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REVIEW PAPER

Three-dimensional printed models in congenital heart disease

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Abstract The purpose of this article is to discuss technical considerations and current applications of three-dimensional (3D) printing in congenital heart disease (CHD). CHD represent an attractive field for the application of 3D printed models, with consistent progress made in the past decade. Current 3D models are able to reproduce complex cardiac and extra-cardiac anatomy including small details with very limited range of errors (<1 mm), so this tool could be of value in the planning of surgical or percutaneous treatments for selected cases of CHD. However, the steps involved in the building of 3D models, consisting of image acquisition and selection, segmentation, and printing are highly operator dependent. Current 3D models may be rigid or flexible, but unable to reproduce the physiologic variations during the cardiac cycle. Furthermore, high costs and long average segmentation and printing times (18–24 h) limit a more extensive use. There is a need for better standardization of the procedure employed for collection of the images, the segmentation methods and processes, the phase of cardiac cycle used, and in the materials employed for printing. More studies are necessary to evaluate the diagnostic accuracy and cost-effectiveness of 3D printed models in congenital cardiac care.

Keywords 3D models · Congenital heart disease

Abbreviations

CHD	Congenital heart disease
3D	Three dimensional
CT	Computed tomography
MRI	Magnetic resonance imaging

Introduction

In the last decade, there has been an increasing interest in the field of three-dimensional (3D) printing for manufacturing of models, which are able to reproduce complex anomalies of the heart and great vessels [1–18]. Congenital heart disease (CHD), with its diverse and often complex pathology, the need for complete representation of anatomy and personalized treatment approaches, [1, 2, 10, 18] represent an ideal field to test the potential, accuracy, and clinical effectiveness of this technology. Management of CHD is challenging due to the broad spectrum of conditions and high variability between individual patients. Optimal surgical outcome is related to a thorough understanding of the complex spatial relationships between anatomical structures in order to avoid unexpected findings at surgical repair, and thereby reduce

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operative time and mortality. Visualization using conventional 3D imaging techniques is limited due to presentation on a flat screen, which may not allow full comprehension of complex intracardiac anatomy. The purpose of this paper is to provide an overview of 3D printing in CHD, focusing on strengths, weaknesses and technical considerations.

Strengths of 3D printed models

Multiple studies have demonstrated the feasibility and accuracy of 3D printed models for the reconstruction of complex cardiac [2] and extra-cardiac anatomy. These include visualization of aortic arch anomalies [11], pulmonary branches [7], and major aorto-pulmonary collaterals [4]. Printing of 3D models was feasible at all ages, with different imaging techniques including CT, MRI and more recently 3-D echocardiography (Figs. 1, 2). Advantages of 3D models in the understanding of complex anatomy and in the planning of surgical and percutaneous interventions have been highlighted.

The diagnostic accuracy of 3D models has been evaluated in different ways. Most of the current work [3, 5, 10–12] describes similarities of 3D models with cardiac anatomy, and the satisfaction of the surgeon or interventionist. Others have used [2, 4, 7, 18] a more systematic approach and explored correlations of the 3D reconstructions with anatomical details visualized at MRI, angiography or surgery [4, 7, 18]. The 3D printed models were able to correctly reproduce anatomical details within a few millimetres. For example, Schievano et al. [7] found very limited operator error in data reconstruction (3.4%, corresponding to errors of ±0.75 mm) and excellent correlations between the 3D images and printed models. Similar accuracy was shown by Olivieri et al. for 3D printed models of ventricular septal defects [2]. Others have [4] demonstrated that the models could accurately reproduce 93–96% of major aorto-pulmonary collaterals (MAPCAs) identified during surgery or angiography. Valverde et al. [18] recently used a 3D printed model for simulation of endovascular stenting of a hypoplastic arch, with good agreement

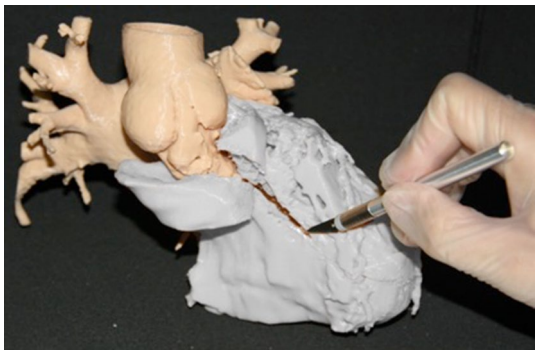

Fig. 2 3D printed model of the myocardium (*grey*) and blood pool (*orange*)

