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REVIEW

Cardiovascular Three-Dimensional Printing in Non-Congenital Percutaneous Interventions

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Three-dimensional (3D) printing technology is emerging as a potential new tool for the planning of medical interventions. In the last few years, increasing data have accumulated on its ability to guide interventional cardiology procedures, going beyond initial reports in congenital heart disease settings. In fact, there is compelling evidence on the advantages of a 3D-printed guided strategy for left atrial appendage closure, suggesting a high success rate with optimal device selection and lower radiation load. Furthermore, there is emerging experience in aortic root printing, which may improve the success rate and safety of transcatheter aortic valve replacement and may be of particular interest for targeting low-risk populations. Additionally, there are stimulating reports in mitral valve intervention, setting the tone for this new field in cardiovascular percutaneous intervention. In this clinically oriented paper, we will review current 3D printing use in interventional cardiology and we will address future directions, with a focus on procedural planning and medical simulation.

Keywords 3D printing • Percutaneous coronary intervention • Simulation training • Structural heart disease

Introduction

Three dimensional (3D) printing is emerging as a new tool for the diagnosis of several diseases and planning of medical procedures [1]. This technique is used to transform digital objects into physical models, providing not only improved anatomical visualisation compared with 3D imaging, but also a tactile experience.

Its use in the medical field has been steadily rising, particularly in surgical practice and in translational research. In 2016, a systematic literature review on 3D printing in medical practice reported that 45.2% of papers were on orthopaedics. Cardiovascular medicine accounted only for 3.5% of publications at that time [2]. That initial experience mainly concerned complex congenital heart disease and 3D-printed models were regarded as valuable instruments to plan interventions [3].

However, there is increasing interest in using this technology for guiding non-congenital interventional cardiology procedures and, accordingly, the number of publications in structural intervention is rising. In this clinically oriented paper, we will review current 3D printing applications in non-congenital interventional cardiology and we will address future directions, with a focus on procedural planning and medical simulation.

Fundamentals of Three-Dimensional Printing in Cardiovascular Medicine

The 3D printing process comprises several steps (Figure 1) that begin with volumetric image acquisition. Computed

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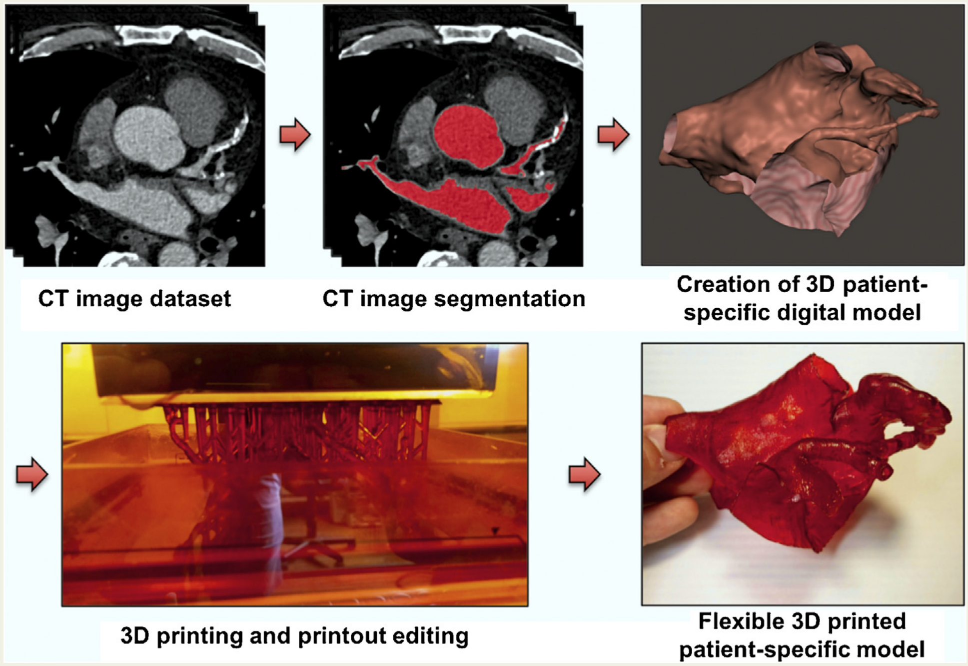

Figure 1 Three-dimensional (3D) printing workflow. Computed tomography (CT) imaging acquisition, followed by segmentation of the volume of interest (left atrial appendage and circumflex artery), high-resolution 3D printing with a stereolithography printer with the creation of a flexible 3D patient-specific model.

tomography (CT), magnetic resonance imaging, or 3D echocardiography datasets are the most frequently used modalities [4]. However, a 3D angiography volume may be obtained from a rotational angiography acquisition or from software-based reconstruction of planar angiographic images. These later modalities offer the advantage of being obtained locally in the catheterisation laboratory. However, one should bear in mind that the quality of the final 3D model will largely depend on the quality of the image dataset. Therefore, image acquisition is a critical step in obtaining high-quality, accurate 3D prints of cardiovascular structures.

