Blood-Pool or Myocardial 3D Printing, Which One is Better for the Diagnosis of Types of Congenital Heart Disease?

Jixiang Liang

Xi'an Jiaotong University

Xin Zhao

Beijing City University

Guangyu Pan

Peking University International Hospital

Gen Zhang

The Affiliated Traditional Chinese Medicine Hospital of Southwest Medical University

Dianjiang Zhao

Peking University International Hospital

Jianping Xu

Peking University International Hospital

Diangyuan Li

Peking University International Hospital

Bingheng Lu (✉ bhlu@mail.xjtu.edu.cn)

Xi'an Jiaotong University

Research Article

Keywords: Three-dimensional printing, Congenital heart disease, Blood pool, Myocardium, Effectiveness, Assessment

Posted Date: July 27th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-722298/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License. [Read Full License](#)

Abstract

The aim of this study was to evaluate the effectiveness of blood pool and myocardial rigid models made by stereolithography in the diagnosis of different types of congenital heart disease (CHD). Two modeling methods were applied in the diagnosis of 8 cases, and two control groups consisting of cardiac experts and cardiac students diagnosed the cases using computed tomography (CT), blood pool models, and myocardial models. The importance, suitability, simulation degree, and preference of different models were analyzed. The average diagnostic rate of CT and 3D printing in the 8 cases was 88.75% and 95.9% in the expert group and 60% and 91.6% in the student group, respectively. 3D printing was considered to be more important for the diagnosis of complex CHDs (very important; average, 87.8%) than simple CHDs (very important; average, 30.8%). Myocardial models were considered most realistic regarding the structure of the heart (average, 92.5%). In cases of congenital corrected transposition of great arteries, Williams syndrome, coronary artery fistula, tetralogy of Fallot, patent ductus arteriosus, and coarctation of the aorta, blood pool models were considered more effective (average, 92.1%), while in cases of double outlet right ventricle and ventricular septal defect, myocardial models were considered optimal (average, 80%).

Introduction

The presentation of the cardiac structure is of great significance in the diagnosis and treatment of structural, valvular, and congenital heart diseases (CHDs)^{1–4}. 3D printing can provide good insight into the 3D anatomy^{5,6}, and it has been extensively used in surgical planning and simulation, medical education, interventional procedures, and research for device innovation^{6–8}. Fused deposition modeling (FDM), selective laser sintering (SLS), stereolithography (SLA), and material jetting are the most frequently reported 3D printing technologies in cardiovascular medicine^{1,9,10}. In addition, to obtain a better sensation of the heart to simulate an operation, vacuum casting technology has been used for the creation of superflexible heart models¹¹. Each 3D printing method and material has advantages and disadvantages¹⁰. However, in practical applications, the effectiveness, cost, and availability are important factors that restrict the large-scale application of 3D printing in heart disease diagnosis¹². Concerning the techniques used, SLA is a widely used, relatively low-cost, high-precision, and high-speed^{13,14} technique for the fabrication of heart models. Among existing 3D printing heart models, blood pool models^{15,16}, myocardial models^{7,11}, and their combination⁴ have been used for diagnosis in different studies. There has been some comparison of rigid and flexible models; rigid models provide a static representation of the anatomy, while flexible models may be more suitable for surgical simulation^{11,17}. SLA is usually used to fabricate different kinds of rigid models and has been widely used in the diagnosis of CHDs^{18,19}. Matthew Lee et al¹⁹ evaluated the feasibility of using rigid blood pool 3D-printed models in cases of coronary artery anomalies. Jiajun Xu et al¹⁵ assessed the application of blood pool 3D printing in preoperative planning for the treatment of anomalous pulmonary venous connection (APVC) and investigated the roles of 3D-printed blood pool models using SLA technology in presurgical planning for the treatment of complex CHDs in 15 children with total anomalous pulmonary venous connection (TAPVC), complete transposition of the great arteries (TGA), patent ductus arteriosus (PDA), ventricular septal defect (VSD), and atrial septal defect (ASD)¹⁸. Existing studies have mainly focused on the feasibility of application in one or more cases, and a comparison of the applicability of blood pool and myocardial 3D printing in different CHDs is lacking. In practical application, which one is more effective for the diagnosis of different types of CHD is unknown. Here, we applied different printing methods in the diagnosis of different CHDs in a retrospective study. Blood pool models and myocardial models cut at multiple angles were 3D printed and used for the diagnosis of different types of CHD. The advantages and disadvantages of the different methods were compared. Through the diagnosis and statistical analysis of typical cases, the improvement in the diagnostic results, satisfaction, accuracy, necessity and personal preferences of the 3D-printed models in the diagnosis of different CHDs were assessed. This study is of great significance in selecting the type of rigid 3D-printed model for use in the diagnosis of various CHDs.

