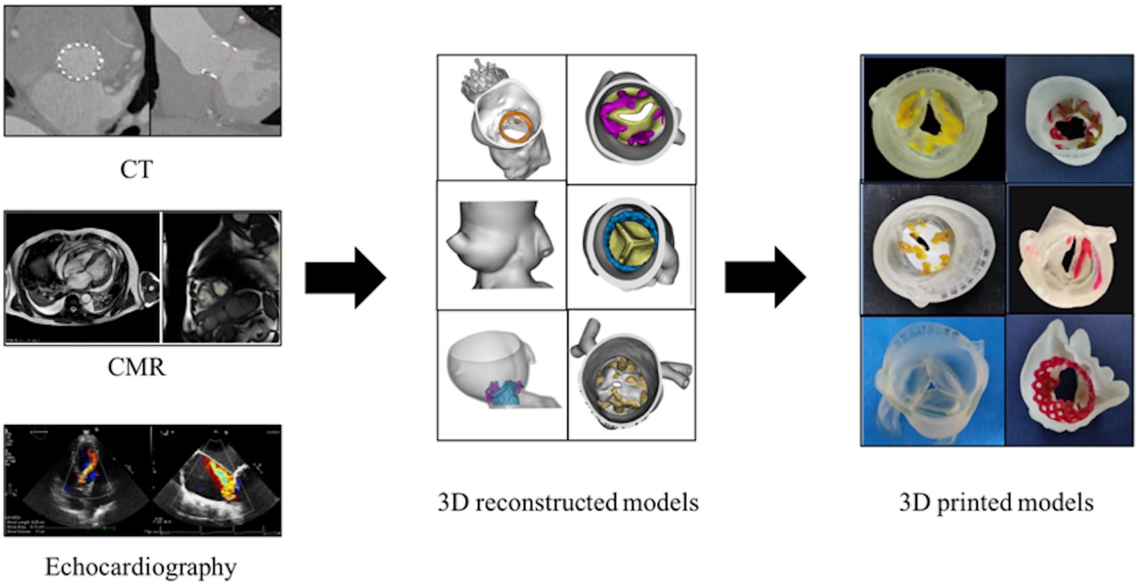

Fig. 1. The printing process for 3-dimensional models. CT, computed tomography; CMR, computed magnetic resonance; 3D, 3-dimensional.