Advanced visualisation of the cardiac structures in a computer system is possible using volume-rendering software features. However, it is necessary to select and separate the cardiovascular structure of interest, a process called segmentation. Image segmentation may be a manual or automatic process but, in clinical practice, a combination of both is usually used [5]. The next step is to convert the segmented volume to a 3D digital model. Usually, a Standard Tessellation Language (STL) file is generated. Postprocessing using STL editors is usually required, as the segmentation process creates some artefacts, as well as occasional holes within the mesh [6]. Luminal vascular structures are frequently the target for segmentation as intravascular contrast outlines cardiac cavities with great detail. In this case, there is an additional step to offset the mesh, which represents the lumen, in order to simulate the vascular or cardiac walls. Then, the file can be sent to a 3D printer.

There are multiple 3D printing techniques allowing for the model to be flexible or rigid. A detailed discussion is beyond the scope of this review. Briefly, the most accurate techniques include selective laser sintering (SLS), stereolithography (SLA), and material jetting. The two latter technologies use photopolymeric resins and ultraviolet (UV) light to cure the plastics additively. In SLA, there is a set of dynamic mirrors which direct a UV laser onto a resin bed, curing a specific cross section layer by layer. Material jetting applies the technology used in ink-jet printing to deposit small amounts of UV photocurable plastic resin in layers. Several print heads can simultaneously print different colours and materials, including support structures. The SLS technology uses a laser to melt a layered bed of powder in the shape of the 3D object. Fused deposition modelling 3D printing technology, which uses a fused filament of plastic deposited layer by layer, is widely available, but limitations in resolution and dimensional accuracy may be troublesome for medical use [6].

The 3D printout can then be used in different ways: as the final product or as a mould, requiring a coating that is the definite anatomical structure. Additionally, 3D modelling software can be used to add functional mechanical parts to the 3D-printed models, which may allow the connection of the printout to a system of tubes, for simulation purposes.

Left Atrial Appendage Occlusion

Left atrial appendage (LAA) occlusion is the interventional cardiology field where 3D printing has been used most extensively. This is because of the complex and highly variable LAA anatomy and owing to the importance of accurately sizing the occluder device in order to avoid leaks and procedural complications. Device sizing is usually done using angiography, angio-CT, transoesophageal echocardiogram (TOE), or a combination of these latter techniques for a multimodality imaging approach. However, 3D-printed models may provide better preprocedural planning with in vitro testing of several sizes of occluder devices in order to achieve optimal LAA exclusion, proper compression, and to avoid leaks (Figure 2). Additionally, the best location to perform the transseptal puncture may be tested using the 3D-printout-guided approach. Although CT-derived segmentation is the most commonly used method to produce the 3D printout, some authors have used 3D-TOE images to build the final model.

Initial reports using 3D printing showed its utility and feasibility using the Watchman device (Boston Scientific, Marlborough, MA, USA), namely by imaging the 3D model after deployment of different devices in order to select the optimal deformation required [7]. It was also useful in complex anatomies such as occlusion of a double-lobed LAA [8] and small LAA [9]. Complex anatomical settings have also been the target of 3D printing using the Amplatzer Amulet device (Abbott, Abbott Park, IL, USA), in which the 3D-printed model allowed not only a better selection of the device, but also the swift management of a device leak [10].

In a recent feasibility study of 29 patients scheduled for LAA closure, CT-based 3D-printed models were retrospectively assessed by three interventional cardiologists in order to predict the occluder size used in the actual procedure [11]. Interestingly, all physicians predicted anatomical device mismatch that led to the aborted procedures (n = 2).

