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STATE-OF-THE-ART REVIEW

Translating Imaging Into 3D Printed Cardiovascular Phantoms

A Systematic Review of Applications, Technologies, and Validation

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HIGHLIGHTS

- **3D printed patient specific phantoms can visualize complex cardiovascular anatomy**
- **Common imaging modalities for 3D printing are CCT and CMR**
- **Material jetting/PolyJet and stereolithography are widely used printing techniques**
- **Standardized validation is warranted to compare different 3D printing technologies**

SUMMARY

Translation of imaging into 3-dimensional (3D) printed patient-specific phantoms (3DPSPs) can help visualize complex cardiovascular anatomy and enable tailoring of therapy. The aim of this paper is to review the entire process of phantom production, including imaging, materials, 3D printing technologies, and the validation of 3DPSPs. A systematic review of published research was conducted using Embase and MEDLINE, including studies that investigated 3DPSPs in cardiovascular medicine. Among 2,534 screened papers, 212 fulfilled inclusion criteria and described 3DPSPs as a valuable adjunct for planning and guiding interventions (n = 108 [51%]), simulation of physiological or pathological conditions (n = 19 [9%]), teaching of health care professionals (n = 23 [11%]), patient education (n = 3 [1.4%]), outcome prediction (n = 6 [2.8%]), or other purposes (n = 53 [25%]). The most common imaging modalities to enable 3D printing were cardiac computed tomography (n = 131 [61.8%]) and cardiac magnetic resonance (n = 26 [12.3%]). The printing process was conducted mostly by material jetting (n = 54 [25.5%]) or stereolithography (n = 43 [20.3%]). The 10 largest studies that evaluated the geometric accuracy of 3DPSPs described a mean bias $<\pm 1$ mm; however, the validation process was very heterogeneous among the studies. Three-dimensional printed patient-specific phantoms are highly accurate, used for teaching, and applied to guide cardiovascular therapy. Systematic comparison of imaging and printing modalities following a standardized validation process is warranted to allow conclusions on the optimal production process of 3DPSPs in the field of cardiovascular medicine. (J Am Coll Cardiol Basic Trans Science 2022;7:1050–1062) © 2022 The Authors. Published by Elsevier on behalf of the American College of Cardiology Foundation. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

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Three-dimensional (3D) printing, also known as additive manufacturing (AM), is an emerging technology that translates images into physical models. 3D printed patient-specific phantoms (3DPSPs) can visualize complex anatomy, provide haptic feedback, and allow personalized training, planning, and tailoring of interventions.[1-3] Recent refinements in the technology, affordable prices, increasing capacity in image acquisition, and advances in postprocessing have contributed to the growing interest and resulted in many studies' reporting the use of 3DPSPs. The manufacturing processes for 3DPSPs encompass image acquisition, image postprocessing, direct or indirect AM, and validation.[4] Compared with other fields of application in which mostly the pure anatomy is of interest and rigid 3DPSPs are applicable (eg, orthopedic surgery), imitation of soft tissue properties (eg, surface texture, dispensability, puncturing behavior, elasticity) and geometric changes during the cardiac cycle constitute an additional challenge in cardiovascular 3DPSPs, especially if phantoms are used for training of surgery or transcatheter interventions. So far, only a few soft materials are available, and no consensus exists on the optimal choice of imaging modalities, printing techniques, and materials, and thus important obstacles remain to the widespread use of cardiovascular 3DPSPs. Recent introduction of new materials, improved 3D printers, and advanced postprocessing techniques might overcome some of these limitations and merit updated review. In this systematic review our aim is to analyze the entire process of 3DPSP production in the field of cardiovascular medicine, including imaging, materials, printing technologies, and validation (**Figure 1**). Furthermore, current limitations and insights into future directions to improve tissue properties of 3DPSPs are discussed.

METHODS

Two independent reviewers conducted a systematic review in the databases Embase and MEDLINE, using the search items "3D printing," "3D phantom," "rapid prototyping," or "additive manufacturing" plus 1 of the terms "cardiovascular," "cardiac" or "valve," "left atrial appendage," "aortic," or "coronary arteries." Inclusion criteria were the use of at least one 3DPSP in cardiovascular disease between 2005 and April 2021. Included studies were checked for cross-references fulfilling the inclusion criteria. Reviews, conference abstracts, editorials, studies of nonpersonalized models, case reports with ≤5 patients in settings that were previously investigated in larger trials, and bioprinting techniques were excluded (a Consolidated Standards of Reporting Trials flowchart is provided in **Figure 2**). This review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses statement for reporting systematic reviews.[5]

RESULTS

A total of 212 studies were included in this systematic review, in which 1,597 3DPSPs were evaluated (Supplemental Table 1). Purposes of 3DPSPs were planning and guiding of cardiovascular interventions (n = 108 [51%]), simulation of physiological or pathological conditions (n = 19 [9%]), teaching of health care professionals (n = 23 [11%]), patient education (n = 3 [1.4%]), evaluation or optimization of 3DPSP manufacturing processes (n = 14 [6.6%]), outcome prediction (n = 6 [2.8%]), other purposes (n = 3 [1.4%]), and proof-of-concept studies to demonstrate the possibility to manufacture 3DPSPs in specific settings (n = 36 [17%]). The number of studies investigating 3DPSPs continuously expanded over the past 16 years, with more than half of the included studies published within the past 4 years (**Figure 3**). Among the 9 identified randomized controlled trials, 7 were conducted in the field of education and training.[6-12] Results were inconsistent in terms of knowledge gain for students and trainees compared with nonpersonalized models or standard lectures. The only randomized controlled trial investigating the use of 3DPSPs in cardiovascular intervention demonstrated a reduction of intervention time during left atrial appendage occlusion.[13] Across the largest studies, all investigators concluded that the use of 3DPSPs was positive and enhancing in the clinical management of patients with complex geometric cardiovascular conditions.[14-21] Tissue mimicry and poor representation of the cardiac valves were frequently shared concerns, particularly with single-material 3DPSPs.[22]