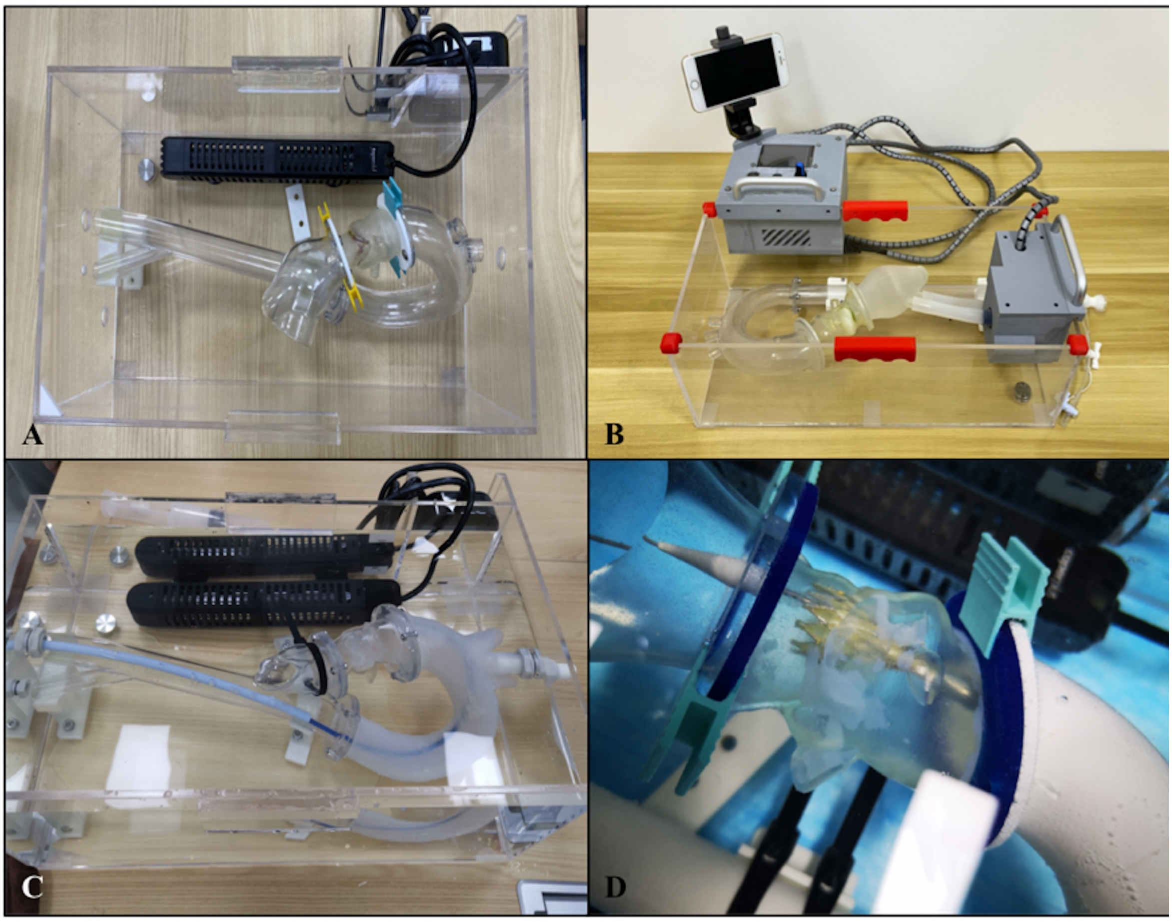

Fig. 2. The pulsatile platform for the simulation of transcatheter aortic valve replacement (TAVR) using 3-dimensional printed models. (A) Multiapproach TAVR simulator; (B) Transcatheter femoral artery TAVR simulator; (C) The TAVR simulation process; and (D) Stent expansion.

Fig. 3. Teaching by using 3-dimensional (3D) printed models. (A) An experienced physician teaches young clinicians about the morphology of the aortic root using a 3D printed model. (B) An experienced physician teaches trainees using a model combined with echocardiography.

thus provide a more intuitive understanding of the aortic root, including its morphology, size, and position; the structures of the adjacent tissues; and clear examples of aortic valve stenosis or regurgitation, leaflet calcification, and the distribution of calcification (Fig. 3).

Surgical Simulation

TAVR training is very important for the growth of young clinicians. With the rapid development of imaging, bioengineering, and digital modeling, a training system based on 3D printing provides more training opportunities. Through virtual surgical design and hemodynamic simulation, 3D printing can display and predict quantitative changes in hemodynamic parameters during surgery, providing reliable information for reducing surgical risks. As 3D printing continues to improve, the individualized aortic root model can be printed, allowing trainees to obtain an intuitive impression of the anatomical structures of a specific patient.

To closely simulate TAVR, the aortic root model is placed in a pulsatile platform. From there, all kinds of connections and covert attachments are established to formulate a TAVR training device. Young clinicians may use the device to practice skills such as threading across the annulus, exchanging the guidewire, and positioning the stent, all of which will improve operating skills and proficiency to promote more rapid movement along the learning curve (Fig. 4 and **Supplementary Videos 2,3**).

Preprocedural Planning

3D printing is not only consistent in its production of surgical models but it also provides a new approach for surgical training. The individual model printed by 3D reconstruction may assist doctors in understanding the patient's individual anatomical structures more intuitively and provide clinical help for determining the patient's preprocedural planning. Olivieri *et al*. [31] reported that different types of stents were tried on the 3D printed model before the operation for a patient diagnosed with complete transposition of the arteries accompanied by right pulmonary vein obstruction. Appropriate stents were selected for successful treatment due to the advantages of clearly displaying the positions of the arteries [31], which led to successful treatment outcomes. Hermsen *et al*. [32] used the 3D model of hypertrophic cardiomyopathy to simulate the operation.