Small prospective trials using 3D printing technology to guide LAA occlusion have recently been published. The use of 3D-printed models to guide LAA occlusion using the Watchman device was tested in a single-centre study of 22 patients [12]. Briefly, an interventional cardiologist blinded to TOE and CT-based LAA sizing, deployed devices in a 3D model (CT-based, silicone material), selecting the device that provided optimal anchoring. Then, the procedure was undertaken using the information provided by the 3D-printed guided tests. There was a 95% (n = 21/22) agreement between the predicted size by 3D modelling and the inserted device, while TOE and angio-CT agreement were 55% and 77%, respectively. In another single-centre trial, 42 patients were randomly assigned to LAA occlusion guided by 3D printing or standard methods (TOE, CT, angiography) [13]. The device size in the 3D group

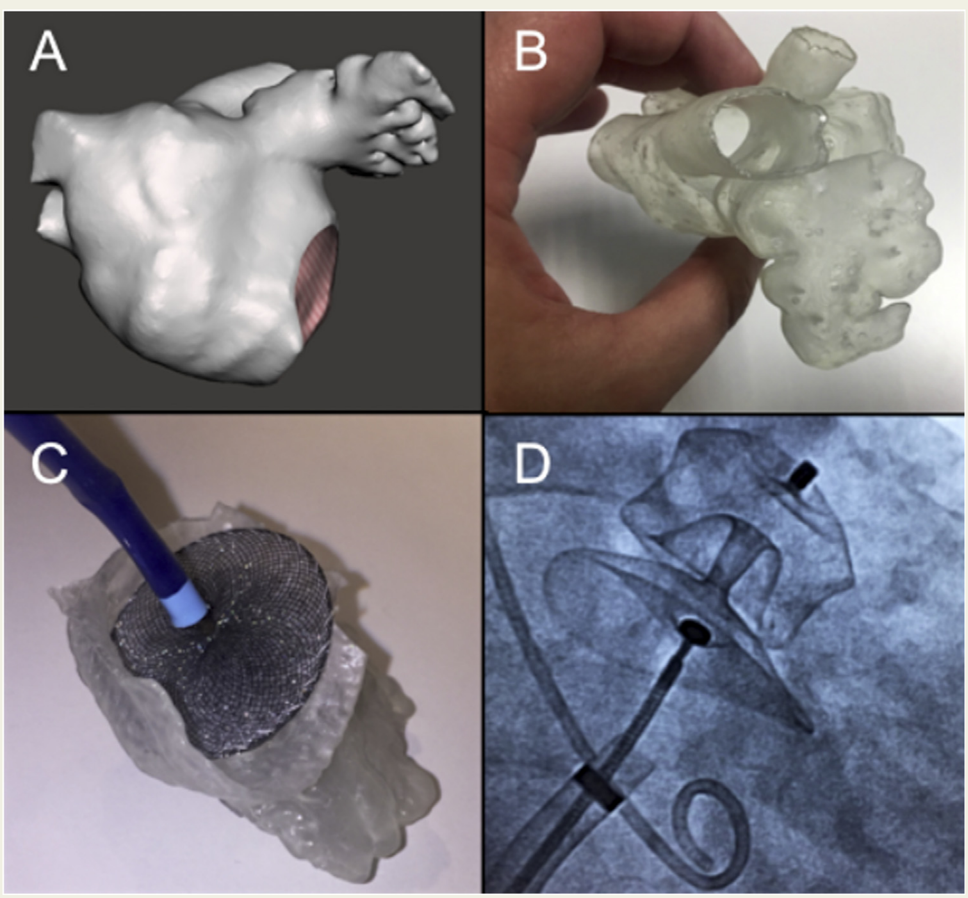

Figure 2 Left atrial appendage (LAA) closure. A shows the three-dimensional (3D) digital model of the left atrium of a patient scheduled for LAA occlusion. B shows the 3D-printed left atrium. C shows Amplatzer Amulet testing in a flexible 3D-printed LAA and D shows the Amulet placement procedure.

(n = 21) was significantly larger than suggested by angiography. Importantly, the authors reported successful implantation in all patients, without any complication. In the TOE follow-up there were no leaks in the 3D group, while there were three mild leaks in controls. Also, the radiation dose was significantly reduced in the 3D group.

More recently, a single-centre group randomised 24 patients to 3D-CT or TOE-guided LAA occlusion with the Watchman device [14]. The 3D-CT (n = 12) protocol included 3D printing to choose the delivery catheter. Three-dimensional–CT guidance was associated with improved first device selection accuracy (90% vs 27%) and procedural efficiency (reduced number of devices and catheters, procedure time 55 ± 17 vs 73 ± 24 min). These results are in line with the experience from an European centre that conducted both retrospective and prospective analysis on the added value of CT-based 3D-printing on top of conventional imaging-guided LAA closure with the Amplatzer device [15]. In a retrospective study of 55 patients, the mismatch between the 3D model and device was the best predictor of leakage (area under the curve 0.88 vs 0.53 and 0.60 for CT and TOE sizing, respectively). For the prospective non-randomised series comparing 3D printing-guided (n = 21) and conventional imaging (n = 51), there was a significant reduction on the number of devices used, leakage detection, procedural time, and radiation dose (see Table 1). Although previous studies showed a slim reduction in radiation with a 3D-printing strategy, this group reported a robust threefold decrease in fluoroscopy dose (median, 1978 vs 7921 mGy·cm^2), which can be significant in terms of safety not only for the patient, but particularly for the busy interventional team. Moreover, as the authors printed a model including the interatrial septum, they realised that in up to half of the anatomies a different transseptal puncture location other than the usual postero-inferior was more useful to avoid an off-axis device position, which was, indeed, significantly reduced in the prospective series (5 vs 25% in the retrospective series; $p < 0.01$).