Materials And Methods

Study design

This study's protocol was reviewed and approved by the Medical Ethics Committee of Peking University International Hospital, all methods were carried out in accordance with relevant guidelines and regulations. All the participants signed the informed consent, if the patients are under 18, the informed consent was signed by their parent or legal guardian. To evaluate the effectiveness of different types of 3D-printed models in the diagnosis of different types of CHD, several cases, including cases of complex and simple CHDs, were randomly selected for the study. Rigid blood pool and myocardial models were applied in each case. Control groups with doctors and students diagnosed the disease using computed tomography (CT), blood pool models, and myocardial models. The final results were subject to the consensus of the experts and the results of intraoperative exploration. No doctors or engineers involved in data collection, modeling, 3D printing, and case collation participated in the questionnaire. In this study, 3D printing was only used for diagnostic statistics and did not interfere with surgical decision-making.

Case selection

All cases of CHD in our hospital between January 2020 and December 2020 were included in the study. The cases selected met the following criteria: (1) features consistent with the diagnosis of CHD; (2) patient suitable for CT examination; and (3) nonemergent situation. To verify the effectiveness of the method, all selected cases were classified by disease subtype. One case from each subtype was randomly selected for detailed comparison.

Image acquisition, processing, and 3D printing

CT was performed with a Siemens SOMATOM Definition Flash Dual-source CT scanner (Siemens Healthcare, Erlangen, Germany). Plain and enhanced CT scans were acquired in turn. The scan was centered on the precordial area, and the scanning range was from 10–15 mm below the trachea to the diaphragm of the heart. The data were recorded in Digital Imaging and Communications in Medicine (DICOM) format and imported into Mimics Innovation Suite 19.0 (Materialise HQ, Leuven, Belgium) for processing. To show the complete intracardiac structure, the blood pool area consisting of the aorta, pulmonary artery,

atria, ventricles, and superior and inferior vena cavae was selected by the "threshold" method as the region of interest (Fig. 1a) and used for model generation (Fig. 1b). The myocardial model was cut with a flexible surface displaying the anatomical structure of the heart at multiple angles under the guidance of a surgeon familiar with the case (Fig. 1c-1d). The software was operated by engineers with more than three years of experience with the assistance of cardiac surgeons with more than five years of experience. For each case, the blood pool model (Fig. 1b) and the myocardial model cut with a flexible surface (Fig. 1d) were exported for 3D printing.

The final volume meshes of the blood pool and myocardial models were exported as .stl (stereolithography) files. The models were repaired and hollowed using an inward offset; then, a scaffold was added, and the models were sliced in Magics (Materialise HQ, Leuven, Belgium). The models were then printed using SLA equipment (Shaanxi Hengtong Intelligent Machine Co., Ltd., Shannxi, China) with rigid white resin.

Qualitative assessment of clinical value

To assess the clinical value of 3D-printed models of the blood pool and myocardium, a self-designed survey was conducted in two control groups: one consisting of 40 cardiac surgery experts and ultrasound experts (with more than 10 years of working experience) and the other consisting of 40 students majoring in cardiac surgery and ultrasound (third-year postgraduates). Each participant had access to the CT dataset as well as 3D-printed models produced by four different methods and made independent diagnoses in each case. The interval between each diagnosis was one week to reduce the influence of previous assessments. The diagnostic results and time spent on diagnosis using the CT data and the two different models were counted and compared with the correct diagnosis.