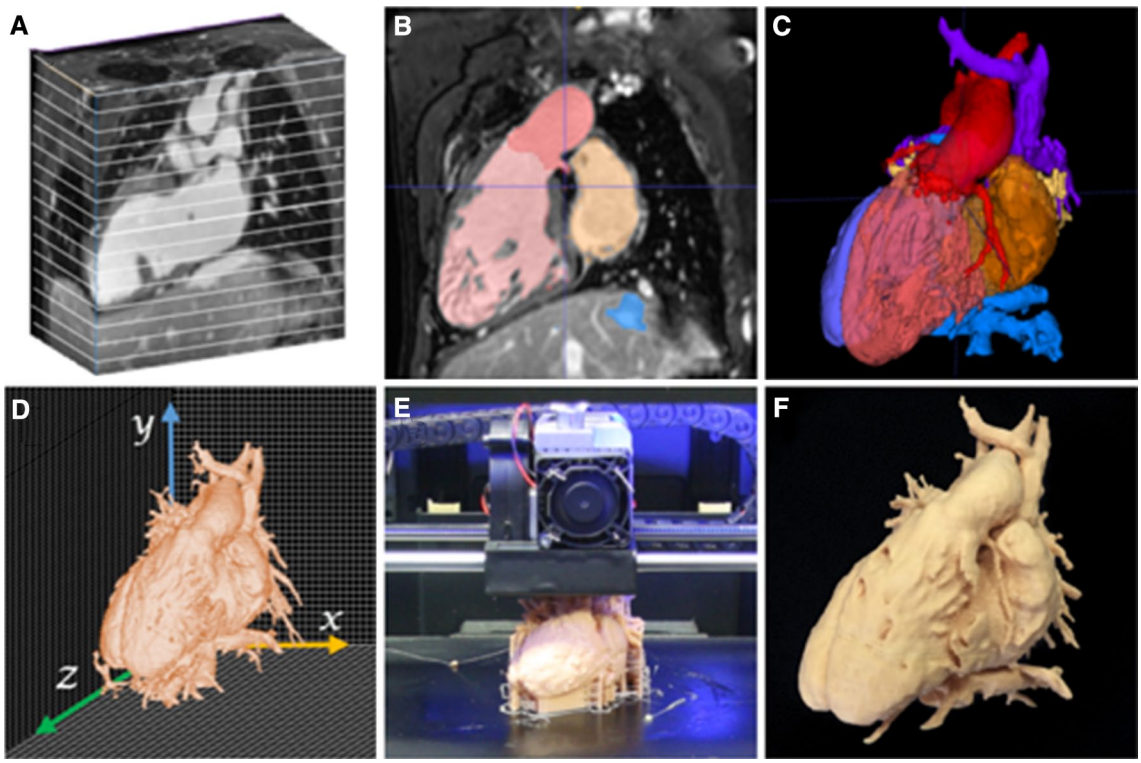

Fig. 1 The 3D printing process. **a** Radiological image. **b** Segmentation. **c** 3D volume render. **d** Computer aided design. **e** 3D printing by fused deposition modeling. **f** Final 3D printed model