Although these results look promising, larger, multicentre trials are warranted to investigate the role of 3D-printed models in device sizing for LAA occlusion. The time and resources expended on 3D modelling are not trivial, and even though it is an appealing concept, cost-effectiveness analyses are important to appraise the applicability of this concept. Also, several techniques have been used to obtain 3D printing models of LAA and comparison between them is lacking. However, this technology offers a personalised approach to the procedure, potentially increasing efficiency in device selection and decreasing the invasiveness of the technique. Regarding the latter, careful planning with CT-based models, in association with device delivery guided by intracardiac echocardiography [16], might obviate the need to perform TOE, and therefore tracheal intubation and general anaesthesia.

Aortic Valve Intervention

Transcatheter aortic valve replacement (TAVR) is a cornerstone of structural intervention in modern cardiology centres. To achieve a successful result, it is key to characterise the aortic root anatomy and choose the best device (type and size) to avoid complications. In particular, perivalvular leakage (PVL) is more common than surgical replacement and is associated with increased mortality [17].

In this context, 3D models of the aortic root and valve can be printed in order to better understand the anatomy and aid in the preparation of the TAVR procedure [18], especially in cases of complex vascular anatomy, when complications are more frequent (Figure 3) [19]. The anatomical and functional properties of severe calcific aortic stenosis can be accurately modelled in three dimensions, as shown in a study of eight patient-specific printouts, which included dynamic measurements of gradient and valve area with excellent correlation to in vivo measurements [20,21]. In a validation study, there was a good agreement of the aortic annulus dimensions obtained in vivo (during surgery) and in a 3D patient-specific phantom, a parameter that is essential for TAVR planning [22].

Moreover, it is possible to test the actual procedure in 3D models to predict complications. Schmauss et al. [23], following a fatal ischaemic complication in a TAVR procedure, printed a 3D model and reperformed the intervention. They realised that the prosthesis was too close to both coronary arteries, which could be avoided by positioning the device as deeply as possible in the aortic annulus. The first study that aimed to predict post-TAVR PVL using 3D printing retrospectively analysed 16 patients implanted with balloon-expandable Sapien valves (Edwards Lifesciences, Irvine, CA, USA) [24]. After prostheses deployment in the 3D models, light was projected through the left ventricular outflow tract across the valve and recorded in a camera. In cases where gaps existed between the aortic wall and the valve, there was more light projected, and this was used to predict PVL. In this fashion, 3D models correctly identified PVL in six of nine patients and correctly excluded it in five of seven patients, with accurate location of the leak. More recently, another group performed a very elegant retrospective study with the same objectives but using more advanced 3D printing techniques [25]. After a standard TAVR procedure, 18 patient-specific 3D aortic root phantoms were produced and deployed with the same CoreValve (Medtronic, Minneapolis, MA, USA) prostheses to simulate the actual procedure. The printing process was undertaken after semi-automatic CT segmentation using multimaterial 3D printing, accounting for calcification areas. Then, post-TAVR aortic root strain was quantified in vitro. This was accomplished by attaching radiopaque beads to the phantom that served as landmarks for the circumferential strain determination on two CT scans (after and before deployment). Next, a bulge index was calculated to detect areas of focal uneven strain, which was the second-best predictor of significant PVL. Furthermore, bulge index was the only predictor of PVL after balloon postdilatation. The authors concluded that it might be feasible to perform simulations on a 3D-printed phantoms for TAVR planning, especially in those patients who are at high risk for post-TAVR PVL. This technique may refine the

Table 1 List of the main three-dimensional (3D) printing modelling studies to guide percutaneous intervention.