Statistical analysis

The results of the diagnosis and survey were recorded, and the diagnostic rate and distribution of answers to each question were calculated. Significant differences in the survey results between the two groups were identified using chi-square tests and Kruskal-Wallis tests according to the change in the value. All tests were performed with a level of significance of $\alpha = 0.05$ ($P\text{-value} < 0.05$). Statistical analyses were performed using SPSS 21.0 (IBM Corporation, Armonk, NY, USA).

Results

Forty-five cases of 8 CHD subtypes were collected. One case for each of the 8 subtypes was randomly selected to draw a specific comparison. The diseases included congenital corrected transposition of the great arteries (ccTGA), double outlet right ventricle (DORV), Williams syndrome (WS), coronary artery fistula (CAF), tetralogy of Fallot (TOF), PDA, coarctation of the aorta (CoA), and VSD. Eight cases were selected for image acquisition, segmenting, modeling, 3D printing, and application evaluation. The results were statistically analyzed.

Modeling and 3D printing

Blood pool and myocardial models were 3D printed in actual size for 8 typical cases. Both parts of the segmented myocardial model were 3D printed, and the larger part of the myocardium that can present more of the cardiac anatomy is shown in the figures. Models from the eight typical cases are presented in Fig. 2. The demographic and clinical characteristics of the cases are shown in Table 1.

Table 1
Demographic and clinical characteristics

Patient demographics					Echocardiography reports		Time of modeling (min)		Time of 3D printing and postprocessing (hour)		Average time of the diagnosis by CT or 3D printing (min)			Cost of 3D (\$)
No.	Age (years)	Weight (kg)	Sex	\			Blood pool	Myocardial	Blood pool	Myocardial	CT	Blood pool 3D printing	Myocardial 3D printing	Blood pool model
1	19	52	Male	ccTGA			16	25	13	11.5	2.8	0.9	1.8	80
2	38	62	Female	DORV			14	21	8	9	2.74	0.74	1.3	50
3	9	32	Male	WS			11	24	5	5.5	2.4	1.35	1.98	35
4	3	16	Male	CAF			13	22	4.5	4.5	2.53	1.08	1.65	30
5	2	13	Female	TOF			9	23	3.5	4.5	2.36	1.05	1.32	22
6	48	56	Female	PDA			6	11	3	5	1.56	0.51	0.93	45
7	5	18	Male	CoA			5	9	2.5	4	1.69	0.42	0.51	25
8	36	51	Female	VSD			8	19	7.5	6	1.91	0.48	0.35	42
Average	\	\	\	\			10.25	19.25	7.06	6.25	2.25	0.82	1.23	41.13
ccTGA: congenital corrected transposition of the great arteries; DORV: double outlet right ventricular; WS: Williams syndrome; CAF: coronary artery fistula; TOF: tetralogy of Fallot;														
PDA: patent ductus arteriosus; CoA: coarctation of the aorta; VSD: ventricular septal defect.														

