Review Article

3D printing in adult cardiovascular surgery and interventions: a systematic review

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Abstract: 3D printing in adult cardiac and vascular surgery has been evaluated over the last 10 years, and all of the available literature reports benefits from the use of 3D models. In the present study, we analyzed the current applications of 3D printing for adult cardiovascular disease treated with surgical or catheter-based interventions, including the clinical medical simulation of physiological or pathology conducted with 3D printing in this field. A search of PubMed and MEDLINE databases were supplemented by searching through bibliographies of key articles. Thereafter, data on demographic, clinical scenarios and application, imaging modality, purposes of using with 3D printing, outcomes and follow-up were extracted. A total of 43 articles were deemed eligible and included. 296 patients (mean age: 65.4±14.2 years; male, 58.2%) received 3D printing for cardiac and vascular surgery or conditions [percutaneous left atrial appendage occlusion (LAAO), TAVR, mitral valve disease, aortic valve replacement, coronary artery abnormality, HOCM, aortic aneurysm and aortic dissection, Kommerell's diverticulum, primary cardiac tumor and ventricular aneurysm]. Eight papers reported the utility of 3D printing in the medical simulator and training fields. Most studies were conducted starting in 2014. Twenty-six was case report. The major scenario used with 3D printing technology was LAAO (50.3%) and followed by TAVR (17.6%). CT and echocardiography were two main imaging techniques that were used to generate 3D-printed heart models. All studies showed that 3D-printed models were helpful for preoperative planning, orientation, and medical teaching. The important finding is that 3D printing provides a unique patient-specific method to assess complex anatomy and is helpful for intraoperative orientation, decision-making, creating functional models, and teaching adult cardiac and vascular surgery, including catheter-based heart surgery.

Keywords: Three-dimensional (3D) printing; adult; cardiovascular surgery; intervention

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Introduction

Three-dimensional (3D) printing is a fabrication technique used to transform digital information into physical models and has been demonstrated to have utility in multiple clinical scenarios in recent decades (1). 3D printing technology has been rapidly applied in the field of medical in recent years. In cardiovascular surgery, 3D printing can provide improved visualization of the anatomical details and guide precision operations, so the most widely reported applications have been for congenital heart diseases (2). With increasing aging and complexity of cardiac conditions, current surgical or transcatheter procedures require advanced peri-procedural imaging and individualized treatment. 3D printing may to prepare for well-tolerated treatment and provide substantial information on the accuracy of surgical reconstruction in complex cardiovascular anatomy (3). Although the use of 3D printing in cardiovascular surgery is still a relatively new development, the applications for adult cardiac and vascular surgery or catheter-based interventions are also emerging, and contemporary reviews and reports are warranted. In this review, we examine the current clinical applications of 3D printing in adult cardiovascular surgery and transcatheter interventions. We also present the clinical medical simulation of physiological or pathology conducted with 3D printing in this fields. We present the following article in accordance with the PRISMA reporting checklist (available at http://dx.doi.org/10.21037/jtd-20-455).

Methods

This systematic review was performed and reported in line with the PRISMA statement (4). We searched the PubMed and MEDLINE databases up to the end of June 2019 using medical subject headings and text words supplemented by scanning the bibliographies of the recovered articles. We combined "Three-dimensional printing", "3D printer", "3D printing", "3D printed", "rapid prototyping model", "cardiac", "cardiovascular", "heart surgery", and "adult" using the Boolean operator "AND". The results were limited to articles written in English. Two separate researchers (CW and LZ) analyzed the data set to ensure accuracy and to identify all available studies. The details of each publication were checked to avoid duplicates. Any differences were resolved by consensus.

Inclusion criteria

All cases reported the application of 3D printing for cardiovascular surgery and interventions in the adult. To review the current extended utility of 3D printing in adult cardiovascular surgery, the articles about applications of 3D printing in the clinical medical simulator and training fields were included. Only articles published in English were included.