Reference	Objective	Design	3D printing methodology	Material	Main findings
LAA closure					
Hell et al. [12]	Preprocedural device selection (Watchman)	Prospective, single arm, single centre (n = 29)	CT-based, FDM printer	Silicone rubber	95% agreement between the predicted size by 3D modelling vs TOE 55% and CT 77%
Li et al. [13]	Preprocedural device selection (Watchman)	Double-arm randomised trial, single centre, (n = 44), 3D models vs standard LAA measurements	CT-based, SLA printer	NR	Successful implantation (100%); radiation exposure was reduced in the 3D group (561.4 ± 25.3 vs 651.6 ± 32.1 mGy, $p < 0.05$), mild shunting only in control group (n = 3)
Liu et al. [44]	Preprocedural device selection (Watchman)	Prospective, single arm, single centre (n = 8)	3D TOE-based, material jetting	Rubber-like material	100% agreement between 3D model-guided sizing and the selected device
Goitein et al. [11]	3D printing-guided device selection feasibility (Watchman and Amplatzer)	Retrospective single-centre study (n = 29), investigators assessing 3D models were blinded to devices employed in the procedure	CT-based, material jetting	Rubber-like material	3D model analysis predicted all aborted procedures due to anatomy and device mismatch (n = 2); correlation between 3D model-based selection and the employed device higher for Amplatzer (r = 0.78) than Watchman (r = 0.32)
Eng et al. [14]	Device selection accuracy and procedural efficiency (Watchman)	Double-arm randomised trial, single centre, (n = 24), 3D-CT (with 3D printing) guided vs TOE-only guidance	CT-based	NR	3D-CT and control group: single device used 92% vs 27%; 1.3 ± 0.7 vs 2.5 ± 1.2 devices employed, 1 vs 1.7 ± 0.8 guiding catheters: procedure time: 55 ± 17 vs 73 ± 24 min (all $p < 0.05$)
Ciobotaru et al. [15]	Leakage predictors and procedural outcomes (Amplatzer)	Single centre: (a) retrospective analysis of leakage predictors using 3D printing (n = 55); (b) prospective comparison of procedural outcomes with 3D printing-guided vs conventional imaging	CT-based, SLA printer	Flexible photopolymer resin	Best predictor of leakage: mismatch between model and device size; mean prosthesis number 1.05 ± 0.21 vs 1.20 ± 0.52, (p = 0.04); incidence of leaks 5% vs 27% ($p < 0.01$), fluoroscopy time 13.5 vs 19.0 min (p = 0.012)
TAVR					
Ripley et al. [24]	Post-TAVR PVL prediction (Edwards Sapien prosthesis)	Retrospective analysis, single centre (n = 16), prosthesis deployment in patient-specific 3D phantoms	CT-based, SLA printer	Clear, flexible resin, 2 mm thick	3D models dimensions accurate; using a light transmission test, 3D models correctly identified PVL in 6/9 patients and correctly excluded it in 5/7

Table 1. (continued).

Reference	Objective	Design	3D printing methodology	Material	Main findings
Quian et al. [25]	Post-TAVR PVL prediction (Corevalve prosthesis)	Retrospective analysis, single centre (n = 18), prosthesis deployment in patient-specific 3D phantoms	CT-based (semi-automatic segmentation), material jetting	Multimaterial	Bulge index (calculation based on 3D phantom analysis, detects areas of focal strain unevenness in the aortic root) was the second-best predictor of significant PVL after initial deployment and the only predictor of PVL following postdilatation

Abbreviations: LAA, left atrial appendage; CT, computed tomography; FDM, fused deposition modelling; TOE, transoesophageal echocardiography; SLA, stereolithography; NR, not reported; TAVR, transcatheter aortic valve replacement; PVL,perivalvular leakage.

Figure 3 Aortic valve three-dimensional (3D) model. The left image shows the flexible 3D aortic model of a patient scheduled for transcatheter aortic valve replacement. The right image shows the rigid 3D aortic model.

selection of valve type and size and hypothetically reduce the rate of post-TAVR PVL.

In summary, 3D printing is not only a useful tool to visualise complex anatomy, but can also predict, with advanced technology, the occurrence of postprocedural complications. Even though these are preliminary data, it is exciting to consider the potential of 3D modelling in such a vast and important field of percutaneous valvular intervention. A list of modelling studies to guide percutaneous intervention is provided in Table 1. However, we acknowledge some limitations of these interesting proof-of-concept studies. In particular, PVL is being progressively reduced with novel devices, and it can be predicted with good-quality CT; therefore, 3D printing might be less valuable in native aortic valvular disease. Despite this, the proportion of complex procedures will surely increase in the coming years, and the value of this technology should be further studied in some subsets. For valve-in-valve procedures, coronary occlusion is difficult to predict; bench testing with valve implantation in rigorously printed patient-specific 3D models (using advanced multimaterial printers) might be a promising method to minimise risk, by choosing the best device and appropriate implantation depth. In a recent review on device embolisation retrieval techniques, the authors proposed that in vitro 3D testing should be used to avoid embolisation in valve-in-valve interventions [26]. Additionally, challenging anatomies with ''hostile'' annular and subannular calcium might also be previously tested in 3D phantoms.