Survey and subjective evaluation

Eight typical cases were classified into two groups: complex CHDs (including ccTGA, DORV, WS, CAF, and TOF) and simple CHDs (including PDA, CoA, and VSD). As shown in Fig. 3, the diagnostic accuracy for complex CHDs of CT between the two control groups was significantly different ($P < 0.05$), and the opposite was true for simple CHDs ($P > 0.05$). The average diagnostic rate of CT and 3D printing in the 8 cases was 88.75% and 95.9% in the expert group and 60% and 91.6% in the student group, respectively. This proves that 3D printing improved the rate of CHD diagnostic, especially among students and inexperienced doctors, and this improvement was more obvious for complex CHDs. In the subjective survey of the importance of 3D-printed models for the diagnosis of CHDs, the models were considered more important for complex CHDs than simple CHDs, and the demand of students was stronger than that of experts, although not all cases exhibited a significant difference. The diagnostic improvement of the blood pool and myocardial models was different. In most cases, the improvement rate of the blood pool model was higher. However, in the case of VSD, the improvement rate of the myocardial model for disease diagnosis was higher. In the survey of which model was better for the diagnosis of each case, most respondents selected the blood pool model (average, 74.1%) since the blood pool model could clearly show the spatial relationship of cardiac structures, facilitating rapid understanding of the disease. In the case of VSD, the myocardial model was considered the optimal model, as it could more effectively show the location and structure of the VSD; additionally, the blood pool model did not show the location of the VSD very well. In the case of DORV, there was no significant difference in the survey results. In more in-depth interviews, some respondents stated that the combination of the two could be better for diagnosis of the disease. In the survey of the realism of the structure of the heart, most of the surgeons selected the myocardial model (average, 92.5%) because it was consistent with the perspective of the doctor. Although there were no significant differences, the experienced doctors generally preferred the myocardial models to the blood pool models. This is probably because they see more hearts in the first view, while the students are trained to establish the spatial relationship of various parts in the heart cavity, which is more similar to the blood pool models.

Discussion

3D printing is a promising technology, with exciting potential applications in medicine. It creates the opportunity to examine a physical model of a patient's anatomy before entering the operating room²⁰. Various types of 3D printing technology have been used to fabricate cardiovascular models, and we have been exploring an economic, universally accessible type of technology for this purpose. To the best of our knowledge, FDM and SLA are the most common types of 3D printing technology. Considering the speed of FDM and the limitation of support removal, SLA is the most suitable technology for manufacturing rigid cardiovascular models. Rigid blood pool and myocardial models can be made by SLA, but their effectiveness in different types of CHD has not been evaluated. In this paper, we conducted a multicase study evaluating the application of 3D printing for the first time.

The improvement of 3D printing over CT in the diagnosis of CHDs was obvious, and it was equally effective for complex and simple CHDs; in contrast, in the diagnosis of CHDs based on CT, the accuracy was lower for complex than simple CHDs. However, when 3D-printed models were used for the diagnosis, the accuracy in the student group was significantly improved, becoming similar to that in the expert group, while the diagnosis rate in the expert group also increased. 3D printing improved the rate of CHD diagnosis, especially among students and inexperienced doctors, and this effect was more obvious for complex CHDs.

In the investigation of the necessity of 3D-printed models for the diagnosis and treatment of CHDs, most surgeons considered it necessary, although we were informed by a few experts that they could identify the diseases accurately relying on their rich experience. It is undeniable that experienced experts can

correctly diagnose most CHDs using CT or echocardiography. However, we must admit that the distribution of these experts is extremely uneven, and their experience is based on extensive case training. For most doctors or students, 3D printing is necessary.

Both blood pool models and myocardial models improved the diagnostic accuracy, although they had different effects in different cases. In cases of ccTGA, DORV, WS, CAF, and TOF, blood pool models improved the diagnostic accuracy more than myocardial models. In the research on which of the two models is more suitable for different types of CHD, the results showed a difference. In cases of ccTGA, WS, CAF, TOF, PDA, and CoA, i.e., CHDs with “structural heterotopia”, blood pool models were considered to be more effective, as they were good at illustrating arteriovenous connections, vessel stenosis/obstruction, and chamber volumes. However, the results were the opposite in cases of VSD and DORV. In the case of VSD (Fig. 2h1), the location of the VSD was occluded by the left and right ventricles, so it was not easy to find. In the myocardial model (Fig. 2h2), the VSD was shown as a hole, which was easy to find and understand. Similarly, in the case of DORV (Fig. 2b1), the blood pool model was useful for finding the origin of the root of the aorta and the pulmonary artery. However, when we performed in-depth research, the surgical plan and myocardial model (Fig. 2b2) were found to be more important, as they helped doctors accurately estimate the exact location of the VSD (Fig. 4a) within the septum, the relationship of the VSD to the septal leaflet of the tricuspid valve, the subaortic or subpulmonary outflow tract, and the distance between the upper margin of the VSD and the nearest arterial valve (Fig. 4b). In addition, the model allowed the doctor to simulate channel establishment (Fig. 4c-4d) and estimate the volume of the remaining right ventricle after application. Furthermore, the ability to perform rapid demonstrations using the myocardial model is of great significance in surgical communication and education.

