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ORIGINAL ARTICLE

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Three-dimensional printed models for surgical planning of complex congenital heart defects: an international multicentre study

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Abstract

OBJECTIVES: To evaluate the impact of 3D printed models (3D models) on surgical planning in complex congenital heart disease (CHD).

METHODS: A prospective case-crossover study involving 10 international centres and 40 patients with complex CHD (median age 3 years, range 1 month–34 years) was conducted. Magnetic resonance imaging and computed tomography were used to acquire and segment the 3D cardiovascular anatomy. Models were fabricated by fused deposition modelling of polyurethane filament, and dimensions were compared with medical images. Decisions after the evaluation of routine clinical images were compared with those after inspection of the 3D model and intraoperative findings. Subjective satisfaction questionnaire was provided.

RESULTS: 3D models accurately replicate anatomy with a mean bias of -0.27 ± 0.73 mm. Ninety-six percent of the surgeons agree or strongly agree that 3D models provided better understanding of CHD morphology and improved surgical planning. 3D models changed the surgical decision in 19 of the 40 cases. Consideration of a 3D model refined the planned biventricular repair, achieving an improved surgical correction in 8 cases. In 4 cases initially considered for conservative management or univentricular palliation, inspection of the 3D model enabled successful biventricular repair.

CONCLUSIONS: 3D models are accurate replicas of the cardiovascular anatomy and improve the understanding of complex CHD. 3D models did not change the surgical decision in most of the cases (21 of 40 cases, 52.5% cases). However, in 19 of the 40 selected complex cases, 3D model helped redefining the surgical approach.

Keywords: Congenital heart defects • Surgery • Imaging • 3D printing • Medical computer-aided design

CONGENITAL

INTRODUCTION

Surgical planning for complex congenital heart defect (CHD) is challenging due to the broad spectrum of conditions and high variability between individuals. A thorough understanding of the complex spatial relationships between anatomical and defective structures may avoid unexpected findings and therefore may reduce operative time and mortality.

However, visualization of conventional 3D imaging techniques is limited by presentation on a flat screen and can hamper full comprehension of complex intracardiac anatomy. 3D printed cardiovascular models may exploit these imaging techniques to physically reproduce an accurate representation of the patient's anatomy, allowing surgical simulation and manoeuvres to be performed as in the live operating theatre [1–3]. For all this promise, however, only case series of this application for surgical planning have been published, which provide only qualitative evidence and no statistical support [4–10].

The goal of this study was to validate in a large international multicentre study and statistical evidence the utility of 3D printed models for planning of complex CHD surgery. We hypothesized that 3D heart models: (i) are accurate replicas of patient anatomy; (ii) improve the overall satisfaction of surgeons and paediatric cardiologists involved in this process; and therefore, (iii) have an impact on the decisions that govern surgical management in complex CHD.

MATERIALS AND METHODS

Study design

A prospective case-crossover, international, multicentre study was conducted between April 2013 and June 2015 involving 10 hospitals (Supplementary Material). The study complies with the Declaration of Helsinki and was approved by the institutional review board of each participating centre. Patients were included at their local multidisciplinary meeting (MDM, including cardiac surgeons, paediatric cardiologists and imaging specialists), where anatomical complexity meant that significant differences in opinion between members of the care team were initially expressed prior to surgical management pathway being collectively agreed. To evaluate the incremental diagnostic value of 3D models, the study design comprised 3 sequential surgical planning stages (Fig. 1) in which a questionnaire was filled.

At Stage I, surgical management decision was based in the absence of a 3D model, relying only on routine clinical practice observations and available conventional imaging data including 2D and 3D echocardiography, magnetic resonance imaging (MRI) and computed tomography (CT), where virtual 3D image reconstructions of the anatomy were shown by imaging specialists.

At Stage II, a 3D model was requested for surgical reassessment. Demographic, clinical and imaging data (CT and MRI) were collected by participating centres, de-identified and uploaded to a dedicated cloud server (Supplementary Material, Fig. S1). Data were downloaded by a single centre (Hospital Virgen del Rocio, Seville, Spain) for consolidation and 3D printing. 3D printed models were sent by urgent delivery post to the referral centre for surgical re-evaluation by the same MDM, in order to know whether the additional information of the 3D model changed the surgical decision. Surgeons were allowed to examine the model, cutting it with appropriate surgical instruments and plan potential strategies.

Finally, for those cases undergoing surgery, it was evaluated whether after intraoperative inspection the surgical plan was changed compared to the 3D model-based plan. Surgeons and paediatric cardiologists also completed a subjective questionnaire (Supplementary Material, Table S1) to assess the utility of 3D models for surgical planning, communication, education and their overall satisfaction with the models.

Demographics, clinical and imaging data

Patient demographics, clinical characteristics and imaging data were collected. CT scans were performed with a 320-detector row CT scanner (Toshiba AquilionOne, Otawara, Japan) with dedicated paediatric settings according to body weight. MRI was performed using Philips Ingenia 1.5 T (Philips Medical Systems, Best, The Netherlands) and Siemens Signa HDxt 1.5 T scanners (Siemens Healthcare, Erlangen, Germany). Data were acquired using a previously described 3D balanced steady-state free precession pulse sequence [11] at mid-diastole rest period.