Table 1 Overview of major published studies on 3D printing application in CHD

Author	Imaging technique	Sample size and age	CHD	Comments
Ngan et al. [4] Alberta, Canada 2006	CT	6 cases 6 months to 2 years	PA + VSD and MAPCAs	Models accurately reproduced 96 % of MAPCAs identified during surgery and 93 % of those identified during angiography. 3D models are helpful to plan intervention and orientate surgeon
Noecker et al. [5] Cleveland, USA 2006	CT	11 cases Median age, 3 years; range, 2 days to 13 years	With and without CHD	3D models provided visual and tactile representation of complex cardiac and chest anatomy, and were particularly helpful for the development and placement of medical devices
Schmauss and Sodian et al. [14] Germany 2014	CT/MRI	4 cases 3 month–16 years	1 ARSA, right descending Ao, 1 VSD, 2 failing SV	3D models are helpful to plan surgical or percutaneous interventions
Sodian et al. [6] Germany 2007	CT and MRI	1st case: 16 years old child 2nd case: 3 month old baby	1st case: child with tracheal stenosis due to ARSA and RAA (MRI) 2nd case: 3 month old baby with subpulmonary VSD (CT)	3D models are helpful to plan interventions and help surgeons with orientation
Sodian [3] Germany 2008	CT	1st case: 2 years old boy 2nd case: 14 years old girl	1st case: failing Glenn 2nd case: failing TCPC in list for transplantation	3D models are helpful to plan intervention and help surgeons with orientation
Schievano [7] London, UK 2007	MR	12 cases Mean age, 20 years; range, 9–39 years	Patients requiring pulmonary valve implantation	3D models improved patient selection for percutaneous pulmonary valve implantation
Shiraishi et al. [13] Japan 2010	CT	8 patients 4 days–4 years	Various CHD: Interrupted aortic arch, Aco, HLHS, DORV, PAVSD, APVR, PDA	3D models allowed surgeons to simulate operations
Vranicar et al. [11] Lexington, KY, USA 2008	CT	12 cases 19 days–29 years	Aortic arch anomalies (9 Aco, 3 vascular ring)	3D models are helpful to plan interventions
Motti-Link et al. [10] USA 2008	MRI	1 case	1 patient with L-TGA, PA, ASD, VSDs, TR, and dextrocardia	3D models are helpful to plan interventions
Ryan et al. [15] USA 2015	CT	1 case	PA + VSD + MAPCAs	3D model was helpful to plan intervention in patient without cardiac catheterization
Greil et al. [8] London, UK 2007	CT and MRI	5 cases 12.6 years (range 41 days–21 years)	Various CHD (TOF, D-TGA, and DORV)	3 models may be helpful for teaching, research and to plan intervention
Olivieri et al. [16] Washington, USA 2014	CT	1 case	D-TGA after Mustard	3D model may be helpful to plan percutaneous intervention, reduce radiation exposure and reduce complications
Olivieri et al. [2] Washington, USA 2015	3D echo	9 cases	8 VSD, 1 prosthetic peri-valvular leak	3D models are feasible and may help to plan intervention
Valverde et al. [9, 18] Spain 2015	MRI	2 cases 1st 15 years old boy 2nd 1.5 years old boy	1st Aco + Hypoplastic transverse arch 2nd TGA + VSD + PS	3D models are accurate and may help to plan intervention

Ao aorta, *Aco* aortic coarctation, *APVR* anomalous pulmonary venous return, *ARSA* anomalous right subclavian artery, *ASD* atrial septal defect, *CHD* congenital heart disease, *CT* computed tomography, *DORV* double outlet right ventricle, *HLHS* hypoplastic left heart syndrome, *MRI* magnetic resonance imaging, *3D* three dimensional, *MAPCAs*: major aorto-pulmonary collaterals, *PA* pulmonary atresia, *PDA* patent *ductus arteriosus*, *SV* single ventricle, *TOF* tetralogy of Fallot, *TCPC* total cavo-pulmonary connection, *TGA* transposition of the great arteries, *TR* tricuspid regurgitation, *VSD* ventricular septal defect

shown between aortic luminal diameters of the model and those obtained by MRI and angiography, assisting with pre-procedural device selection. These models also have excellent potential for teaching purposes (Table 1). Another interesting area is application for doctor-patient communication, as it has been shown to improve overall patient satisfaction.

Limitations of 3D printed models

At the present time, there are limitations to a widespread use of 3D printing in the management of patients with CHD. Major issues are the lack of standardized approaches, long processing times, and high costs. The current model is a rigid or flexible 'static' reproduction of cardiac anatomy, and does not allow reproduction of physiologic changes occurring during the cardiac cycles. To overcome this limitation, 'dynamic' models have been proposed [20].

Because this is a relatively new and experimental field, there is lack of standardization in the procedures and materials employed. Imaging techniques and acquisition modalities within each technique varied. The segmentation processes were also greatly different due to differences in software and automation. Furthermore, there were differences in printing related material and printers, producing changes in the physical properties of the models.

Lack of standardization in any process could introduce bias, as well as result in operator dependency. With regard to 3D printing, operator dependency is relevant in all steps from image acquisition and selection to the choice of areas to be segmented. Selection of systole or diastole for segmentation remains arbitrary, which may introduce bias in the final model. For instance, a pulmonary artery branch segmented in diastole is significantly smaller than in systole. Only one report has thus far indicated the phase of cardiac cycle chosen [2]. The influence of other confounding variables including image quality, differences among imaging techniques, and operator variability in image acquisition have never been investigated. Studies using a multi-modality approach of CT, MR and 3D echocardiography for the printing of 3D models are needed. Finally, the pediatric age poses additional technical issues for 3D imaging related to high heart rates and small cardiac structures.