ABBREVIATIONS AND ACRONYMS

3D = 3-dimensional

3DPSP = 3-dimensional printed patient-specific phantom

AM = additive manufacturing

CCT = cardiac computed tomography

CMR = cardiac magnetic resonance

DICOM = Digital Imaging and Communications in Medicine

FDM = fused deposition modeling

PBF = powder bed fusion

SLA = stereolithography

TEE = transesophageal echocardiography

VP = voxel printing

The authors attest they are in compliance with human studies committees and animal welfare regulations of the authors' institutions and Food and Drug Administration guidelines, including patient consent where appropriate. For more information, visit the Author Center.

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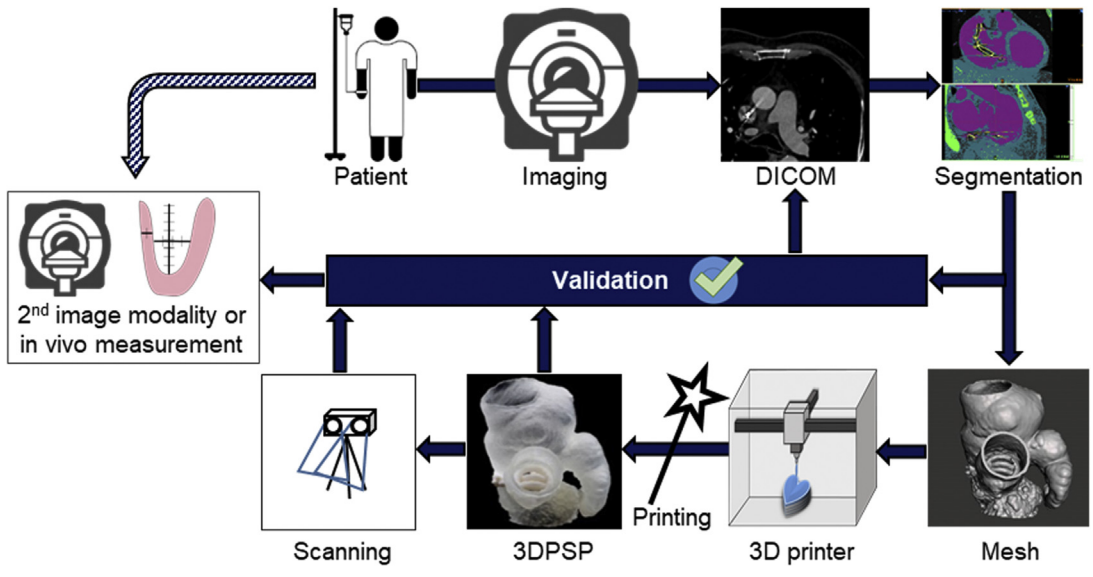
FIGURE 1 Different Steps in the Production of 3DPSPS



3D = 3-dimensional; 3DPSP = 3-dimensional printed patient-specific phantom; DICOM = Digital Imaging and Communications in Medicine.

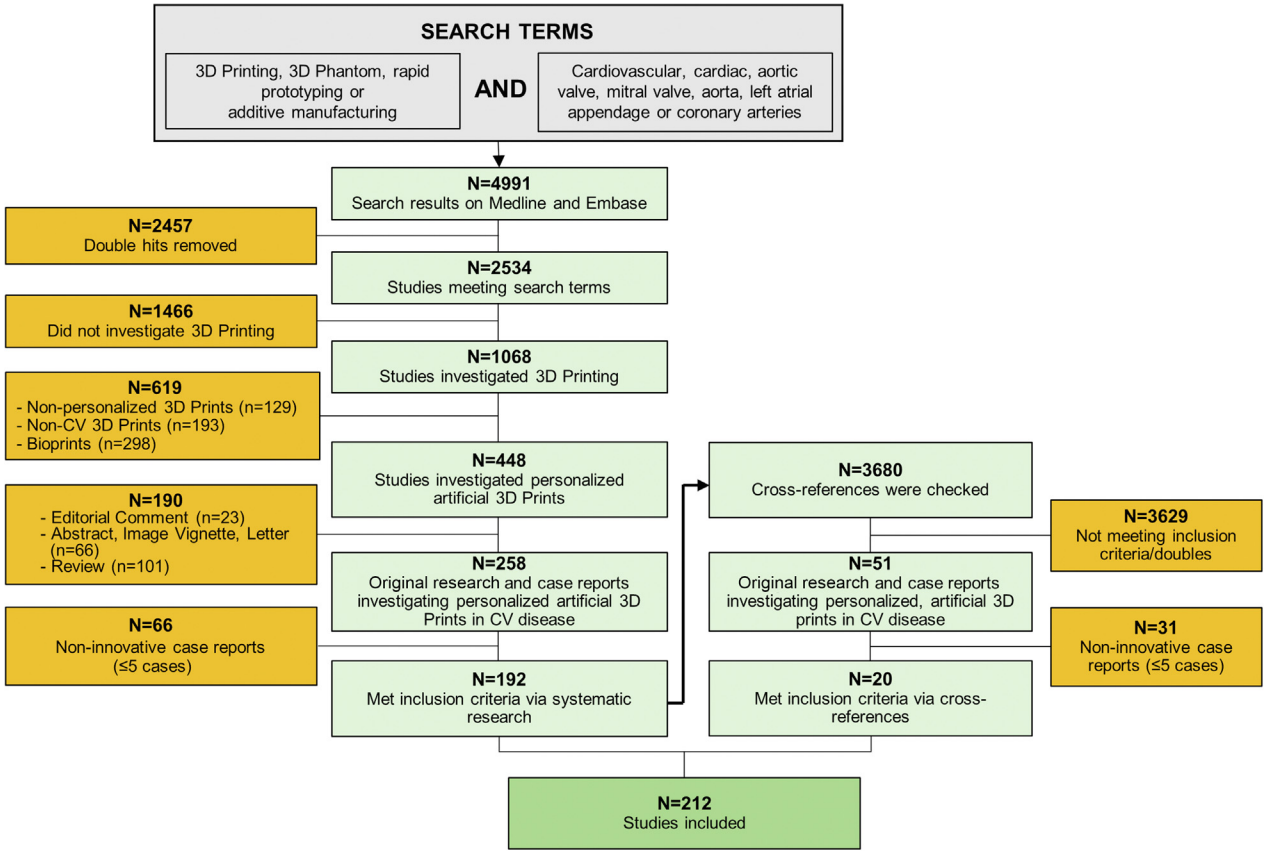
The most common imaging modalities to derive 3DPSPs were cardiac computed tomography (CCT) (n = 131 [61.8%]) and cardiac magnetic resonance (CMR) (n = 26 [12.3%]), whereas 3D transthoracic echocardiography and transesophageal echocardiography (TEE) (n = 23 [10.8%]) and rotational 3D angiography of large vessels (n = 2 [<1%]) were less common. Another 24 studies (11.3%) applied a mixture of modalities across included patients (CCT and CMR, n = 21; CCT and 3D TEE, n = 2; and CCT, CMR, and 3D TEE, n = 1), while 2 studies (<1%) merged data from several modalities; 4 papers (1.9%) did not provide information on the sources of images. Echocardiography-derived 3DPSPs were limited to the depiction of cardiac valves (n = 16),[23-34] ventricular or atrial septal defects (n = 3),[26,35,36] the left atrial appendage (n = 3),[17,37,38] or fetal hearts (n = 1).[39]