3D printing

The 3D printing process comprises several sequential stages [2] as shown in Fig. 2. The image segmentation is the process of isolating the anatomical structures of interest from medical images (CT and MRI) and was performed using ITK snap [12] software by a consultant CHD cardiologist with more than 5 years expertise in cardiac imaging. The segmented geometry was exported as a 3D surface file into Meshmixer version 11.0.544 (Autodesk Inc., San Rafael, CA, USA) for computer-aided design. A 0.8-mm outer shell was added outside of the blood pool interface. The geometry was processed by Cura version 15.02 (Ultimaker BV, Netherlands) and sent to the 3D printer (BQ Witbox, Spain). All models were fabricated in polyurethane filament by fused deposition modelling.

3D model dimension accuracy evaluation

In 20 randomly selected cases, 2 orthogonal diameters of 10 anatomical structures were measured in both the medical images (using Osirix software) and in the 3D model (using a digital calliper) (Fig. 3; Supplementary Material). To assess intra-observer variability, one observer repeated the same measurements 3 months after the initial analysis in 10 random cases. For interobserver variability, an additional independent observer analysed 10 cases.

Statistical analysis

Normally distributed continuous variables are presented as mean ± standard deviation, and continuous variables that were not normally distributed are presented as median and interquartile range (25th, 75th percentile). Normality was assessed by the Shapiro–Wilk test and normal probability plot. Categorical variables are presented as frequency (percentage). To assess the agreement between clinical images and 3D models, a Bland–Altman analysis was used, and statistical differences were evaluated by independent *t*-test. Inter- and intra-observer variance were assessed using the coefficient of variance. Kappa coefficient was calculated to evaluate the agreement in management decision between conventional surgical plan and 3D model surgical plan. The percentage of change in the surgical management decision is expressed as confidence intervals. All tests were assessed

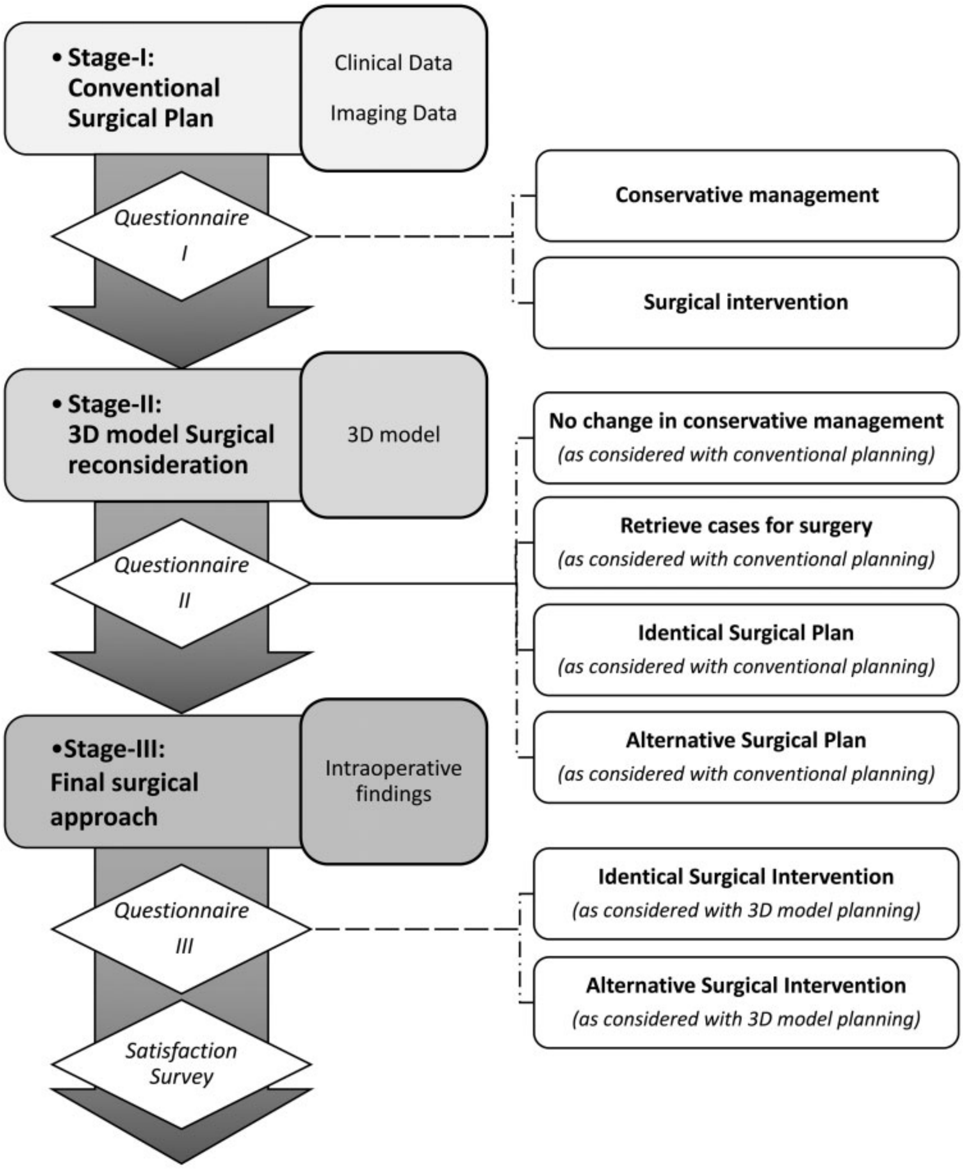

• Stage-I: Conventional Surgical Plan
Clinical Data
Imaging Data
Questionnaire I
Conservative management
Surgical intervention
• Stage-II: 3D model Surgical reconsideration
3D model
Questionnaire II
No change in conservative management
(as considered with conventional planning)
Retrieve cases for surgery
(as considered with conventional planning)
Identical Surgical Plan
(as considered with conventional planning)
Alternative Surgical Plan
(as considered with conventional planning)
•Stage-III: Final surgical approach
Intraoperative findings
Questionnaire III
Identical Surgical Intervention
(as considered with 3D model planning)
Alternative Surgical Intervention
(as considered with 3D model planning)
Satisfaction Survey

Figure 1: Study protocol design.

at the *P*-value <0.05 level of significance. Statistical analyses were performed using SPSS Version 20.0.