Prediction of Transcatheter Aortic Valve Replacement Complications

Paravalvular Leakage

Paravalvular leakage refers to the regurgitation of blood flow to the left ventricle during ventricular diastole, which is one of the most common complications after TAVR [33]. Qian *et al*. [34] successfully used the 3D printed model of the aortic root to predict the incidence of paravalvular leakage during TAVR [35,36]. Preprocedural simulation with the 3D printed model of the aortic root can accurately show the position and severity of the possi-

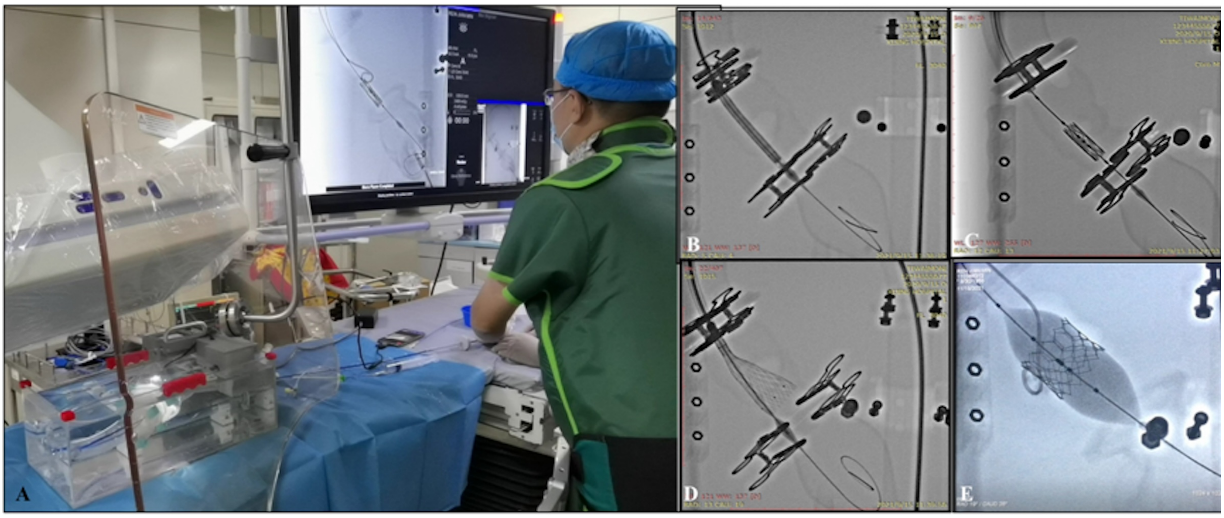

Fig. 4. Simulation of transcatheter aortic valve replacement (TAVR) in the catheterization laboratory using the 3-dimensional (3D) printed models, the pulsatile simulator, and different TAVR devices. (A) An experienced surgeon demonstrates the simulated TAVR procedure. (B) A simulating device passes through the 3D printed model using a self-expandable TAVR system. (C) A simulating device passes through the 3D printed model using a balloon-expandable TAVR system. (D) Simulating the release of the TAVR device in the 3D printed model using a self-expandable TAVR system. (E) Simulating the release of the TAVR device in the 3D printed model using a balloon-expandable TAVR system.

ble paravalvular leakage, which may help young clinicians choose different types of prosthetic valves (Fig. 5A,B).

Conduction Block

After TAVR, the atrioventricular conduction system at the junction between the right coronary sinus and the non-coronary sinus may be continuously suppressed or permanently damaged due to displacement of the calcification, and the prosthetic valve may also damage the conduction system, which is positioned in the interventricular septum. Therefore, 3D printing can be used to print a model of aortic stenosis with the calcified areas, which, when combined with the measured data, can be used to choose the correctly sized balloon-expandable valve to help young clinicians estimate the migrated direction of the balloon. Rocatello *et al*. [37] demonstrated that 3D reconstruction of the aortic root is clinically significant because it reduces the incidence of postprocedural conduction block. In addition, different stents could be selected to simulate TAVR, stents which, when influenced by calcification, could be observed to migrate in a particular direction. The young clinicians could then estimate the probability of conduction block (Fig. 5C,D).