Exclusion criteria

Papers or cases reporting on the utility of 3D printing for congenital heart diseases, technology or basic sciences were excluded. Studies based on conference abstracts, editorials or review articles were also excluded.

Data extraction

We collected the data on the first author, published year, clinical scenarios, number of patients, age, sex, study design, clinical application and imaging modality. The study purposes and main study findings were also collected. We also recorded the outcomes of patients who were treated with 3D printing technology during the perioperative period, including morbidity, mortality, and follow-up.

Statistical analysis

Data collected were organized on an Apple Numbers (version 6.6.2) spreadsheet. Descriptive statistics were used to describe the demographic and continuous data (e.g., mean ± standard deviation). Dichotomous variables were expressed as numbers with percentages.

Results

The literature search yielded 215 publications in PubMed and MEDLINE databases. Of these, a total of 43 publications focused on 3D printing for adult cardiovascular surgery, intervention and clinical medical training were identified from the literature and included in the analysis. The publications spanned a period ranging from 2008 to 2019. In some instances, two papers were published by the same author, and only the most recent manuscript was included in the analysis. *Figure 1* shows the results of the literature search according to the PRISMA.

Characteristics of 3D printing in cardiovascular surgery and transcatheter interventions

Of these 43 publications, 35 were based on the clinical application of 3D printing for adult cardiovascular surgery and transcatheter interventions, and the other 8 (5-12) papers were based on physiological or pathology simulations and clinical training for cardiovascular surgery. Most studies (n=34, 97.1%) on the clinical utility of 3D printing for adult heart surgery or intervention procedures were carried out starting in 2014, and increased year by year (*Figure 2*). Of the 35 papers about clinical applications, 26 (74.3%) were case reports, 4 were cross-sectional studies, and 4 were retrospective studies. One study was a mix of retrospective and prospective analyses (13).

A total of 296 patients were described, with an average

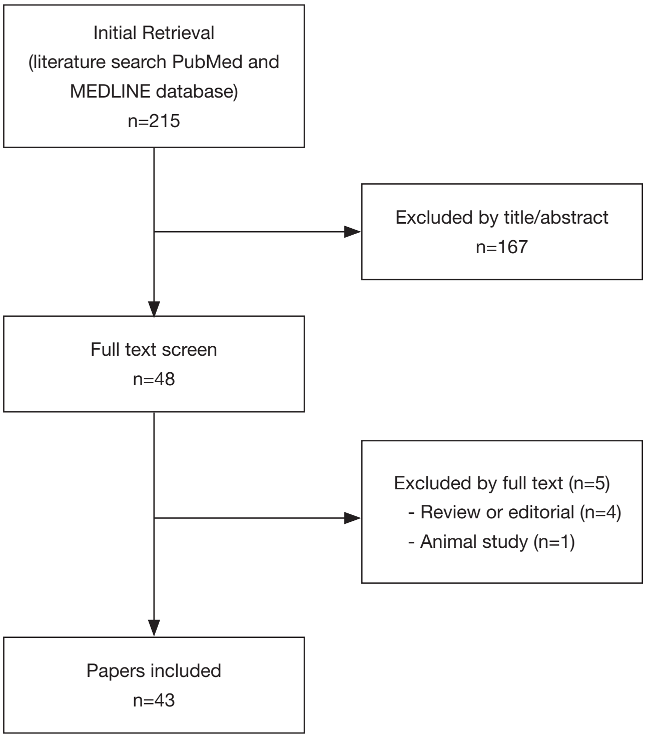

Figure 1 Flow diagram illustrating identification, selection and exclusion criteria for articles used in the review.