Across the 166 reviewed studies that provided data about their preferred printing techniques, material jetting, synonymously described using the trade name PolyJet (Stratasys), was the most common printing technology, with 54 papers (25.5%) reporting its exclusive use (**Central Illustration**). Stereolithography (SLA) was the technology of choice in 43 studies (20.3%), whereas fused deposition modeling (FDM), and binder jetting printing were applied in 35 (16.5%) and 13 (8%) studies, respectively. With only 11 papers (5.2%) reporting its use, powder bed fusion (PBF) was the least common AM technology across the reviewed studies. Ten studies (4.7%) used several printing techniques, and 46 (21.7%) did not provide data on the printing process.

Among the large number of materials available for 3D printing, mostly thermosetting (curing) resins, plastics that solidify irreversibly when the polymeric reaction is initiated, or thermoplastic polymers (plastics that get soft and can be reshaped when heated) were processed. A numeric evaluation of the materials used across studies was not possible, because of the different classification of materials, inconsistent generic terms mixed with brand names, and papers' not providing data on their materials. All studies that applied 3DPSPs in training for interventions (n = 8) used soft materials such as silicone (n = 4)[25,40-42] or PolyJet rubberlike materials (Tango, n = 2[22,43]; Agilus, n = 2[44,45]). Depending on the purpose of the 3DPSP, different frames across the cardiac cycle were selected. Semilunar valves and ventricles were printed mostly in diastolic frames,[46-48] while for the depiction of atria or atrioventricular valves, systolic or late presystolic frames were chosen.[29,49,50]

Among 54 studies (25%) that evaluated the accuracy of their models, only 15 applied qualitative criteria, and only another 5 validated functional aspects. In the remaining 34 studies, validation processes yielded high variability and included Pearson correlation, mean or median difference or bias, and

FIGURE 2 Consort Diagram of the Study Selection



3D = 3-dimensional; CV = cardiovascular.

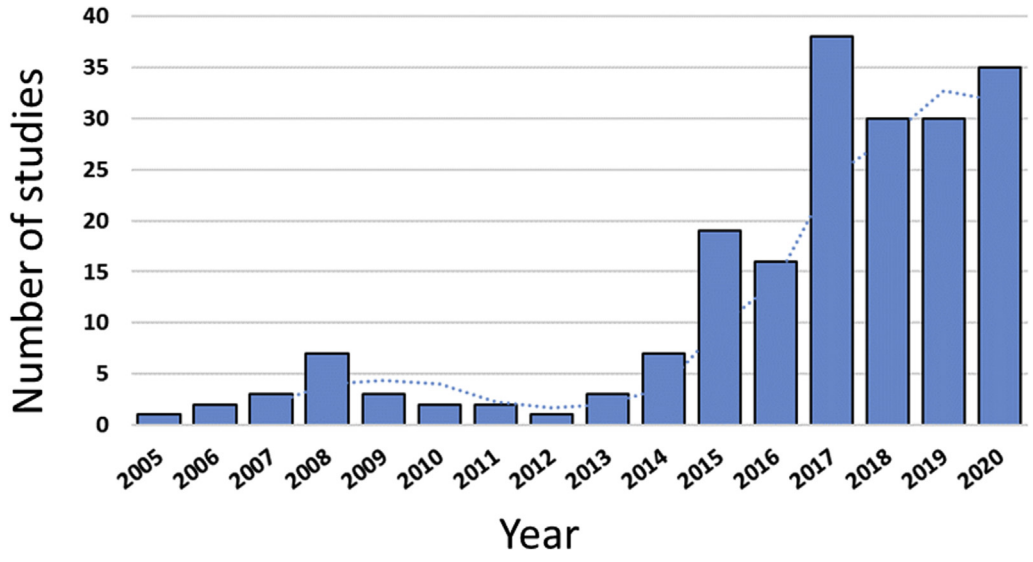
mean error. The number of validated structures ranged from only 1 in each model to complete surface scanning. Original imaging data were mostly chosen as reference standards, while 4 studies used data from other imaging modalities,[13,51-53] and another 4 studies used in vivo findings as a reference standard.[47,52,54,55] Among the 10 largest studies (according to the validated number of 3DPSPs) that evaluated the geometric accuracy of 3DPSP, mean bias was $<\pm 1$ mm, although heterogeneity in the validation process must be taken into account (Table 1).