RESULTS

Forty patients were included in the study from 10 international centres involving over 80 paediatric cardiologists and 22 surgeons. Table 1 describes the demographic and clinical characteristics of the study cohort.

3D printing

All MRI ($n = 28$) and CT ($n = 12$) studies provided adequate image quality for image segmentation, and all 40 cases were successfully fabricated. Mean segmentation time was 75 ± 32 min and mean computer-aided design time was 89 ± 22 min. Mean printing time was 35 ± 26 h, and it was directly related to the patient's heart size ranging from 8 h to 24 h for small children hearts and from 48 h to 72 h for adult-size hearts. The time interval between the model request and delivery to the surgical unit also depended on the urgency request, with the shortest response time in 48 h and the mean response time of 7–10 days for non-urgent cases. In 13 cases, printing was unsuccessful due to wall collapse or the printing head clogging and had to be repeated.

3D model dimension accuracy

A total of 320 vascular diameters were measured. Excellent agreement was found between caliper measurements on the 3D model and measurements on the MRI (mean difference -0.30 ± 0.67 mm, $P = 0.66$) and on the CT images (mean difference -0.16 ± 0.85 mm, *t*-test $P = 0.85$) (Fig. 3C). Overall, the 3D models marginally overestimated measurements made by both CT and MRI but by only 0.27 ± 0.73 mm, $P = 0.6$. There was excellent reliability in repeated measurements with an intra-observer intraclass correlation coefficient of 0.998 and an inter-observer variability of 0.996.

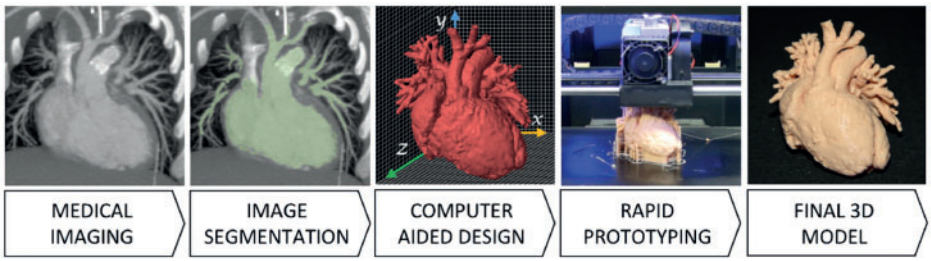


Figure 2: The sequential 3D printing process.