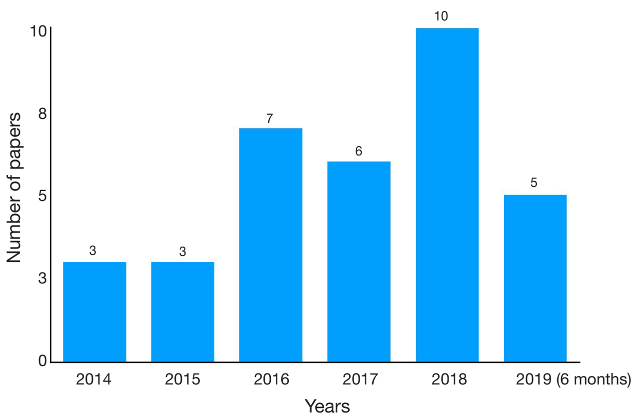

Figure 2 The development of the clinical utility of 3D printing in adult cardiovascular surgery and interventions.

age of 65.4±14.2 years. In the group, 160 patients were men, and 115 patients were women. Seven reports (21 patients) did not provide the patients' sex. Only 4 case reports (including 23 patients) provided follow-up data (6–12 months). In this research, there were no series that aimed to determine the effects of 3D printing on morbidity and mortality. Regarding the patients' risk scores, none of the articles reported EuroSCORE data or the Society of Thoracic Surgeons (STS) score. They all reported that the included patients had generic complex anatomy. All reports recognized that a unique patient-specific 3D printing model before surgery or intervention could intuitively present complex anatomy, assist in preoperative surgical decision-making and provide intraoperative surgical guidance. *Table 1* summarizes the characteristics of the eligible studies in this review.

The clinical applications of 3D printing in cardiovascular surgery and transcatheter intervention

In this review, ten clinical scenarios were included: left atrial appendage occlusion (LAAO), transcatheter aortic valve replacement (TAVR), mitral valve disease treated with catheter-based intervention or open repair, aortic valve replacement, coronary artery abnormality (fistula), aortic aneurysm and dissection, hypertrophic obstructive cardiomyopathy (HOCM), Kommerell's diverticulum, primary cardiac tumor, and ventricular aneurysm. *Table 2* shows the analysis of clinical scenarios that indicated the utility of 3D printing in adult cardiovascular surgery and transcatheter procedures.

Peri-interventional 3D printing was applied in the treatment of the majority of adult heart diseases, including LAAO, TAVR, and mitral valve interventions. Of all patients, 50.3% underwent LAAO, and 17.6% underwent TAVR. The treatments for other diseases were rarely reported.

Of these 35 studies, 30 reported on 3D printing for preoperative planning or simulations and showed that models were very helpful for preoperative planning and orientation, as well as to simulate procedures due to the exact and life-like illustration of the cardiovascular anatomy. Three studies (19,45,46) reported on the feasibility and diagnostic accuracy of creating 3D-printed heart models. One study reported on visualizing the fit between the native and prosthetic valves and predicting the occurrence of post-procedural paravalvular aortic regurgitation (PAR) with preoperative 3D printing (37).

There are two main imaging techniques that are used to generate 3D-printed heart models, CT and echocardiography. Twenty-eight studies (151 cases) used CT datasets as the data source for 3D printing; 6 studies (145 cases) used transesophageal echocardiography (TEE) datasets, while only 1 study used a combination of CT and

Table 1 Characteristics of 3D printing applications in adult cardiovascular surgical and transcatheter procedure