Coronary Obstruction

Coronary obstruction refers to the phenomenon of myocardial infarction after the stent exerts pressure on the valve or on the calcification to the coronary artery after TAVR or during the long-term follow-up period. Heitkemper *et al*. [38] showed that reconstructing the aortic root by 3D printing preoperatively allowed them to demonstrate the distribution of the calcification to avoid the occurrence of coronary obstruction [39]. For patients with a high risk of coronary obstruction, 3D printing can be used to print the aortic root model, and the model could be used to simulate balloon expansion *in vitro*, which may help young clinicians estimate the possibility of coronary obstruction after TAVR (Fig. 5E,F).

Vascular Complications

The approaches for TAVR are now mainly divided into the peripheral vascular approach and the apical approach, among which the femoral artery approach has the advantage of a convenient operation and fewer complications, thus accounting for more than 90% of the approaches. Under the usual circumstances, patients accepting TAVR treatment may have atherosclerosis, calcification, and even, in severe cases, porcelain aorta. These patients are prone to develop vascular complications and other serious consequences when undergoing TAVR via the peripheral vascular approach [40]. As a result, simulation using the preprocedural 3D printing model may remind clinicians to perform the balloon expansion first and TAVR later. Ovcharenko *et al*. [41] used a phantom of the vascular system to simulate all stages of delivery system movement along the vascular bed, and the numerical analysis was used to assess the force arising from the passage of the delivery system. Similarly, Rotman *et al*. [42] reported a novel benchtop patient-specific arterial replicator designed for testing TAVR and