DISCUSSION

Our results demonstrate the current role of 3D printing in cardiovascular medicine, which is so far based on descriptive, observational, and mostly retrospective data, whereas the quantification of the benefit of 3DPSP remains challenging. The manufacturing process for cardiovascular 3DPSPs comprises: 1) imaging (performed mostly using CCT and CMR); 2) printing (commonly using the PolyJet technique); and 3) validation (with large variation across studies), each of which is discussed in the following sections.

IMAGE ACQUISITION. High-resolution imaging modalities that offer the possibility of 3D acquisition are required for AM, which predisposes to CCT and renders it the most commonly used modality. Slice thicknesses of about 1 mm were chosen in most studies, because higher resolutions can go along with higher noise levels, complicating postprocessing and segmentation, although common 3D printers can translate even higher spatial resolution.[3,56] This also applies for small voxel size and sharp kernels.[57] In contrast to CCT, CMR does not expose patients to radiation, which makes it the preferable modality in younger patients. Additional blood pool segmentation with either CMR angiography or 3D balanced steady-state free precession data sets has been shown to be the most accurate method to acquire images for

FIGURE 3 Number of Studies Investigating Three-Dimensional Printed Cardiovascular Phantoms and 3-Year Trend Line

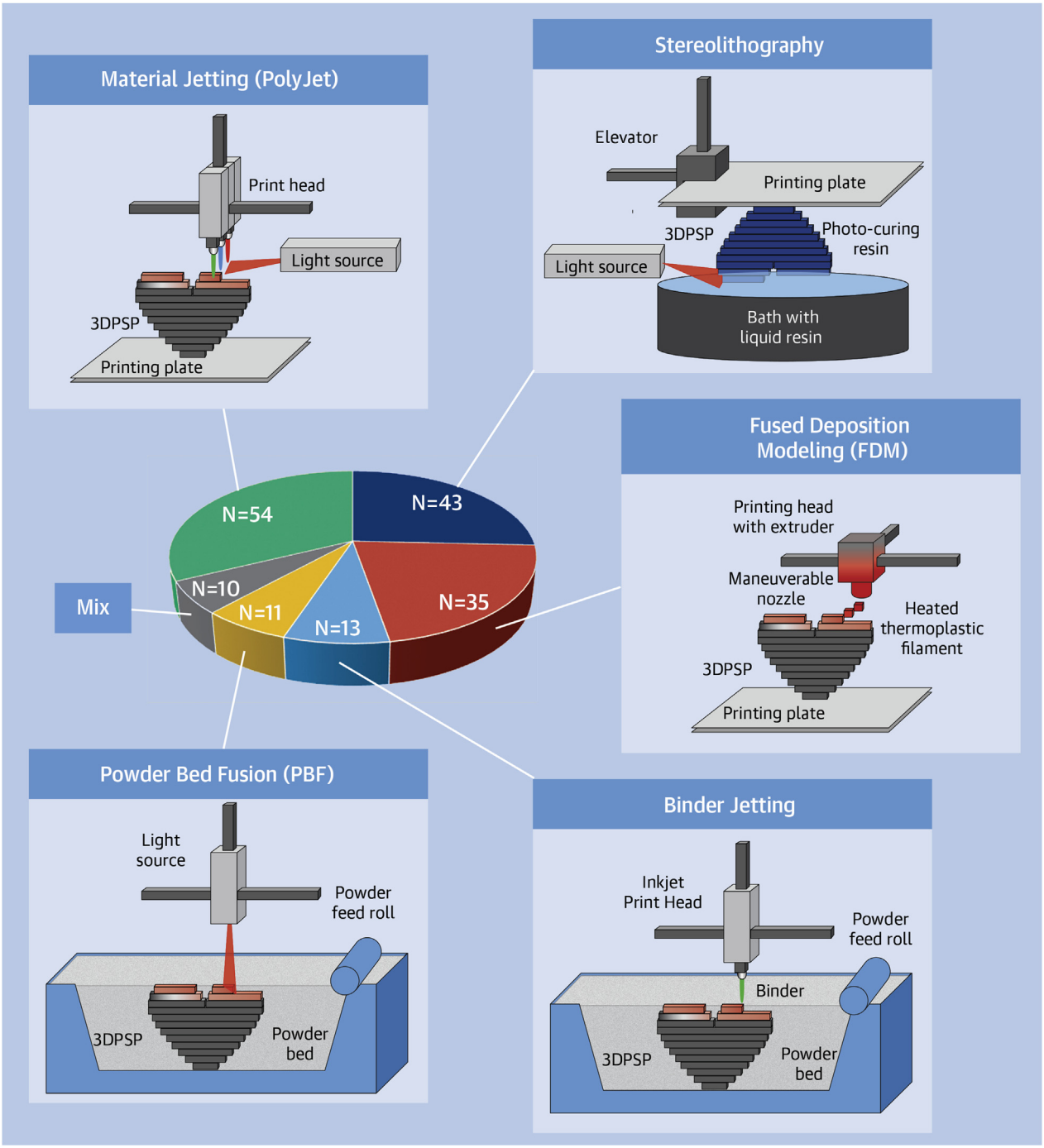


AM by CMR.[46] As demonstrated by Gatti et al,[52] CCT and CMR provide similar accuracy when comparing 3DPSPs with intraoperative findings. Multiplane reconstructions of consecutive high-quality 2-dimensional images have recently made also 3D echocardiography[24,34,58] and rotational 3D angiography of large vessels[59,60] suitable to the requirements of AM.[23] Three-dimensional TEE, as well as 3D transthoracic echocardiography, is widely available, is cost effective, and provides excellent temporal resolution while producing no radiation exposure,[36] although variable reproducibility caused by poor acoustic windows and variations in probe position and acquisition angles are important limitations. High frequencies, going along with higher spatial resolution and harmonic imaging to suppress noise, are beneficial for image quality.[32] However, also under optimal conditions, echocardiography can assess only predefined structures and cannot provide raw data for larger 3DPSPs (ie, models including the ascending and descending parts of the aorta). CCT and CMR offer better blood pool-to-myocardial contrast because of the possibility for contrast agent application,[61] and echocardiographic assessments require extensive postprocessing compared with CCT in specific settings.[50] Similar to echocardiography, rotational angiography is currently a niche application reserved for specific settings of AM, such as printing of malformed vessels.