On the other hand, from the aspect of shape similarity, the myocardial model was more similar to the actual heart, with no significant difference in either group. The result is different from that of the demand for models in the diagnosis of some CHDs, such as ccTGA, WS, CAF, TOF, PDA, and CoA. This may have something to do with our habit of understanding the structure of the heart. Usually, each cavity, such as the left and right ventricles, is considered as an entity, which is the same as the structure of the blood pool. This could be why the students preferred the blood pool models. This habit gradually changed after they looked at the heart from the first perspective for a long time.

Compared with colorful blood pool models applied for the diagnosis of CHDs^{4,21}, monochrome blood pool models have a disadvantage on first glance, but they do not affect the accuracy of the diagnosis. In terms of surgical simulation, flexible myocardial models can better train doctors for surgery, which is a significant advantage of hard myocardial models. However, considering the cost of the models, this difference can be ignored. A study on the time and price of modeling, 3D printing, and postprocessing showed that the average cost of 3D printing of blood pool and myocardial models was approximately 41.8 dollars, which is much less expensive than printing multicolor models or soft models²². The average time of modeling for the blood pool and myocardial models was approximately 10 minutes and 20 minutes, respectively, and the average time of 3D printing and postprocessing was within 7 hours, which allows large-scale application.

Research on the average time of diagnosis using CT or 3D printing has shown that 3D printing allow a diagnosis to be made faster. The diagnosis of CHDs mainly depends on judgment of the cardiac structures. When diagnosing using CT or other tomographic images, 3D spatial relationships are produced through planar images, which is a very difficult and time-consuming process because it requires the comparison of almost every slice. However, 3D printing establishes and displays these spatial relationships, leaving only a judgment to be made based on the visible 3D model. In some cases, only one glance is needed to find the location and condition of the lesion, such as in cases of VSD, PDA, and CoA. Even though differences between 3D-printed models and normal models need to be determined, which may include the location affected by the disease, this approach greatly simplifies the diagnostic process, especially for inexperienced doctors and students.

Before 3D printing, the virtual model created can also be used for the diagnosis of CHDs. The advantages and disadvantages of augmented reality, mixed reality, virtual reality, and 3D printing have been compared²³. On the whole, virtual models have the advantages of fast, low-cost, and repeatable application, but this method also requires more skills from the operator. The advantage of 3D printing lies in the physical characteristics of the model and high quality of simulation. The perception of spatial relationships will be biased on a virtual screen, but the 3D printing of objects can eliminate this bias because the objects can be touched as if they were on a real operating table, and all the perceptions and simulations of the physical model can then be applied to the real heart.

Several limitations of this study must be noted. First, we compared two 3D printing methods with CT in the diagnosis of CHDs and did not compare them with echocardiography. The combination of 3D printing and echocardiography may offer new advantages in the diagnosis of CHDs. Second, only one case of each CHD was selected in the comparative study, while each CHD usually includes a wide spectrum of anatomical variations. Many other types of complex CHD should be considered in subsequent studies.

Conclusion

The use of rigid 3D-printed models can improve the diagnosis of CHDs, and this improvement is more obvious for complex CHDs. Blood pool models and myocardial models had different effects on improving the diagnostic accuracy in different cases. In cases of ccTGA, WS, CAF, TOF, PDA, and CoA, which are characterized as CHDs with “structural heterotopia”, blood pool models were more effective; in cases of VSD and DORV, myocardial models showed more advantages in showing the structure of the lesion. The model should be selected with consideration of the category of CHD in practical application.

Declarations

Acknowledgments

The project was supported by **Beijing Municipal Science & Technology Commission Z191100006619005**, and **Peking University International Hospital Research Grant, YN2019ZD01**. The funders had no role in study design, data collection and analysis, decision to publish, or manuscript preparation.