First author (Ref.)	Year	Country	Clinical scenarios	No. of patients	Age (years)	Gender (M/F)	Study design	clinical application	Imaging modality
Hachulla *et al.* (14)	2019	Switzerland	Percutaneous LAA occlusion	15	75.4 (mean)	9/6	Cross-sectional study	Pre-surgical simulation	CT
Hosny *et al.* (15)	2019	USA	TAVR	30	84.9 (mean); 84.4 (mean)	13/17	Retrospective study	Pre-surgical simulation	CT
Zhang *et al.* (16)	2019	China	Recurrent coronary artery fistula	1	NA	NA	Case report	Preoperative planning	CT
Misra *et al.* (17)	2019	USA	Coronary-pulmonary artery fistula	1	NA	NA	Case report	Preoperative planning	CT
Fan *et al.* (13)	2019	China	Percutaneous LAA Occlusion	104	72 (mean)	66/38	Retrospective [72], prospective [32]	Preoperative planning	TEE
Shijo *et al.* (18)	2018	Japan	Multiple aneurysms combined with coarctation	1	69	0/1	case report	Pre-surgical simulation	CT
Faletti *et al.* (19)	2018	Italy	AVR	20	78.6 (mean)	12/8	Retrospective study	Preoperative planning	CT
Lee *et al.* (20)	2019	UK	Coronary artery abnormality	7	13, 10, 36, 48, 18, 52, 56	3/4	Retrospective study	Medical education	CT
Sun *et al.* (21)	2018	China	HOCM	1	47	1/0	Case report	Preoperative planning	CT
Gomes *et al.* (22)	2018	Brazil	Aortic aneurysm/ dissection	6	65, 67, 75, 68, 64, 67	5/1	Case report	Preoperative planning	CT
Guo *et al.* (23)	2018	China	HOCM	7	40 (mean)	3/4	Case report	Preoperative planning	CT
Ginty *et al.* (24)	2018	Canada	Mitral valve repair for MR	10	78 (mean)	6/4	Cross-sectional study	Pre-surgical simulation	TEE
Bagur *et al.* (25)	2017	Canada	TMV-in-R replacement	1	69	1/0	Case report	Pre-surgical simulation	CT
El Sabbagh *et al.* (26)	2018	USA	TMVR	8	85, 90, 57, 83, 79, 88, 80, 91	4/4	Case report	Pre-surgical simulation	CT
Aroney *et al.* (27)	2019	Australia	Cardiac fistulae	4	21, 69, 25, 55	1/3	Case report	Preoperative planning	CT
Sun *et al.* (28)	2017	China	Kommerell's diverticulum	5	46, 72, 42, 66, 64	4/1	Case report	Preoperative planning	CT
Song *et al.* (29)	2017	China	LAA occlusion	18	73, 58, 55, 68, 60, 66, 71, 80, 62, 64, 71, 82, 65, 70, 74, 61, 55, 66	10/8	Cross-sectional study	Preoperative simulation	TEE
Hamatani *et al.* (30)	2017	Japan	HOCM	1	41	0/1	Case report	Preoperative planning and simulation	CT

Table 1 (*continued*)

Table 1 (*continued*)

First author (Ref.)	Year	Country	Clinical scenarios	No. of patients	Age (years)	Gender (M/F)	Study design	clinical application	Imaging modality
Hermsen *et al.* (31)	2017	USA	HOCM	2	52, 35	1/1	Case report	Preoperative planning and simulation	CT
Vukicevic *et al.* (32)	2017	USA	The mitral valve for catheter-based structural intervention	3		NA	Case report	Preoperative simulation	3D TEE and CT
Ho *et al.* (33)	2017	Australia	Aortic aneurysm and aortic dissection	2		NA	Case report	Simulator of aortic disease	CT
Pracon *et al.* (34)	2016	Poland	LAA occlusion	1	84	0/1	Case report	Preoperative planning and simulation	CT
Liu *et al.* (35)	2016	China	LAA occlusion	8		NA	Cross-sectional study	Preoperative planning and simulation	TEE
Pellegrino *et al.* (36)	2016	Italy	LAA occlusion	2	69, 42	1/1	Case report	Preoperative planning and simulation	TEE
Ripley *et al.* (37)	2016	USA	TAVR	16	74, 85, 79, 87, 74, 79, 88, 85, 69, 89, 89, 91, 78, 86, 77, 87	11/5	Retrospective study	Visualize the fit between the native and prosthetic valves, predict the occurrence of post-procedural PAR.	CT
Gallo *et al.* (38)	2016	Italy	TAVR in redo ascending AA surgery	1	79	1/0	Case report	Preoperative planning	CT
Al Jabbari *et al.* (39)	2016	USA	Malignant cardiac tumors	2	50, 67	1/1	Case report	Preoperative planning	CT
Hossien *et al.* (40)	2016	Germany	Type A aortic dissection	3	74, 63, 71	1/2	Case report	Preoperative planning and simulation	CT
Son *et al.* (41)	2015	Korea	Primary cardiac schwannoma resection	1	42	0/1	Case report	Preoperative planning	CT
Otton *et al.* (42)	2015	Australia	LAA occlusion	1	74	1/0	Case report	Preoperative planning	CT
Schmauss *et al.* (43)	2015	Germany	AS, primary right ventricular tumor, pseudoaneurysm, TAVR	4	81, 43, 50, 70	3/1	Case report	Preoperative planning	CT
Dankowski *et al.* (44)	2014	Poland	Percutaneous mitral annuloplasty	1	41	1/0	Case report	Preoperative planning	CT
Maragiannis *et al.* (45)	2014	USA	TAVR	4	–	NA	Case report	Created 3D printed models	CT