Other Structural Interventions

Percutaneous mitral valve intervention is challenging because it is difficult to predict how the device will interact with complex native anatomy and if it will actually reduce regurgitation. Therefore, 3D printing methodology might be a powerful aid to such complex procedures [27]. The first report of preprocedural 3D printing to test transcatheter mitral valve intervention was published in 2016 [28]. It was a case of a patient with severe mitral valve regurgitation and posterior leaflet perforation due to endocarditis and prohibitive surgical risk. After successful CT-based multimaterial printing of a model of the mitral valve leaflets and subvalvular calcium, the authors selected the optimal size of an Amplatzer Duct Occluder II (Abbott) to seal the perforation. Then the procedure was performed using the selected device and a MitraClip (Abbott), with good final result.

A research group studied mitral valve apparatus modelling in two patient-specific scenarios—mitral regurgitation amenable to MitraClip repair and mitral valve perforation due to endocarditis scheduled for percutaneous occluder device implantation [29]. Both 3D TOE and CT datasets were used. The authors managed to include the subvalvular apparatus in the printout and used multimaterial 3D printing in order to replicate the mechanical properties of the native valve. These phantoms were used to test several devices. The authors concluded that they were able to replicate the material properties of the mitral leaflets sufficiently well to permit implantation of catheter-based devices and determine the ''best fit''. Hypothetically, 3D printing guidance has greater potential for the subset of mitral valve interventions where there might be interaction with relevant surrounding structures, such as valve-in-valve or de novo mitral valve replacement, in order to study the risk of left ventricular outflow tract obstruction. Preprocedural 3D simulations could therefore improve outcomes by predicting increased risk of complications [26], a hypothesis that should be formally tested in the future.

In addition to the potential reduction of PVL incidence following TAVR when implantation is guided by 3D printing, patient-specific models can offer superior anatomical characterisation of PVL, and contribute to preinterventional planning and device selection (Figure 4). This proof-of-concept use has been recently reported in two complex PVL cases [30].

There are other examples of 3D-printed guided structural interventions. In severe tricuspid regurgitation with right heart failure scheduled to transcatheter caval valve implantation, a preprocedural caval vein model was important to select optimal valve size and attain an excellent final result [31]. Another example is postinfarct ventricular septal defect in a patient at high surgical risk [32]. A 3D model allowed an in vitro trial of multiple devices with variable sizes to assess their fit. The patient was then treated with an Amplatzer PIVSD occluder device (Abbott) with hospital discharge 4 days after the procedure. Also, 3D silicone models of the right heart and tricuspid valve have been developed in order to simulate tricuspid valve percutaneous intervention [33]. This is a novel interventional field that might benefit from precise anatomical characterisation. A group from the Cleveland Clinic published a series of six cases with advanced printing techniques of the right heart, including segmentation based on MRI (due to kidney dysfunction), fusion of CT and TOE images (inability to see tricuspid leaflets on CT), and pacemaker leads printing in order to improve procedure planning [34].

Coronary Intervention

Three-dimensional printing has been infrequently used for planning coronary intervention. However, there is a report of 3D-printed models of complex coronary artery fistulae in four patients, which improved anatomical visualisation and were useful in planning the intervention [35]. Interestingly, an Asian group optimised stent implantation guided by 3D printing, in order to prevent restenosis. Specifically, the authors built a digital coronary model based on angiography, and in addition to testing different stent positions with a computational hydrodynamic model, they validated the results using 3D-printed micro-channels [36]. Coronary