Author contributions

Jixiang Liang, Bingheng Lu, and Dianyuan Li designed the study. Guangyu Pan, Dianyuan Li, and Jianping Xu provided case information and performed the surgery. Jixiang Liang and Gen Zhang operated the software for 3D modeling. Xinzhaio 3D printed all the models. Genzhang and Dianyuan Li organized the questionnaire survey and analyzed the data. Jixiang Liang prepared the figures and wrote the main manuscript text. All authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

Data availability

All data are available on request at the Department of Cardiovascular Surgery, Peking University International Hospital, No.1, Zhongguancun Life Science Park, Beijing, China.

References

1. Giannopoulos, A. A. *et al.* Applications of 3D printing in cardiovascular diseases. *Nature Reviews Cardiology* **13**, 701-718, doi:10.1038/nrcardio.2016.170 (2016).
2. Kim, M. S., Hansgen, A. R., Wink, O., Quaife, R. A. & Carroll, J. D. Rapid Prototyping. *Circulation* **117**, 2388-2394, doi:10.1161/circulationaha.107.740977 (2008).
3. Witschey, W. R. T. *et al.* Three-Dimensional Ultrasound-Derived Physical Mitral Valve Modeling. *The Annals of Thoracic Surgery* **98**, 691-694, doi:10.1016/j.athoracsur.2014.04.094 (2014).
4. Anwar, S. *et al.* 3D Printing in Complex Congenital Heart Disease. *JACC: Cardiovascular Imaging* **10**, 953-956, doi:10.1016/j.jcmg.2016.03.013 (2017).
5. Hadeed, K. *et al.* Cardiac 3D printing for better understanding of congenital heart disease. *Archives of Cardiovascular Diseases* **111**, 1-4, doi:10.1016/j.acvd.2017.10.001 (2018).
6. Yoo, S.-J., Spray, T., Austin, E. H., Yun, T.-J. & van Arsdell, G. S. Hands-on surgical training of congenital heart surgery using 3-dimensional print models. *The Journal of Thoracic and Cardiovascular Surgery* **153**, 1530-1540, doi:10.1016/j.jtcvs.2016.12.054 (2017).
7. Loke, Y.-H., Harahsheh, A. S., Krieger, A. & Olivieri, L. J. Usage of 3D models of tetralogy of Fallot for medical education: impact on learning congenital heart disease. *BMC Medical Education* **17**, doi:10.1186/s12909-017-0889-0 (2017).
8. Liu, P. *et al.* The Value of 3D Printing Models of Left Atrial Appendage Using Real-Time 3D Transesophageal Echocardiographic Data in Left Atrial Appendage Occlusion: Applications toward an Era of Truly Personalized Medicine. *Cardiology* **135**, 255-261, doi:10.1159/000447444 (2016).
9. Fan, Y., Wong, R. H. L. & Lee, A. P.-W. Three-dimensional printing in structural heart disease and intervention. *Annals of Translational Medicine* **7**, 579-579, doi:10.21037/atm.2019.09.73 (2019).
10. Sun, Lau, Wong & Yeong. Personalized Three-Dimensional Printed Models in Congenital Heart Disease. *Journal of Clinical Medicine* **8**, doi:10.3390/jcm8040522 (2019).
11. Hoashi, T. *et al.* Utility of a super-flexible three-dimensional printed heart model in congenital heart surgery†. *Interactive CardioVascular and Thoracic Surgery* **27**, 749-755, doi:10.1093/icvts/ivy160 (2018).
12. Lau, I. *et al.* Quantitative and qualitative comparison of low- and high-cost 3D-printed heart models. *Quantitative Imaging in Medicine and Surgery* **9**, 107-114, doi:10.21037/qims.2019.01.02 (2019).
13. Salmi, M., Paloheimo, K.-S., Tuomi, J., Wolff, J. & Mäkitie, A. Accuracy of medical models made by additive manufacturing (rapid manufacturing). *Journal of Cranio-Maxillofacial Surgery* **41**, 603-609, doi:10.1016/j.jcms.2012.11.041 (2013).
14. Martelli, N. *et al.* Advantages and disadvantages of 3-dimensional printing in surgery: A systematic review. *Surgery* **159**, 1485-1500, doi:10.1016/j.surg.2015.12.017 (2016).
15. Xu, J. *et al.* Utility of three-dimensional printing in preoperative planning for children with anomalous pulmonary venous connection: a single center experience. *Quantitative Imaging in Medicine and Surgery* **9**, 1804-1814, doi:10.21037/qims.2019.08.01 (2019).
16. Yoo, S.-J. & van Arsdell, G. S. 3D Printing in Surgical Management of Double Outlet Right Ventricle. *Frontiers in Pediatrics* **5**, doi:10.3389/fped.2017.00289 (2018).
17. Shiraishi, I., Yamagishi, M., Hamaoka, K., Fukuzawa, M. & Yagihara, T. Simulative operation on congenital heart disease using rubber-like urethane stereolithographic biomodels based on 3D datasets of multislice computed tomography. *European Journal of Cardio-Thoracic Surgery*, doi:10.1016/j.ejcts.2009.07.046 (2009).
18. Xu, J.-J. *et al.* Patient-specific three-dimensional printed heart models benefit preoperative planning for complex congenital heart disease. *World Journal of Pediatrics* **15**, 246-254, doi:10.1007/s12519-019-00228-4 (2019).
19. Lee, M. *et al.* Evaluating 3D-printed models of coronary anomalies: a survey among clinicians and researchers at a university hospital in the UK. *BMJ Open* **9**, doi:10.1136/bmjopen-2018-025227 (2019).
20. Odeaa, A. J. *et al.* Use of three-dimensional models to assist in the resection of malignant cardiac tumors. *Journal of Cardiac Surgery* **31**, 581-583, doi: 10.1111/jocs.12812
21. Ryan, J., Gregg, C., Frakes, D. & Pophal, S. Three-dimensional printing. *Current Opinion in Cardiology* **32**, 86-92, doi:10.1097/hco.0000000000000352 (2017).