Technical considerations

Image acquisition

The choice of the imaging technique primarily depends on institutional preferences and availability. Most work in this field used CT [4, 6, 8, 11, 13, 15, 16] and MRI [6–8, 10, 17]. Both modalities have been used separately [4, 5, 10, 11, 13, 15] or interchangeably [6, 8, 16, 17] within the same study protocol. Issues related to image spatial resolution and motion artefacts in CT and MRI might hamper segmentation of thin intra-cardiac structures such as valves and papillary muscles [7]. One study [2] used data from 3D echocardiography. Table 2 outlines protocols of CT/MRI acquisition from published studies [7, 10, 13]. Slice thicknesses of images acquired were consistent, varying from 0.625 [4] to 2 mm [3, 6]. General anaesthesia [4] or sedation [13] was used in some studies, while others performed examinations in awake patients [7, 10]. MRI acquisitions employed free breathing or [10] breath holding [7]. For CT, electrocardiogram gated acquisition was reported in one study [10]. In our opinion, gated-CT might offer the best image spatial resolution, however in children MRI based sequences may be preferred due to the avoidance of ionising radiation. Diastolic acquisition could be advantageous for evaluation of cardiac chamber size and intra-cardiac structures such as ventricular septal defects. Systolic acquisition is preferred for evaluation of vascular structures as diameters may be larger.

Translation of DICOM files into printable formats

A key step in the process is the conversion of DICOM images files into printable formats. Software for conversion (example Mimics, Materialize, The Netherlands) are commercially available, but expensive. A version of the Osirix software (Pixmeo, Geneva, Switzerland) is available free of cost, but the free version has limitations compared to the standard commercial product. Some institutions have custom-built software, for example, AYRA [21]. Semi-automated segmentation methods are commonly used [2, 13, 22] while manual [7, 10], or a combination of manual, semi-automated and automated segmentation options are available [2]. An in-depth review of the segmentation methodologies is provided in recent publications [22, 23].

The printing process

Table 3 shows the variety of printers and materials that have been used. The available materials include solid acrylic or plastic [4], urethane [5, 6, 12–14], or thermoplastic resin [7]. The choice of material could have an impact on applications. Rigid models provide a static representation of anatomy, while flexible models may be more suitable for surgical simulation [13]. Cold gas has been used for sterilization of models for intra-operative use in the operating room [4, 14].

Cost and times

Costs are related to [1] the software used to translate DICOM images, and [2] the process of printing itself. The combined cost has been estimated from 200 to 440 Euros [13, 14], up

Table 2 MRI/CT image acquisition for the building of 3D models

Authors	Technique	Scanner	Sequences/projections	Acquisition details
Sodian et al. [3, 6] Germany 2006–2008	CT/MRI	Not reported	Not reported	Only slice thickness (1–2 mm) reported
Schievano et al. [7] London, UK 2007	MRI	1.5T Symphony-Maestro: Siemens, Germany	Full description	3D gradient echo sequences TR/echo time (ms) 4.4/2.3 Flip angle 12° Slice thickness 1.3–1.5 mm Matrix 256 × 512, FOV 400–500 mm 0.4 ml of gadolinium
Motti-Link et al. [10] USA 2008	MRI	1T (Philips Intera CV, Best, NL; Intera 1.5T, Philips, Germany)	Full description	Slice thickness: 1.2 mm (reconstructed 0.7 × 0.9 mm), slice orientation: axial Single phase; TR/echo time (ms) 4.6/2.3 Flip angle 100°; FOV: 360 Matrix 304; SENSE factor 2.2 T2 preparation pulse (echo time = 50 ms) Free breathing
Ngan et al. [4] Alberta, Canada 2006	CT	General electric light Speed CT (GE Milwaukee, USA)	Partial description	Slice thickness 0.625 –1.25 mm Slice overlap 50 %, breath-hold under general anesthesia, contrast 2 ml/kg over 10–15 s
Shiraishi et al. [13] Japan 2010	CT	Philips Brillance 64 slice CT or Toshiba Aquili on 16 slice CT	Full description	Tube voltage 80–120 kv 100–300 mA Slice thickness 1.0 mm 0.5-s gantry rotation time 0.600–687mm beam pitch
Schmauss and Sodian et al. [14] Germany 2014	CT/MRI	CT (64 or 128 slices)	Not reported	Not reported
Greil et al. [8] London, UK 2007	CT/MRI	CT (64–32 slices) MRI 1.5T (Philips Medical Systems, Best, NL and Sonata, Siemens Medical, Erlangen, Germany)	Full description	CT: slice thickness: 0.6 mm 1 breath hold and 1 intubated ECG gated MRI (SSFP): slice thickness: 1.2–2.2 mm ECG gated; Sedated patients
Valverde et al. [9, 18] Spain 2015	MRI	Philips Ingenia 1.5T (Philips medical), (HVR, HUM, HRSC) and Siemens signa HDXT 1.5T scanners	Full description	MRI (SSFP) ECG gated Slice thickness 1.5 × 1.5 × 1.5 mm TR/echo time (ms) = 3.4/1.7, flip angle = 90°