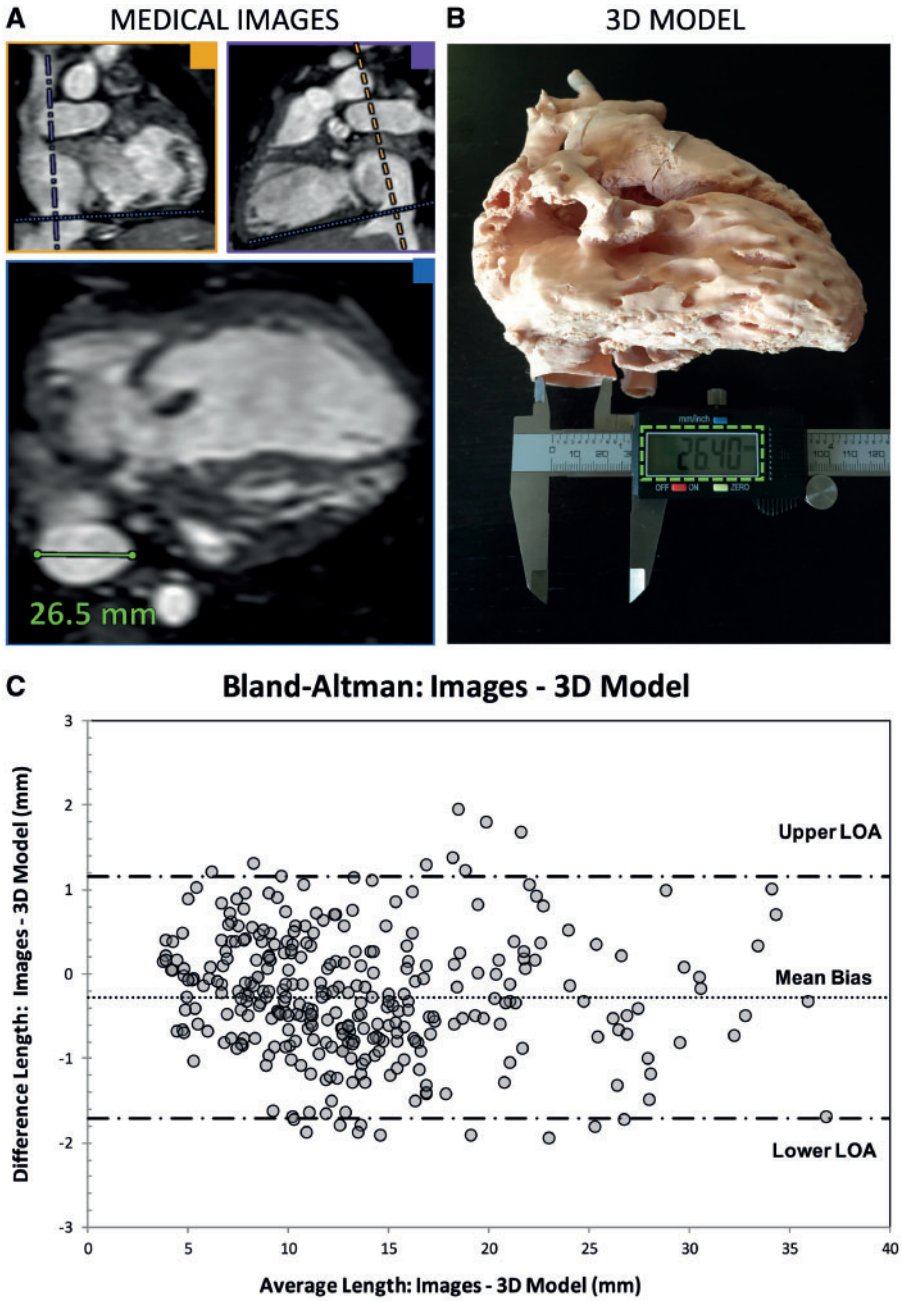


Figure 3: 3D model dimension accuracy evaluation. (**A**) Multiplanar reformat of medical images (MRI 3Dbssfp) in coronal (orange box) and sagittal view (purple box) to obtain a cross-sectional plane (blue box) to measure the inferior vena cava. (**B**) Measurement of the inferior vena cava in the 3D model in the same orientation as in A using a digital caliper. (**C**) Bland–Altman plot measurement agreements between medical images (magnetic resonance imaging/computed tomography) and 3D models. LOA: limits of agreement, ±2 SDs. Values expressed as millimetre.

Table 1: Demographic and clinical characteristics

Patient demographics	
Patients (*n*)	40
Age (years)	3 (1 month–34 years)
Weight (kg)	13 (2.9–82)
Height (cm)	90 (50–182)
Body surface area (m^2)	0.6 (0.2–2)
Female:male (*n*)	22:18
Congenital heart disease (*n*)	
DORV	19
Complex TGA	6
UVH physiology	4
Large VSD	5
Criss-cross heart	3
LVOTO	1
Heterotaxy syndrome	1
Discordant AV and VA connections	1
Imaging modality characteristics	
MRI (*n*)	28
In-plane resolution (mm)	1.51 ± 0.66
Thickness (mm)	2.33 ± 0.78
Slices (*n*)	116 ± 81
CT (*n*)	12
In-plane resolution (mm)	0.33 ± 0.08
Thickness (mm)	0.65 ± 0.0.22
Slices (*n*)	397 ± 65
3D printing	
Segmentation time (min)	75 ± 32
Printing time (h)	35 ± 26

Demographic data are median and range. Imaging modality and 3D printing parameters expressed as mean ± standard deviation.
DORV: double-outlet right ventricle; TGA: transposition of the great arteries (concordant AV and discordant VA connections); UVH: univentricular heart; LVOTO: left ventricular outflow tract obstruction; AV and VA: atrioventricular and ventriculo-arterial; VSD: ventricular septal defect.

Questionnaire satisfaction survey

A total of 13 surgeons and 30 paediatric cardiologists completed the questionnaire across all cases. For the purposes of surgical planning, 82% of the surgeons strongly agreed that the 3D models provided better understanding of the CHD and 88% strongly agreed that they could become a routine tool for surgical planning in complex CHD (see Fig. 4); 89% of the surgeons strongly agreed that the 3D model was useful for the education of trainees and fellows. All of the surgeons and paediatric cardiologists agreed or strongly agreed that 3D models were useful for better communication with other colleagues. Less substantially but still positively, 67% of surgeons agreed or strongly agreed that the model was useful to communicate with parents and patients. However, it must be considered that 29% of them did not know as they had not used the 3D model at patient consultation. Overall, surgeons and paediatric cardiologists rated their satisfaction with 3D models as 9.3 and 9.0 out of 10 respectively.

Surgical management decision change

After conventional surgical planning, 12 cases were considered for conservative management and 28 patients were candidates for surgical intervention. A comparison of the surgical decisions made at stages is summarized in Fig. 5. A detailed description of all the cases is included in Videos 1 and 2 and Supplementary Material, Table S2.

In most of the cases, i.e. 21 of the 40 cases (52.5% of the cases, confidence interval 38.5–70.7%), the information provided by the 3D models did not result in any change to the surgical decision based on conventional imaging planning. On the other hand, 3D models modified the surgical decision in 19 cases (47.5% of the cases, confidence interval of 29.6–61.5%). The difference in surgical decisions made conventionally and those aided by a 3D model is summarized by the kappa coefficient ($\kappa = 0.36$, confidence interval 0.19–0.51, $P < 0.001$), which indicates only fair agreement.