Table 1 (*continued*)

Table 1 (*continued*)

First author (Ref.)	Year	Country	Clinical scenarios	No. of patients	Age (years)	Gender (M/F)	Study design	clinical application	Imaging modality
Witschey *et al.* (46)	2014	USA	Mitral valve repair	2	–	NA	Case report	Created 3D printed mitral valve models	TEE
Jacobs *et al.* (47)	2008	Germany	Ventricular aneurysm/ malignant cardiac tumor	3	81, 50, 50	1/2	Case report	Preoperative planning and intraoperative orientation	CT
Total	35 publications	–	–	296	65.4 (mean)	M=160 (58.2%)	Case report =26 (74.3%)	–	CT =151, TEE =145

Values are expressed as numbers and %. LAA, left atrial appendage; HOCM, hypertrophic obstructive cardiomyopathy; TAVR, transcatheter aortic valve replacement; TMVR, transcatheter mitral valve replacement; AS, aortic stenosis; CT, computed tomography; MRI, magnetic resonance imaging; 3D TEE, Three-dimensional transesophageal echocardiography.

Table 2 Analysis of clinical scenarios of the utility of 3D printing in adult cardiovascular surgery and transcatheter procedure

Clinical scenarios	No. of cases	%
Percutaneous LAA occlusion	149	50.3
TAVR	52	17.6
Mitral valve disease	25	8.4
AVR	21	7.1
Coronary artery abnormality (fistula)	13	4.4
HOCM	11	3.7
Aortic aneurysm and aortic dissection	13	4.4
Kommerell's diverticulum	5	1.7
Primary cardiac tumor	5	1.7
Ventricular aneurysm	2	0.7
Total	296	100

Values are expressed as numbers and %. LAA, left atrial appendage; TAVR, transcatheter aortic valve replacement; HOCM, hypertrophic obstructive cardiomyopathy; AS, aortic stenosis.

echocardiographic datasets, and no 3D-printed models were created from MRI. This is different from the 3D-printed models created for congenital heart diseases, which MRI is the most commonly used imaging modality (2). In the cohort that used TEE datasets, LAAO was the most common treatment method (88.6%).

The utility of 3D printing for clinical medical simulators or training

There were 8 papers focused on the application of 3D printing for clinical medical simulator and training in adult cardiac and vascular surgery. Six studies successfully created aortic valves, mitral valves, aortic roots or heart simulators for surgical training or improved the understanding of disease among surgical trainees (7-12). Two studies demonstrated the utilization of 3D-printed models for *in vitro* physiological simulations to better replicate and understand the functional physiology of the coronary artery or mitral valve (5,6). All studies assessed the usefulness of 3D-printed models in medical teaching, surgical trainee training, and patient-doctor communication and the most recent applications of 3D models in surgical planning and simulation.