CT computed tomography, *MRI* magnetic resonance imaging, *3D* three dimensional, *NR* not reported, *ECG* electrocardiogram, *FOV* field of view, *TR* repetition time, *SENSE* sensitivity encoding

Table 3 Segmentation software, printers and materials for 3D printing

Author	Software for segmentation	Printer/prototyping machine	Material
Ngan et al. [4] Alberta, Canada 2006	Magic 8.01 software (Materialise, Lueven, Belgium) Hardware Free FORm modelling system version 7.0 and PHANTHOM desktop hepatic device, Sensable technology, Woburn, Mass	Stratasys prodigy plus (Stratasys Inc, Eden Praire, MN, USA) or InVisionsi2 3-d printer (3D system, Valencia, CA, USA)	Solid acrylic or plastic anatomic model
Noecker et al. [5] Cleveland, USA 2006	Stereolithography machine (SLA 250/30A, 3D Systems, Valencia, CA, USA)	Z printer 310, Z Corporation, Burlington MA, USA	Two-part polyurethane (Synair Corporation, Chattanooga, TN), two-part silicone rubber (MED 4210 NuSil,Carpenteria, CA, USA)
Schmauss and Sodian [14] Germany 2014	Amira (Mercury computer systems, Chelmsford, MA, USA)	Spectrum Z™ 510, Z Corporation, Burlington, MA, USA	Starch/cellulose powder (zp 15e) bound with polymer (zb 60) and elastomeric urethane resin (Por-A-Mold 2030)
Sodian [6] Germany 2007	NR	Z corporation, Burlington MA, USA	NR
Sodian [3] Germany 2008	NR	Z corporation, Burlington MA, USA	NR
Schievano et al. [7] London 2007	NR	P1500 polyester, Stratasys, Eden Prairie, MN, USA	Thermoplastic resin
Shiraishi et al. [13] Japan 2010	Stereolithography biomodeling company (JMC, Yokohama, Japan)	NR	Rubber like models urethane
Motti-Link et al. [10] USA 2008	Produced by authors	Z printer 310, Z Corporation, Burlington MA, USA	NR
Ryan et al. [15] USA 2015	NR	NR	NR
Greil et al. [8] London, UK 2007	Marching cube algorithm	Eosint P 385, EOS, GmbH, Electro Optical Systems, Germany	NR
Olivieri [16] Washington, USA 2014	Magic 8.01 software (Materialise) Lueven, Belgium	Object 500, Connex, Polyjet printer; Stratasys Prodigy Plus (Stratasy Inc, Eden Praire, MN, USA)	NR
Olivieri et al. [2] Washington, USA 2015		Object 500, Connex, Polyjet printer; Stratasys Prodigy Plus (Stratasy Inc, Eden Praire, MN, USA)	NR
Valverde et al. [9, 18] Spain 2015	AYRA	(BQ Witbox, Spain)	Polyurethane

CT computed tomography, *MRI* magnetic resonance imaging, *3D* three dimensional, *NR* not reported

to 870 Euros [10]. Process time represents a limitation currently, because manual segmentation may take hours [7], and the entire process may take a few days [13]. Rapid segmentation process (<30 min) has been described [10]. A more widespread use of 3D models in multiple medical settings [24, 25] may help decrease costs related to software, printers, and materials. It may also implement more rapid semi-automated or automated processes [10]. The use of 3D models could also potentially reduce costs by diminishing operative times and improving outcomes [26, 27]. Superior procedural planning could result in savings derived from reduced interventional time, radiation time and optimal device selection. However, true cost-analysis assessment of 3-D models has not yet been performed [26, 27].

Conclusion

Recent technology allows good quality three-dimensional printing of models for CHD in all ages. These models could be used for planning of surgical or percutaneous management of CHD with satisfactory results. At the present time, experience with these models in CHD remain limited to case reports or small studies. More investigations into assessment of outcomes and cost-effectiveness of 3D printed models in endovascular and surgical management of CHD are warranted.

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Compliance with ethical standards

Conflict of interest None declared.

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