No change to conservative management after 3D model evaluation. A decision to conservatively manage was maintained in 9 cases (Cases 1–9), all with univentricular heart (UVH) physiology. All cases were asymptomatic with balanced parallel circulations, either with pulmonary stenosis (Cases 6–9), pulmonary artery banding (Cases 2, 4 and 5; see Fig. 6), or BCPC (Cases 1 and 3).

Change from conservative management to surgery after 3D model evaluation. Three of the 12 cases (25% of the cases, confidence interval 5.5–57.2%), which were initially considered for conservative management, were subsequently referred for surgical repair, after evaluation of the 3D model: 2 for biventricular repair (Cases 10 and 11) and 1 for UVH physiology staged palliation (Case 12).

No change to the surgical plan after 3D model evaluation. In 12 cases initially considered for surgery, the surgical approach was maintained. Biventricular repair was employed in 7 cases (Cases 13–19). UVH palliation was maintained in 5 cases (Cases 20–24). In all the 12 cases, the same approach as predicted using the 3D model was successfully achieved.

Change to the surgical plan after the 3D model evaluation. In 15 of the 28 cases conventionally considered candidates for surgery, the surgical approach was modified after evaluation of the 3D model. This is a 53.6% change in the surgical plan (confidence interval 33.9–72.5%).

In 4 cases (Cases 25–28), the initial approach favoured univentricular palliation surgery, however, after inspection of the 3D model, this was rejected for biventricular repair, which was subsequently performed successfully in all cases.

In 2 cases (Case 29 and 30), the conventional surgical plan included biventricular repair. However, after consideration of the 3D model, this was changed for univentricular staged palliation.

In 1 case (Case 31), the inspection of the 3D model modified the Fontan conversion by not only replacing the original extracardiac tube but also enlarging the restrictive ventricular septal defect (VSD).

In 8 cases (Cases 32–39), the 3D model helped to modify the planned biventricular repair for left ventricular outflow tract obstruction (see Fig. 7; Supplementary Material and Supplementary Material, Table S2).

Change from surgery to conservative management after the 3D model evaluation. In Case 40, the decision to surgically close a large VSD was changed in favour of conservative

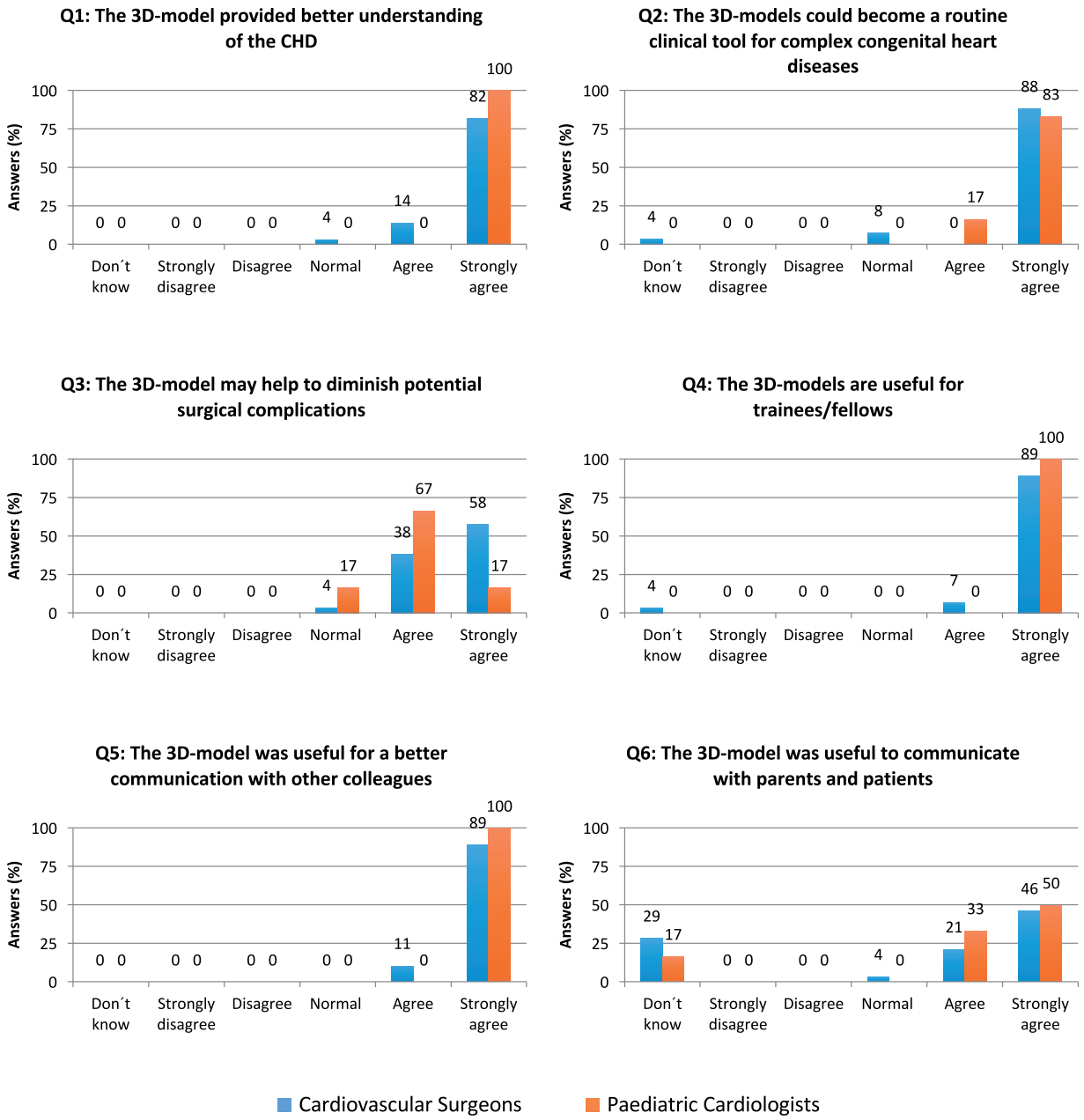


Figure 4: Questionnaire evaluation.

management after the 3D model evaluation, as it was considered that the VSD could be closed percutaneously when the child grows.