Discussion

Identifying and visualizing anatomy is critical for any surgical intervention, and digital and physical preoperative anatomical assessments are an important adjunct to surgical planning (48). Advanced surgical and catheter-based procedures for structural heart disease require precise preprocedural planning and intraoperative orientation. In the past ten years, 3D printing has seen a rapid increase in adoption rate for adult cardiovascular surgery and interventions, and this technology offers unique advantages for complex anatomy, morphology and pathology, with great potential for tailored diagnostic assessments and preoperative planning.

The clinical application of 3D printing in adult heart surgery and interventions

The purpose of 3D printing for adult heart disease can be summarized into three main fields: preoperative planning or simulation, medical teaching and clinical consultations. Given the data analysis in this review, preoperative planning or simulation was the major clinical utility of 3D printing.

Perioperative 3D printing

According to the data of this research, 3D printing in adult cardiac surgery was primarily used for complicated lesions, including coronary artery abnormalities, HOCM, primary cardiac tumors and ventricular aneurysms. 3D-printed models have been reported to minimize the surgical risks and optimize surgical planning and intraoperative decision-making (16,17,21,28,47). In great vessel surgery, 3D printing can be used to accurately replicate the anatomical details of complex congenital malformations of the aorta and aortic aneurysm and dissection, including the intimal flap (33,40). 3D valve models of AS and mitral valve pathology are useful for preoperative patient-specific hemodynamic testing and are potentially helpful in improving the ability of inexperienced surgeons and the efficiency of experienced surgeons performing complex valve repairs (24).

Peri-interventional 3D printing

The benefits of peri-interventional 3D printing have been shown for percutaneous LAAO, TAVR, and mitral valve interventions (13-15,25,26,29,32,34-38,42,45). LAAO is highly associated with risks for occlusion-related complications, such as interatrial communication and device malposition, especially in LAA with complex morphology. Song *et al.* (29) reported that the consistency of the morphological classifications of the LAA based on 3D models and cardiac computed tomography was 0.92 ($P<0.01$). 3D models of the LAA prior to the procedure are helpful in finding the correct position and device size and type.

Pre-TAVR 3D printing improves the understanding of the interaction between the prosthetic valve and the patient's anatomy in advance of surgical deployment. A retrospective study (37) showed that an examination of the fit of valves with patient-specific aortic root models correctly predicted PAR in 6 of 9 patients (6 true-positives, 3 false-negatives) and the absence of PAR in 5 of 7 patients (5 true-negatives, 2 false-positives); additionally, the finished pre-TAVR 3D-printed model could be used to visualize the fit between the native aortic valve complex and TAVR prosthetic valves and thus predict the occurrence of post-procedural PAR. For complex anatomy, e.g., extreme porcelain aorta, perivalvular calcifications, and valve-in-valve implantation, pre-TAVR 3D printing may help achieve optimal long-term results after TAVR (43).

Transcatheter mitral valve replacement (TMVR) is an evolving therapeutic option to treat patients with severe MAC who are not surgical candidates. Guerrero *et al.* demonstrated that TMVR in patients with severe MAC was feasible but associated with a mortality of up to 30%, LVOT obstruction rate of 3%, and stroke rate of 3% (49). El Sabbagh *et al.* (26) reported that 3D printing for TMVR was feasible and could simulate valve sizing, apposition, expansion, PVL, and LVOT obstruction risk as well as other potential pitfalls, such as extra-annular calcifications.

Medical teaching and training

After almost three decades of experience with medical 3D printing, this technology is now being used to create models, even those that are very complex, as needed in cardiovascular surgery (50). 3D printing has also been shown to be a novel teaching approach in medical education to help students, cardiologists, and surgeons-in-training gain a better understanding of pathologies and surgical procedures. For young surgeons with little experience, surgical simulations with patient-specific 3D-printed structures could flatten the learning curve for difficult procedures and improve preprocedural planning (31). Moreover, the patients and their families will also be able to understand the pathology and surgical treatment more comprehensively with 3D-printed models.