[59,60] Spatial resolution of 0.2 mm was described, allowing detailed and reproducible 3D printing[59] but restricted to the depiction of hollowed organs with the possibility of contrast agent application and low temporal resolution. More recently, hybrid 3D printing derived from a combination of more than one imaging modality (ie, echocardiography and CCT) has been shown to be a promising technology.[61,62] In fact, fusing and reassembling of 3D data sets from echocardiography and CMR or CCT may allow integration of the strengths of different modalities. So far, experience with this approach is limited to 2 case reports and requires further validation.

Compared with conventional 2-dimensional visualizations of cardiovascular imaging data, 3DPSPs allow in-depth understanding of complex anatomical relationships and therefore allow planning, guiding, and tailoring of cardiovascular therapy and the education of health care professionals.[10] Virtual reality and virtual 3D modeling might challenge 3D printing in terms of visualization of complex anatomy in a user-friendly fashion.[63] However, compared with virtual 3D models, 3DPSPs additionally provide haptic feedback and allow training in practical steps, as demonstrated in several studies.[6-12]

PRINTER TECHNOLOGIES. Across the reviewed studies, 5 different technologies were applied for cardiovascular 3D printing, each providing specific strengths and limitations: 1) material jetting (synonymously described as PolyJet); 2) SLA; 3) binder jetting; 4) FDM; and 5) PBF (**Central Illustration**). All technologies use 1 of 2 concepts, a liquid polymer solution that hardens under a specific condition, so-

CENTRAL ILLUSTRATION **Current Techniques to Print 3-Dimensional Cardiovascular Phantoms Across the Reviewed Studies**



Illi J, et al. J Am Coll Cardiol Basic Trans Science. 2022;7(10):1050–1062.

3DPSP = 3-dimensional printed patient-specific phantom.

TABLE 1 Selected Studies That Validated 3DPSP Geometric Accuracy

First Author	Number of Validated 3DPSPs	Number of Validated Structures	Validation Technique	Image Modality	Ref. # Standard 1	Correlation Coefficient	Mean Bias, mm ± SD
Dorweiler et al[68]	35	35	Surface congruency	CCT	Deriving image		0.12 ± 0.08
Fan et al[17]	32	96	Dimensions	3D TEE	Deriving image	0.92	−0.1 ± 1.4
Huang et al[39]	30	300	Dimensions	3D TTE	Deriving image		0 ± 0.03
Gatti et al[52]	30	30	Diameters	CMR	CCT	0.92	−0.1 ± 1.1
Valverde et al[16]	20	320	Diameters	CCT/CMR	Deriving image		−0.27 ± 0.73
Faletti et al[47]	20	40	Diameters	CCT	Deriving image	0.96	0.05 ± 0.76
Song et al[38]	18	54	Dimensions	3D TEE	Deriving image	0.92	Maximum 0.4 ± 1.3
Birbara et al[69]	16	NA	Surface distance	CCT	Deriving image		0.13 ± 0.21
Ripley et al[88]	16	16	Diameters	CCT	Deriving image	0.867	−0.34 ± 0.66
Seckeler et al[60]	15	NA	Hausdorff distance	Angiography	Deriving image		0.01 ± 0.003[a]

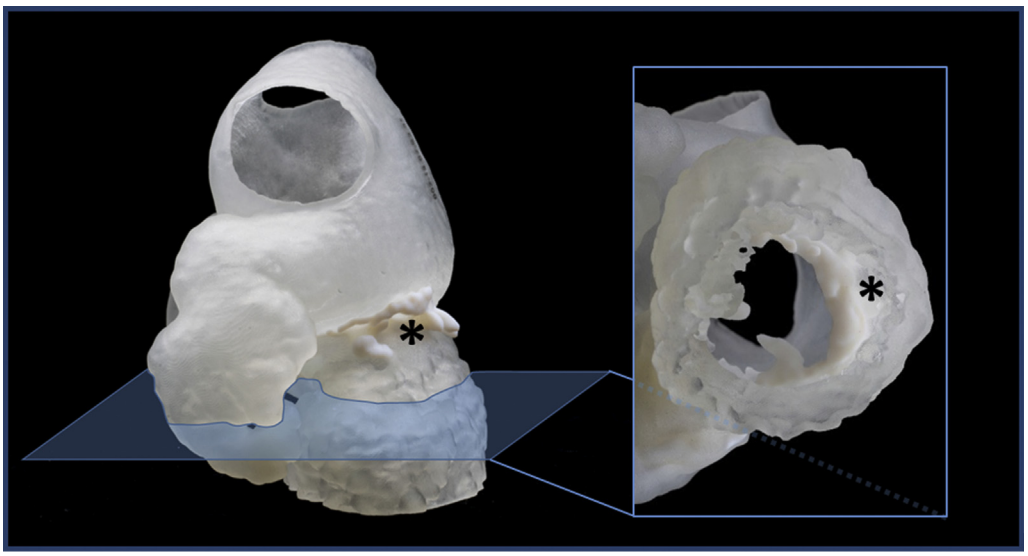
[a]Seckeler et al[60] provided mean relative error instead of mean bias.