Final surgical intervention change

A total of 30 surgeries were finally performed. The surgical approach was maintained after evaluation of the 3D model in 96.7% of the cases (confidence interval of 80–99%). Only in 1 case (Case 39), the surgical plan was changed intraoperatively. All cases survived with good clinical outcome, and no major complications, except Case 39 who died 48 h after surgery. He was a 15-year-old boy with atrioventricular discordant connections and double-outlet right ventricle (see Supplementary Material). Although the coronary arteries were clearly shown in the MRI and 3D model, due to previous surgery and fibrosis its origin and proximal course could not be intraoperatively identified with confidence to undergo a Nikaidoh operation. This unexpected complication increased the surgical procedure time in the context of a long double-switch intervention, changing the surgical approach intraoperatively performing a Senning and an REV procedure.

DISCUSSION

In recent years, we have contemplated a growing optimism that 3D models can enhance planning of CHD surgeries [1–3]. While this position is largely based on anecdotal and qualitative case reports, rigorously obtained statistical studies are lacking [4–10]. Methodologically, this evidence base would be best established by clinical trials. However, this scenario raises ethical issues

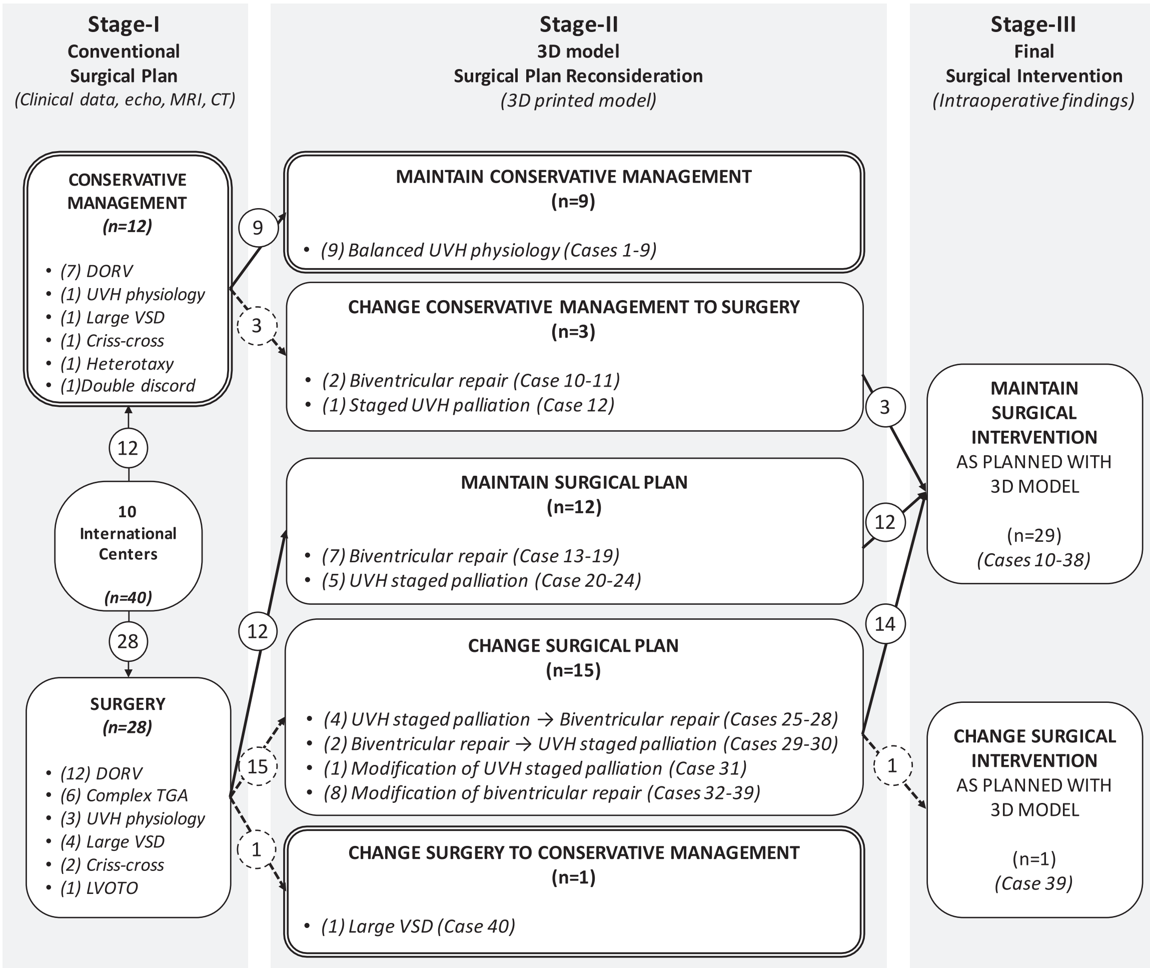
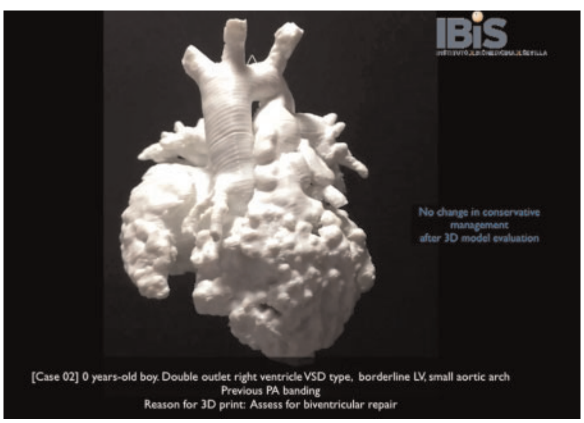
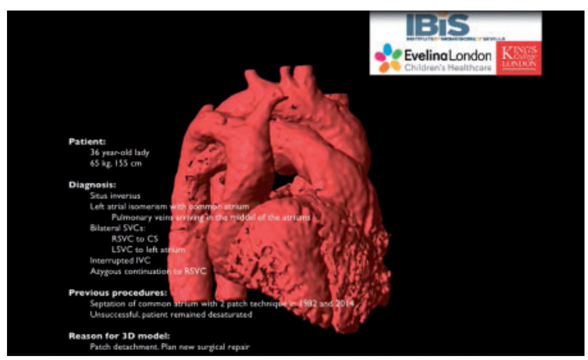