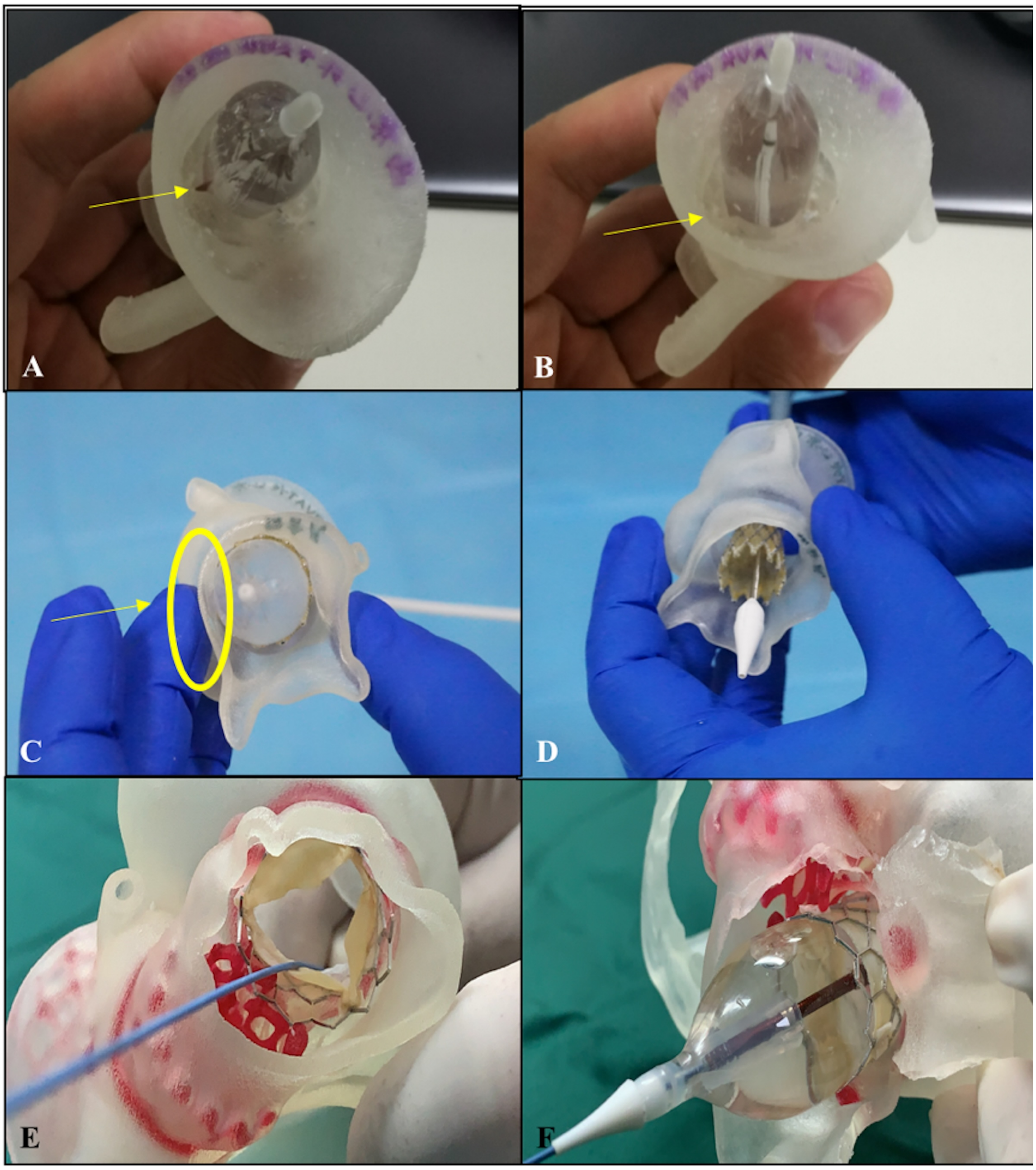

Fig. 5. Prediction of transcatheter aortic valve replacement complications using 3-dimensional printed aortic root models. (A) The 20-mm balloon is expanded in the model; the paravalvular leakage is observed (the yellow arrow). (B) The 23-mm balloon is subsequently expanded in the model, and the paravalvular leakage disappears (the yellow arrow). (C) The yellow circle, which is located between the anterior leaflet of the mitral valve and the membranous part of the interventricular septum, is the possible area of the conduction block. (D) Different sizes of stents are used to ensure the migrated direction of the balloons and then to estimate the position of the conduction block. (E,F) The balloon is expanded *in vitro* to estimate the position of the coronary obstruction.

training interventional cardiologists, which showed the efficacy and reliability in procedural testing. Therefore, 3D printed simulator may be used as an accurate model for surgeons to understand anatomical difficulties and plan procedural strategy.

Discussion and Current Limitations

Studies have shown that among junior residents, selection of a surgical career is most heavily influenced by hands-on participation and positive guidance within a field [11–19,43–45]. Simulation has been used in other fields to provide medical students with early hands-on exposures

[46]. The benefits of simulation-based training have been demonstrated by a meta-analysis, the results of which indicated that the training method used could reliably influence outcomes related to trainees' knowledge and skills [47]. Patient-related outcomes could also be influenced by the training method [47].

Schmauss *et al*. [48] first reported TAVR guided by 3D printing in 2012. Evidence-based studies have clearly suggested the following: First, 3D printing can be used to reconstruct the anatomy of the aortic root realistically, and preprocedural simulations may effectively avoid the complications of TAVR, such as paravalvular leakage, coronary obstruction, and conduction block. Second, the 3D printed models can effectively simulate hemodynamic parameters to provide a more realistic platform *in vitro* for product testing and development. Finally, the simulations based on the 3D printed models may effectively improve the learning curve. As TAVR continues to improve, 3D printing is being used widely in the development of TAVR, device testing *in vitro*, simulation training, preprocedural evaluation, and other aspects with the advantages of reconstructed, realistic aortic root anatomical structures. At present, composite materials (such as silicone, resin, polyethylene, and rubber materials with different levels of hardness) are used to print the aortic root model, which can effectively simulate both the elastic valve structures and the rigid calcification structures. In addition, the nature of the 3D printed models enhances a clear understanding of the anatomical structures and minimizes the risk of misunderstandings. The use of simulators has become a way for trainees to practice in a safe, low-pressure environment outside the operating room [49]. Studies have demonstrated that simulators have been remarkably successful in increasing medical students' interest in general surgery and vascular surgery [45,50]. The 3D printed models provide opportunities for simulation of procedures that are not available on other platforms. Simulations are now more commonly incorporated into residency programs to promote improvement of young clinicians [51,52].