3D = 3-dimensional; 3DPSP = 3-dimensional printed patient-specific phantom; CCT = cardiac computed tomography; CMR = cardiac magnetic resonance; NA = not available; TEE = transesophageal echocardiography; TTE = transthoracic echocardiography.

called thermosetting polymers (PolyJet, SLA, and binder jetting) or solid thermoplastic polymers that can be melted (FDM and PBF).

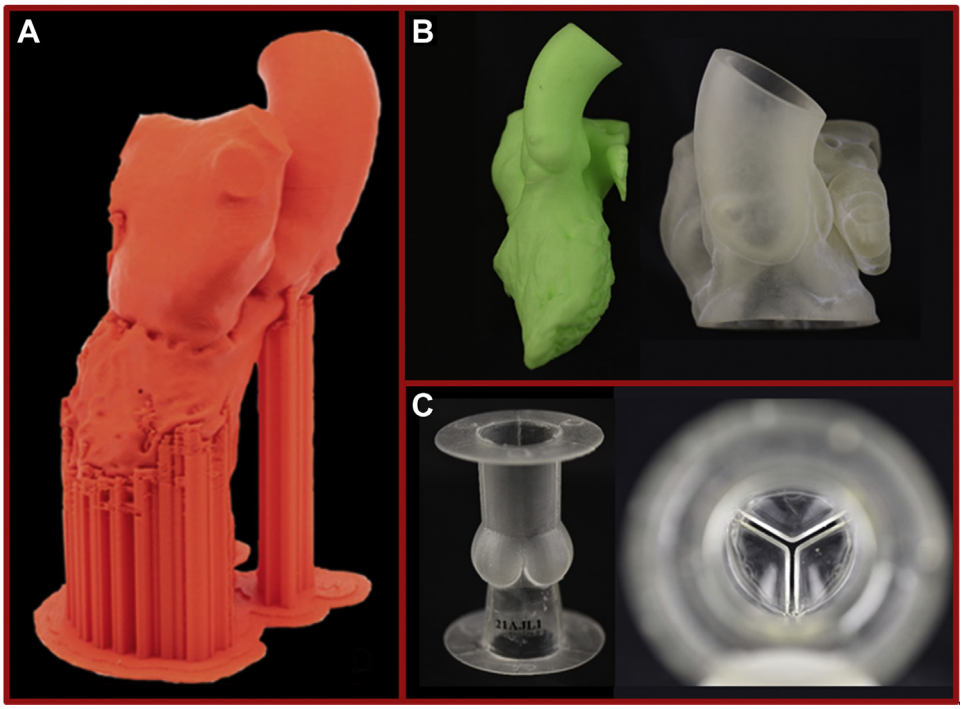
Material jetting printing (PolyJet) was the most common printing technique, using a print head deposing layers of a liquid photopolymer on a printing plate that are hardened by UV light.[64] The use of multiple print heads in an array allows the production of complex multimaterial/multicolor 3DPSPs with modified material properties[65] (**Figure 4**). PolyJet offers the possibility to process elastic materials such as the commercially available photopolymers Tango, Agilus, and Vero (Stratasys), which provide standardized material properties and were found to yield realistic haptic feedback[22] and hemodynamic properties in simulating aortic valve gradients.[66] Resulting from the excellent spatial resolution of up to 14 μm,[67] PolyJet printed models provide high

FIGURE 4 Multimaterial 3-Dimensional Printed Patient-Specific Phantom



Cardiac computed tomography-based compliant multimaterial three-dimensional printed patient-specific phantom of the left atrium and aortic root, including mitral annular calcification **(asterisk)** made by PolyJet printing. Materials: Agilus30 Clear and Agilus30 Clear and Vero Pure White (both Stratasys) mixture for calcifications.

FIGURE 5 Selected Single-Material 3-Dimensional Printed Patient-Specific Phantom



(A) Cardiac computed tomography (CCT)–based fused deposition modeling (FDM) positive of the cardiac blood pool, including supporting structures. **(B)** CCT-based cardiac three-dimensional printed patient-specific phantom made from blood pool segmentation with FDM **(green)** or PolyJet (translucent), the latter one with additional adjusted wall thickness. **(C)** Silicone casted (indirect additive manufacturing) aortic root model made from an FDM printed negative.