Stage-I
Conventional
Surgical Plan
(Clinical data, echo, MRI, CT)
Stage-II
3D model
Surgical Plan Reconsideration
(3D printed model)
Stage-III
Final
Surgical Intervention
(Intraoperative findings)
CONSERVATIVE MANAGEMENT
(n=12)
• (7) DORV
• (1) UVH physiology
• (1) Large VSD
• (1) Criss-cross
• (1) Heterotaxy
• (1)Double discord
12
10 International Centers
(n=40)
28
SURGERY
(n=28)
• (12) DORV
• (6) Complex TGA
• (3) UVH physiology
• (4) Large VSD
• (2) Criss-cross
• (1) LVOTO
9
3
12
15
1
MAINTAIN CONSERVATIVE MANAGEMENT
(n=9)
• (9) Balanced UVH physiology (Cases 1-9)
CHANGE CONSERVATIVE MANAGEMENT TO SURGERY
(n=3)
• (2) Biventricular repair (Case 10-11)
• (1) Staged UVH palliation (Case 12)
MAINTAIN SURGICAL PLAN
(n=12)
• (7) Biventricular repair (Case 13-19)
• (5) UVH staged palliation (Case 20-24)
CHANGE SURGICAL PLAN
(n=15)
• (4) UVH staged palliation → Biventricular repair (Cases 25-28)
• (2) Biventricular repair → UVH staged palliation (Cases 29-30)
• (1) Modification of UVH staged palliation (Case 31)
• (8) Modification of biventricular repair (Cases 32-39)
CHANGE SURGERY TO CONSERVATIVE MANAGEMENT
(n=1)
• (1) Large VSD (Case 40)
3
12
14
1
MAINTAIN SURGICAL INTERVENTION
AS PLANNED WITH 3D MODEL
(n=29)
(Cases 10-38)
CHANGE SURGICAL INTERVENTION
AS PLANNED WITH 3D MODEL
(n=1)
(Case 39)

Figure 5: Surgical management decision. Continuous arrow: no change in management decision. Dotted arrows: change in management decision. Conservative management showed in double line box. Surgery management showed in single line box.



Video 1: 3D models surgical management decision change. Summary of the most interesting cases.

concerning the randomization of children to an inferior care pathway without the potential advantage of a 3D model [13]. This may explain why no prospective control group studies have been performed. Retrospectively matched controls may be preferable. Additionally, when coupled with the relative paucity of complex cases of CHD, the high variance in metrics of operative


Patient:
36 year-old lady
65 kg, 155 cm
Diagnosis:
Situs inversus
Left atrial isomerism with common atrium
Pulmonary veins arriving in the middel of the atriums
Bilateral SVCs:
RSVC to CS
LSVC to left atrium
Interrupted IVC
Azygous continuation to RSVC
Previous procedures:
Septation of common atrium with 2 patch technique in 1982 and 2014
Unsuccessful, patient remained desaturated
Reason for 3D model:
Patch detachment. Plan new surgical repair

Video 2: Surgical planning of complex heterotaxy syndrome. Heterotaxy syndrome, midline liver and dextrocardia. Isomerism of left atrial appendages, bilateral superior vena cava (SVC), right superior vena cava (RSVC) to unroof coronary sinus (CS), left superior vena cava (LSVC) to left-sided atrium, interrupted inferior vena cava (IVC) with azygous continuation, hepatic veins to left sided atrium. Previous surgery: septation of common atrium with 2-patch technique at 2 years and 34 years of age. Clinical status: severe heart failure, desaturated ($SatO_2$ 85% at rest, 80–81% after walking briefly), severe tiredness preventing daily routine activities (NYHA Class III). Surgical question: feasibility of surgical repair. Conventional surgical plan: conservative management: doubts of feasibility for surgical repair. 3D model surgical plan: surgery felt to be feasible: septation of the atrium possible, redirection of the systemic venous flow to the tricuspid valve and commitment of the PV to the mitral valve. The abnormal systemic venous drainage had previously been misunderstood. Final surgical intervention: identical to that planned in the model.