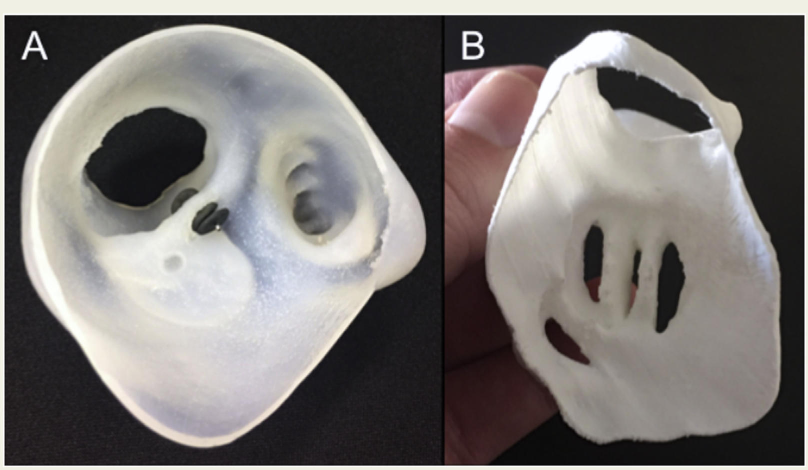

Figure 4 Three-dimensional (3D) perivalvular leak models. A shows the flexible model of a mitral prosthesis perivalvular leak (PVL) with an Amplatzer device (AVP2) in situ. B shows the ventricular view of a mitral PVL in a rigid 3D-printed model.

phantoms offer the possibility of physiological flow simulations for patient-specific anatomies, namely using pumps and pressure sensors [37]. Our group has recently simulated a complex bifurcation PCI in a patient-specific 3D model using a custom-made interventional cardiology simulator to test the strategy beforehand [38]. We noticed a remarkable resemblance between angiographic and optical coherence tomography images of the simulated and real procedure throughout the intervention. This technology may enable the assessment of new devices and could be very useful in the study of bifurcation PCI techniques. As in other clinical scenarios, imaging quality is key. We used angiography-derived 3D data to produce the coronary model, as there are some limitations on CT datasets (e.g., artefacts) that may hamper the accuracy.

Simulation

Three-dimensional model-based simulation may be used for training, individualising medicine, and patient empowerment. In fact, by using simulation in interventional cardiology, the traditional approach "see one, do one, teach one" can be replaced by proper training before engaging in patient management. The Accreditation Council for Graduate Medical Education mandates that cardiovascular fellowship training programs have some component of simulation as part of fellow training [39]. Also, the U.S. Food and Drug Administration considers that simulation training should be part of new procedure device training. However, there are several hurdles in adopting simulation in clinical practice: the high costs, the wide variability among simulation platforms, the lack of standardised