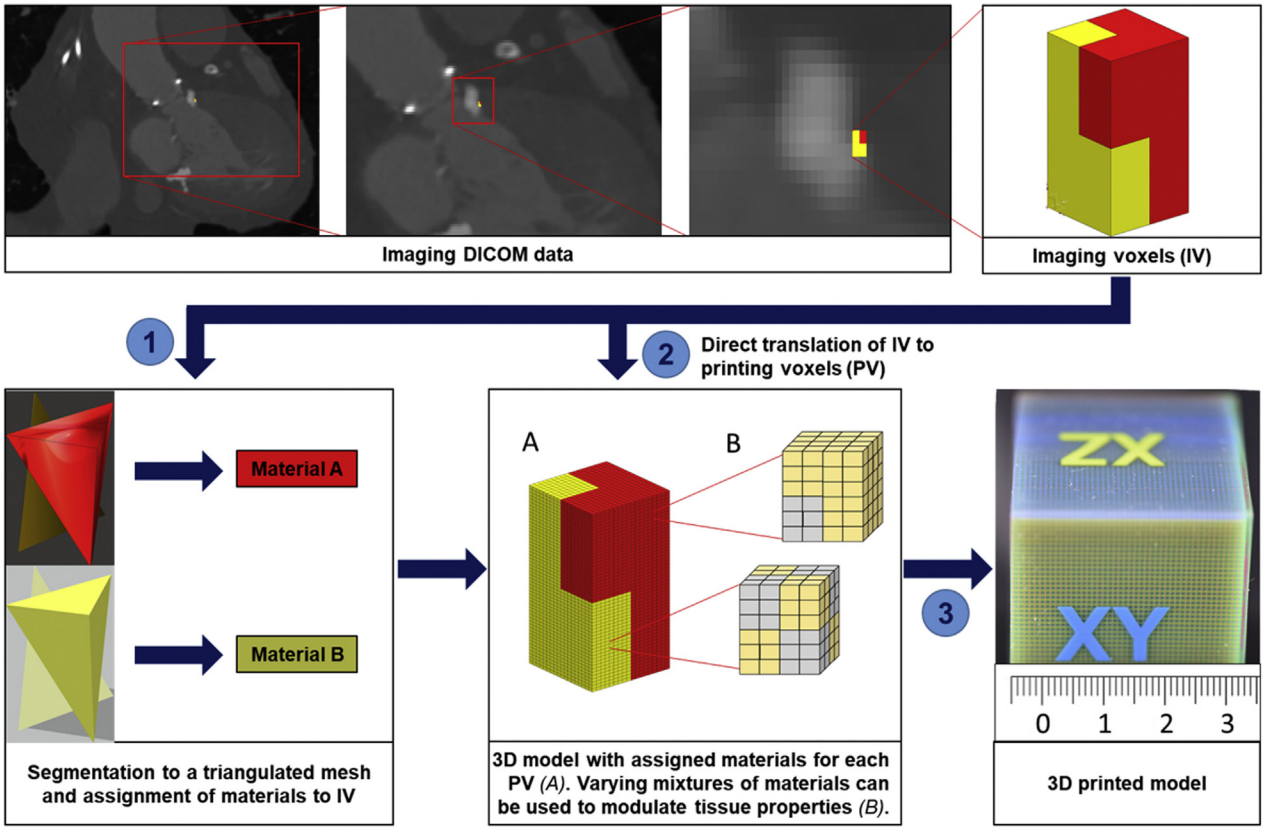
geometric accuracy.[68,69] Higher costs compared with other techniques and the time intensive nature of the printing process remain relevant limitations.[64]

In SLA printing, a print plate is lowered into a bath containing a thermosetting resin and a photo initiator and then gradually raised to build the model at its bottom. The polymerization process is induced at a desired position by UV light, a laser beam (conventional SLA), or a modulated digital micro mirror device (digital light processing).[70,71] Movement of the printing platform and the light source, as well as the liquid viscosity, define the position of resin solidification.[72] Material properties can be postprocessed using additional light exposition or heating.[73] A variety of photoreactive materials are available for SLA, but the finished model is restricted to be made from a single material.[71] Moreover, SLA materials are usually of higher stiffness compared with PolyJet materials, limiting their value for soft tissue mimicry. Currently, SLA offers spatial resolutions higher than the ones of most imaging modalities, with a maximal resolution of 5 μm.[74]

Binder jetting is another thermosetting technique, closely related to material jetting. In contrary to PolyJet, the inkjet head does not deposit the printing material but a binder that hardens the printing material by displacement on a powder bed.[75,76] This allows the production of rigid models meeting the requirements for use in orthopedic surgery,[77] although they are less suitable for cardiovascular 3DPSPs. Furthermore, binder jetting can produce only single-material models and requires extensive postprocessing.[78]

FDM is a material extrusion technique that heats up and liquefies a thermoplastic filament in an extruder, which is brought on a printing plate through a maneuverable nozzle.[79] Curing of material occurs passively by cooling or by a chemical reaction induced by the head of the extruder. Mechanical properties can be modulated by the choice of materials, layer thickness, orientation of printing filaments, and insertion of air gaps.[80,81] Although rubbery materials are available, FDM printing cannot derive highly compliant 3DPSPs and hence is used

FIGURE 6 State of the Art Work Flow for 3-Dimensional Printed Patient-Specific Phantom Printing Using Polyjet



On the basis of attenuation values, different masks for different tissues are created in the region of interest. Voxels of the myocardium **(red)** and aortic valve annular calcification **(yellow)** are segmented and converted to a triangulated mesh. A specific material is assigned to each voxel type that has been segmented before, eg, solid **(yellow)** for the calcification and rubber-like **(red)** for myocardium. Software slices the models and converts them into layer-by-layer commands for the printer.
3D = 3-dimensional; DICOM = Digital Imaging and Communications in Medicine; IV = imaging voxel; PV = printing voxel.

mainly for cast forms or for anatomical models. Spatial resolution relies on the actuation system, the material, user experience, and the geometry of the 3DPSP but is in general lower compared with the previously described modalities. Especially the accuracy of surfaces is a principal concern in FDM printing.[82] Because the material is liquefied, overhanging structures without underlying material support (eg, the roof of a cardiac cavity) are difficult to print and require stabilization of supporting structures (also see **Figure 5A**).[57] The low cost of FDM printers and printing materials and its ease of use make FDM widely available, however.[73]

Similar to FDM, PBF is a thermoplastic technique that melts rigid materials (eg, polyamide or thermoplastic polyurethane), which are distributed in a powder bed.[57] The energy source can be a high-power laser (selective laser sintering) or infrared light (multijet fusion). Material characteristics can be modulated by the laser power, the laser scan speed, and the hatch distance and direction.[78] However, only rigid materials can be processed, limiting the value of PBF for cardiovascular medicine. Furthermore, 3DPSPs usually must be oversized to compensate for material shrinkage during and after the print,[83] and they require postprocessing.[57] The spatial resolution of PBF is adequate for most clinical indications, although structures smaller than 0.5 mm cannot be processed.