However, promoting the teaching and training of TAVR with the guidance of 3D printing may encounter some of the following difficulties: (1) Simulating TAVR is relatively complex because of the specific 3D printing requirements, i.e., a combination of different materials and multiple colors. (2) Teaching and training TAVR guided by 3D printing requires the cooperation of participants from multiple disciplines, a situation that is generally lacking at present. (3) 3D printing machines and materials are expensive. (4) The commercial application of 3D printing in TAVR needs to be expanded.

Future Directions

Cardiovascular Bioprinting

The application of 3D printing in the cardiovascular field is the printing of cardiovascular cells and tissues, known as bioprinting. The material used is bio-ink, not traditional materials. The researchers extracted stem cells from the human body, which were differentiated into different types of other cells, combined with hydrogel matrix and other structures for printing *in vitro*. Recently, a breakthrough has been made in the research on the strong and tough bonding of hydrogels, the basic principle of which is the synergistic effect of interfacial covalent bond, polymer network topology and adhesive energy dissipation [53]. In addition, various strong hydrogel composites have been prepared to simulate the structure of human tissues [54]. Yang *et al*. [55] produced heterogeneous hydrogel composites using stereolithography technology, which showed high fatigue resistance.

Personalized Treatment Device

3D printing technology is one of the most important technological breakthroughs of this era. The characteristics of individual customization allow 3D printing to benefit the manufacturing of cardiovascular implants. Guided by the new patient-centered medical model, it is highly possible to introduce 3D printed implants in the cardiovascular field in the future. With the rapid development of 3D printing technology and material science, including the dynamic 4-dimensional (4D) printing technology in recent years, on the basis of fully simulating the anatomical structure and function of the aortic valve, dynamic stereoscopic deformation and other features, TAVR treatment devices customized according to the functional characteristics of the anatomical structure of patients will also become an important development trend in the future [56,57]. The promising methods can simulate the performance of a range of bioprosthetic valves in a patient-specific left heart environment, which may be possible to customize the TAVR treatment device to lay the foundation of the methodology.

Fluid Mechanics and Fluid-Structure Coupling

The application of computational fluid dynamics and fluid-structure coupling modeling in the structural and functional evaluation of aortic valve was realized by the integration of 3D printing technology and computer simulation. The inclusion of computational fluid dynamics in a CT-derived three-dimensional computational model can evaluate and quantify the pathophysiological status of the aortic valve and specific treatment objectives. The finite element models for simulating the structural dynamics and the fluid structure interaction methods for simulating the performance of bioprosthetic valves may pave the way toward clinically relevant computational models and make it possible to solve important algorithm and model validation challenges that need to be solved in the future. The establishment of this kind of model can also be used to evaluate the influence of the selection of aortic valve interventional therapy instrument types, models and implantation depth on hemodynamics, so as to evaluate and predict the treatment prognosis, including postoperative regurgitation, perioperative complication prediction and patient prognosis assessment, and even future valve durability prediction [58].