3D printing and clinical outcomes

In this review, none of the research reported clinical outcomes, e.g., mortality and morbidity. The clinical benefits of 3D printing, including improved safety and better long-term results, have not been reported. There are no controlled trials that show outcome data. Owing to increasing the accuracy of preoperative planning, it maybe has the potential to decrease morbidity or mortality and improve outcomes in patients with complex heart disease as this technology becomes more widespread. However, clinical control trials with large samples are needed.

3D printing and diagnostic tools

Traditional imaging, e.g., CT, MRI and echocardiography, does not always provide all of the information required for operative planning, especially in complex cases. A 3D-printed model of the heart can provide a more complete understanding of the intracardiac anatomy to better diagnose heart disease. However, the time required for 3D printing depends on the source of the DICOM data (CT, MRI, or echocardiography), the printing technology, the size and complexity of the patient-specific model. With current 3D printing technology, 3D printing typically takes 3–10 hours to build a single piece of the heart model (51). An aortic valve requires approximately 1.5 hours, a whole heart or the aortic wall from the aortic root to the level of the mid-descending aorta requires 6–8 hours (52). A 3D printing model also requires post-processing. The complex segmentation of multiple anatomic elements might take up to 12 hours to print, which may not be suitable for clinical application in an emergency, such as acute aortic dissection (40,53). Another limitation of 3D printing for diagnosis is the possibility of errors during segmentation from the DICOM data when obtaining the STL file. This process is observer-dependent and requires extensive anatomical knowledge. The accuracy of replicating the cardiac and vascular structural geometry must be validated. Any errors may have serious consequences if the model is created for detailed planning. Few studies have noted that 3D-printed heart models only complement the current diagnostic tools and should not be stand-alone tools for diagnosis or preoperative planning (2).

The future of 3D printing in cardiovascular surgery and interventions

A recent meta-analysis of 158 studies found that the most prominent limiting factors for 3D printing were precision, preparation time, and cost (54). To improve the efficiency and accuracy of 3D printing in the adult cardiovascular surgery field, a multidisciplinary team (MDT) involving cardiovascular surgeons, cardiac catheterization specialists, radiologists, and engineers is required. To determine if the use of 3D printing will become a routine clinical tool in the future, the clinical outcomes of patients who were treated with 3D printing must be followed up. Future multicenter randomized studies including more cases are warranted to investigate the clinical value and to confirm the benefits of 3D printing in this field.

However, 3D printing technology has been rapidly applied in the field of cardiovascular surgery in recent years. 3D bioprinting is a very impressive new development, has potential to develop fully functional heart construct that can integrate with native tissues rapidly. In the near future, cardiovascular surgeon will get the tailored valves, vessels or even entire heart from patients' own cells by 3D bioprinting, which will open the door to a new era of personalized medicine (51,55,56).

Limitations

This review presents limitations. Firstly, all of included publications on 3D printing technology in cardiovascular surgery and intervention still consist of single case reports or small case series, and possess all the inherent limitations. Secondly, the sample size is too small to draw conclusions concerning the reliability of the 3D printing technologies in cardiovascular surgery and interventions. Finally, the outcome of mortality, morbidity and follow-up is not available from this analysis. Therefore, general conclusion from solid statistical analysis is lacking.

Conclusions

In conclusion, 3D printing is a promising technology, has been gradually more utilized in adult cardiovascular surgery and interventions and is helpful for preoperative planning, intraoperative orientation, and medical teaching. Despite its advantages, 3D printing in cardiovascular medicine can be accepted in selected cases. Indeed, clinical randomized control trials with large samples are needed to assess its values on the diagnostic tools and clinical outcomes.

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Footnote

Reporting Checklist: The authors have completed the PRISMA reporting checklist. Available at http://dx.doi.org/10.21037/jtd-20-455

Conflicts of Interest: All authors have completed the ICMJE uniform disclosure form (available at http://dx.doi.

org/10.21037/jtd-20-455). The authors have no conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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