The previously mentioned limitations of techniques that derive rigid 3DPSPs (FDM, SLA, and PBF) can be overcome by indirect AM (printing a negative that is processed by casting or brushing to the final 3DPSP). Indirect AM requires laborious further steps besides printing but offers the possibility to derive a large number of nonprintable rubbery materials such

as silicones, more suitable for simulation of cardiac tissue (Figure 5C).[46,49] Silicone rubbers with varying contents of silicone oil can modulate tissue stiffness and were found to provide realistic suture properties in cardiac valve models.[29] However, when directly comparing tissue characteristics of 3DPSPs to those of porcine mitral valve tissue, differences in stiffness and bending modulus are still a relevant concern.[50]

Condensing these findings, we see the value of rigid 3DPSPs that are directly printed using FDM, SLA, PBF, or binder jetting in the visualization of complex anatomical conditions, whereas compliant 3DPSPs from PolyJet printing or indirect AM with silicone casting are applicable for preoperative training and hemodynamic simulations.

MODEL VALIDATION. To delineate potential sources of inaccuracy (eg, imaging resolution, accuracy and resolution of segmentation, the resolution of the 3D printer), a comprehensive validation is needed in cardiovascular 3D printing. However, preferred validation methods exhibited large heterogeneity across the reviewed studies or were completely lacking. Apart from qualitative and visual evaluations, the comparison of anatomical structures of 3DPSPs with imaging data as a reference standard was common to validate the geometric accuracy of 3DPSPs. The geometric accuracy described in the reviewed studies can be considered not to pose a relevant limitation for most current clinical applications of 3DPSPs. However, future fields of use, such as tailored devices (eg, valve prostheses or stent grafts adapted to individual vessel geometry) may require higher accuracy and validation of hemodynamic properties before implantation.

In addition to geometric accuracy, evaluation of functional aspects and tissue mimicry are important aspects of validation that should be oriented according to the 3DPSP application. For example, a 3DPSP used for hemodynamic testing requires validation of flow resistance, tensile strength, and dispensability, whereas puncturing behavior, cutting ability, and surface texture are important features in 3DPSPs used for surgical simulations. Several studies have already demonstrated the validation of flow measurements across modulated valves or vessels and reported high accuracy compared with in vivo measurements.[33,66,84,85] Tissue characteristics in terms of puncture behavior were adequately replicated in 3DPSPs of the fossa ovalis.[86] However most studies in this field evaluated tissue properties with qualitative or semiquantitative approaches and do not allow generalizations on the optimal choice of materials and compositions representative of cardiovascular tissue. Systematic in vitro testing of material compositions and a standardized validation process for finalized 3DPSPs, including several validation checkpoints, would allow systematic comparison of different materials or printing techniques and could identify optimal manufacturing techniques for cardiovascular 3DPSPs in the future.

OUTLOOK

Highly accurate 3D printing might allow the production of personalized 3D printed devices such as vascular stent grafts. So far, biocompatibility is an important limitation of implantable devices that might be improved by the introduction of new materials or a combination of conventional 3D printing and bioprinting (eg, conventionally printed synthetic scaffolds coated with biological tissue[87]). Further developments that might increase the use of 3DPSPs are dynamic models that incorporate anatomical and functional changes through the cardiac cycle and the implementation of physiological properties. Voxel printing (VP) is a promising technology in this respect (Figure 6). Compared with current techniques that are limited to a predefined material, VP allows the allocation of a material to each imaging voxel individually. Hence, tissue characteristics can directly be translated into printing voxels without the need for prior segmentation. Even though imaging voxels (spatial resolution in most settings of about 1 mm) in high-resolution imaging are much larger than the printed voxels (spatial resolution of about 80 μm), printing materials may be mixed and adjusted on a microscopic level to obtain the desired tissue properties. So far, VP is compatible only with PolyJet printing and is not used in clinical cardiovascular applications but might provide 3DPSPs with geometric and mechanical properties similar to human tissue. Furthermore, VP requires a significant amount of technical and medical input, underlining the need to close the gap among clinicians, imaging specialists, and engineers to improve cardiovascular 3D printing.

STUDY LIMITATIONS. The reviewed studies included highly selected patient populations and do not allow generalization of observations to all fields of cardiovascular medicine. Despite careful and systematic selection of these studies, specific applications of cardiovascular 3D printing might have been missed in our search, which was based on predefined search terms.

CONCLUSIONS

Three-dimensional printed cardiovascular phantoms provide sufficient anatomical accuracy for current clinical applications such as the planning, guiding, and tailoring of cardiovascular therapy and the education of health care professionals. As the requirements for 3D models are highly variable, the optimal choice of imaging modalities, printing techniques, and materials as well as their validation so far remains individual to each clinical application. Material jetting and indirect printing with silicone casting can help overcome frequently raised concerns of poor tissue mimicry, whereas directly printed rigid phantoms can visualize complex cardiovascular anatomy. Regarding objectively measurable tissue properties, the incorporation of functional aspects in dynamic models and their comprehensive validation, there is still much room for improvement that could be achieved by VP, contributing to the increased use of 3D printing in the cardiovascular field in the future.

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KEY WORDS 3D printing, additive manufacturing, cardiovascular disease, patient-specific phantoms, personalized medicine, silicone casting, voxel printing

APPENDIX For a supplemental table, please see the online version of this paper.