22. Li, P. *et al.* Personalized Three-Dimensional Printing and Echoguided Procedure Facilitate Single Device Closure for Multiple Atrial Septal Defects. *Journal of Interventional Cardiology* **2020**, 1-8, doi:10.1155/2020/1751025 (2020).
23. Goo, H. W., Park, S. J. & Yoo, S.-J. Advanced Medical Use of Three-Dimensional Imaging in Congenital Heart Disease: Augmented Reality, Mixed Reality, Virtual Reality, and Three-Dimensional Printing. *Korean Journal of Radiology* **21**, doi:10.3348/kjr.2019.0625 (2020).

Figures

Figure 1

Process of segmentation and modeling. (a) Segmentation of CT images. (b) Blood pool model. (c) Cutting of the myocardial model. (d) Myocardial model cut with a flexible surface.

Figure 2

Results of 3D printing of the blood pool and myocardium in eight typical cases. (a1-a2) Case 1: ccTGA. (b1-b2) Case 2: DORV. (c1-c2) Case 3: WS. (d1-d2) Case 4: CAF. (e1-e2) Case 5: TOF. (f1-f2) Case 6: PDA. (g1-g2) Case 7: CoA. (h1-h2) Case 8: VSD.

Figure 3

Survey results for the typical cases. Blue represents the expert group, and red represents the student group. (a) Case 1: ccTGA. (b) Case 2: DORV+PH. (c) Case 3: WS. (d) Case 4: CAF. (e) Case 5: TOF. (f) Case 6: PDA. (g) Case 7: CoA. (h) Case 8: VSD.

Figure 4

Study of the operation plan using the myocardial model in a case of DORV. (a) Exploration of intracardiac structures and the location of the VSD. (b) Direct measurement of key dimensions of the VSD. (c) Establishment of an internal channel from the VSD to the root of the aorta. (d) Simulation and presentation of the surgical plan. Yellow area: location of the inner tunnel patch. Green area: location of the patch for the VSD.