Virtual Reality and Holograms

3D printing, combined with virtual reality and hologram technology, is an important progress of digital simulation technology. It is of great help to surgeons to fully understand the details of the structure. In the previous study, Butera *et al*. [59] reported a holographic augmented reality and 3D printing for surgical management, which could successfully provide the preoperative plan for percutaneous management of abnormal pulmonary venous return. It is a new image mode which is different from the traditional diagnostic image method. In particular, the combination of 4D dynamic image simulation enables surgeons to have a fuller understanding of the structure and function of the aortic root, achieve accurate stereoscopic measurement and dynamic measurement of different phases, and make surgical plan design, instrument type and model selection, and complication prediction more accurate, which is conducive to improving the success rate of surgery, shortening the operation time and improving the prognosis of patients [60].

3D Real-Time Image Fusion

Real-time image fusion technology can assist surgeons in accurate positioning and save operation time. However, the current image fusion technology, no matter 3D CT and fluoroscopy fusion, or 3D ultrasound and fluoroscopy fusion, still has many problems to be solved, including accurate correspondence, dynamic fitting and so on. With the further development of 3D printing and imaging technology and computing technology in the future, there will certainly be more accurate, three-dimensional and higher-fitting operating platforms. Vernikouskaya *et al*. [61] reported patient-specifically co-registration procedures for image fusion of preprocedural CT datasets with real-time X-ray fluoroscopy during TAVR, which improved the performance of procedures and effectively reduce the procedural time, fluoroscopy times, radiation dose and contrast agents. This will provide more auxiliary support for the operation of the surgeon, especially to obtain ideal intraoperative positioning, surgical design and other visual scenes, so as to benefit more patients.

Artificial Intelligence

The potential adaptability of Artificial intelligence (AI) and Deep learning (DL) simulations to measure key positions in the aortic root makes them likely to be the basis for new technologies to flourish in the future. By integrating a complete heart valve model into preoperative evaluation and simulation, AI can significantly improve the surgeon's confidence in the operation of surgical instruments and the application of intraoperative techniques. In Wang *et al*.'s [62] study, they developed a novel algorithm which could perform preprocedural assessments by using CT scans and improve evaluation efficiency compared to observers. In the DL framework, AI is applied in intraoperative image processing to allow the computer to evaluate and feedback the quality of medical images obtained automatically and objectively, which is conducive to improving the success rate of surgery and the prognosis of patients [63].

Conclusion

In summary, 3D printed models of the aortic root can realistically reflect its disease states. 3D printing is bound to play a more important role in pre-TAVR simulations due to its significant advantages, especially greater progress will be made in preprocedural training and prediction of complications for surgeons. The use of simulators by young residents and medical students to acquire knowledge and enhance practical experience through educational activities may have an impact on shortening the learning curve.

Availability of Data and Materials

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author Contributions

YM, YYM and MGZ made substantial contributions to the conception and design of the work; JY and YL made substantial contributions to the design of the work. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript. All authors have participated sufficiently in the work to take public responsibility for appropriate portions of the content and agreed to be accountable for all aspects of the work in ensuring that questions related to its accuracy or integrity.

Ethics Approval and Consent to Participate

Not applicable.

Acknowledgment

We would like to thank Make Medical Technology Co., Ltd. (Xi'an, China) for supplying the 3D printed models.

Funding

This work was supported by the National Key R&D Program of China (2020YFC2008100); the Development and Transformation of New Technology and Construction of Precision Diagnosis and Treatment System for Transcatheter Interventional Diagnosis and Treatment of Structural Heart Diseases (2022YFC2503400); and Research on Key Techniques of Minimally Invasive Treatment for Valvular Heart Diseases (2023-YBSF-105).

Conflict of Interest

The authors paid the corresponding amount for each 3D-printed model made by Make Medical Technology Co., Ltd. (Xi'an, China). The authors declare that no conflict of interest between the company and the authors.

Supplementary Material

Supplementary material associated with this article can be found, in the online version, at https://doi.org/10.59958/hsf.7177.

Video 1. The transcatheter aortic valve replacement pulsatile simulator is used to train main procedures before the operation.

Video 2. The crossing-valve procedure was simulated by surgeons.

Video 3. The TAVR procedures could be simulated by using the model and the simulator vividly, and the accuracy of simulation could be verified by digital subtracted angiography.

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