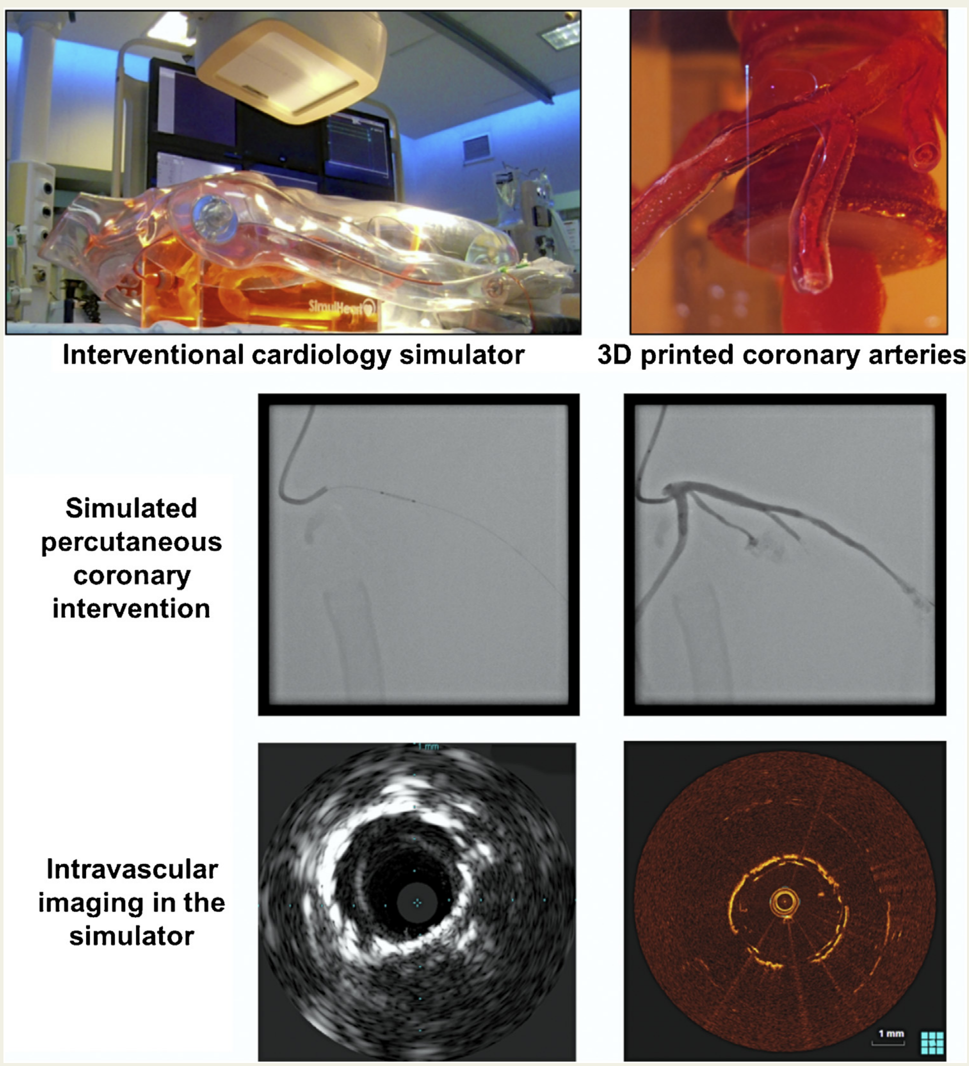

Figure 5 Interventional cardiology simulator. The top images show the custom-made interventional cardiology simulator with radial and femoral access, enabling the use of standard diagnosis and interventional tools, connected to a patient-specific coronary artery flexible model. The middle images show simulated percutaneous coronary intervention and angiography in the catheterisation laboratory. The bottom images show intracoronary imaging in the simulator using intravascular ultrasound and optical coherence tomography.

educational cases, and lack of large-scale trials showing that this technology actually leads to improved operator skills and better patient outcomes [39]. Three-dimensional printing technology can answer at least some of these challenges.

Simulators based on 3D printing offer trainees the opportunity to manipulate standard tools and learn percutaneous intervention skills in a realistic, controlled, and safe setting (Figure 5). In this way, they gain procedural experience, such as learning the sequence of procedural steps and tool selection. Furthermore, 3D models are cheaper than virtual-reality simulators and more practical than cadaveric training. There is indirect evidence from surgical studies showing improved performance of residents during laparoscopic surgery [40]. Recently, Mafeld et al. [41] showed that aortic intervention training in 3D simulators is feasible and operators were highly satisfied with the simulation.

Complex endovascular intervention is an attractive area in which to perform patient-specific 3D model simulation prior to actual treatment. Itagaky [42] treated a multiple splenic artery aneurysm with a 3D-printed model, and then used the same combination of guiding catheter, base catheter, and microcatheter to treat the patient successfully, with a reduced radiation dose [42]. In a more complex case of degenerated aortic sutureless prosthesis planned for valve-in-valve percutaneous treatment, a German group proposed an advanced algorithm that included 3D printing [43]. Using 3D printing technology to simulate the clinical scenario, the authors attained procedural success and maximised patient safety.

Discussion

Three-dimensional printing is gaining relevance in cardiovascular medicine, parallel to the increasing number and complexity of percutaneous procedures. This technology, which was initially restricted to top-notch expert centres when dealing with rare and complex diseases, is now becoming more available and backed up by studies that provide evidence to tackle common, yet complex, percutaneous procedures. Now, there are compelling data on the utility of medical 3D printing to guide LAA closure, achieving a high success rate with optimal device selection and lower radiation load. Moreover, aortic root printing experience is emerging, which may improve the success and safety of TAVR.

However, 3D printing remains a technically demanding technology, which is critically operator-dependent: from image acquisition modality and settings to segmentation methods that rely on subjective visual assessment, choice of materials to mimic the native structure, and different types of bench tests. In this context, it is necessary to standardise the methods. Also, this technique is currently costly: software licences, hours of labour (segmentation, STL rendering, printer programming, bench testing), and printing materials. With top-notch resources and semi-automated methods, time expenditure can be significantly reduced, as reported for TAVR models: 15 minutes to produce the 3D digital model, 10 hours to print 10 models, and $150–200 per phantom printing material. Then, the cost-effectiveness and the added value of these procedures must be investigated in formal trials. Furthermore, time constraints limit the applicability of 3D printing to emergent clinical cases. In our experience, it takes at least 24–48 hours to produce the final patient-specific model, which might be insufficient in emergent settings, such as septum rupture following myocardial infarction.

These limitations will be solved in the future, through both technological advances and growing recognition of 3D printing value in medicine. Specifically, CT scanner technology is improving, with enhanced precision and lower radiation dose. Immediately after acquisition, proprietary automated segmentation software will swiftly generate 3D files ready for printing, with standard materials. We think material choice and postprocessing will still require significant human intervention, especially for simulation purposes. However, the whole process will be easier and faster, which will enable wider application, towards an era of truly individualised medicine.

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Conflicts of Interest

Manuel de Oliveira-Santos, Eduardo de Oliveira-Santos and João Silva Marques are co-founders of a medical three-dimensional printing start-up.

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