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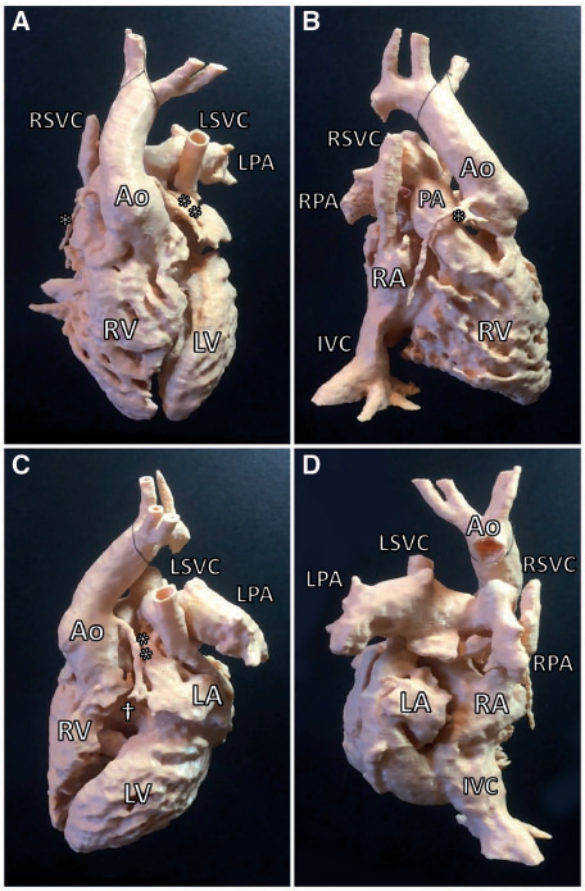

Figure 6: 3D printed model of Case 5. Double-outlet right ventricle with pulmonary artery band palliation. (**A**) Anterior view showing bilateral right (RSVC) and left superior vena cava (LSVC) and the proximal course of the right (*) and left coronary arteries (**). (**B**) Right lateral view clearly demonstrates the double-outlet right ventricle (RV) with both the pulmonary artery (PA) and aorta (Ao) arising from the RV. (**C**) Left lateral view shows the relationship of the aorta (Ao) with the left ventricle (LV) through the VSD (†). (**D**) Posterior view shows both right (RPA) and left pulmonary arteries (LPA), right (RA) and left atrium (LA) and inferior vena cava (IVC). The 3D model was very helpful. Firstly, it demonstrated that biventricular correction might be inappropriate due to the long distance between the VSD (†) and the aorta (Ao). Consequently any such repair would significantly reduce RV volume. Secondly, the 3D model will help to plan the univentricular palliation surgery when required. This will require a Damus–Kaye–Stansel operation plus atrial septostomy and VSD augmentation.

performance (such as cross-clamp or bypass time) necessitates multicentre study design. Unfortunately, the use of retrospectively matched controls within a multicentre study is hampered by variation in surgical practice between different hospitals. Even when selected from a single unit, cases matched on the basis of similar CHD anatomical features, weight, height and clinical status are often drawn from different surgical eras and teams. Variation in surgical practice is a potential confounding factor for a retrospectively controlled, multicentre study.

Our study resolves these limitations using a case-crossover design in which each patient serves as its own control. Each case is firstly evaluated based on routine imaging techniques (echocardiography, MRI and CT). Then each case is re-evaluated by the same clinical and surgical team but with the addition of a 3D model as a further surgical planning tool. This removes bias associated with inconsistent surgical practice but maintains as source of objective and measurable statistical evidence. This solution is supported by previous studies in CHD [14] and is particularly appropriate in children [15], given the ethical concerns surrounding randomization. On the other hand, a limitation of this approach is that it is only sensitive to the impact of 3D models on surgical planning, not on mid- and long-term surgical outcomes. Surgery is performed after experimental/control crossover and data collection. Hence the effect of 3D models on morbidity, mortality and reduced financial costs cannot be evaluated. Another limitation concerns the difficulty of blinding research participants. Having the same clinicians and surgeons assess each case either side of crossover removes bias associated with variation in clinical practice. However, since the same group has requested the 3D model, this lack of blinding may exaggerate the positive effect recorded. To diminish the impact of individual bias, the complete MDM team was involved in the surgical decision. Finally, another limitation is the wide variability of the complex CHD conditions that we included and the limited number of patients included.

In 21 cases (52.5%, confidence interval 38.5–70.7%), the surgical decision was not objectively changed by consideration of a 3D model. This result must be considered in the context of complex case selection, as 3D models were only requested when significant differences in surgical pathway opinions were discussed at the local MDMs. It might be that the impact on surgical planning is lower in structurally simpler cases of CHD. In these instances, the added value of 3D models may not justify the time and expense invested in their fabrication. We also acknowledge that not all senior surgeons or surgeons from large units recognize the advantages of 3D models. Some prefer to rely on their vast experience or their ability to reconstruct the complex geometry in their mind. Nevertheless, in complex cases, there is a subjective value that should not be neglected. As stated by one of the surgeons, 'in complex CHD cases, 3D models helps to increase confidence that the chosen surgical decision and approach is the right one'.

On the other hand, our study suggests that in patients with complex CHD, 3D printed models may have a small but clinically significant impact on clinical practice, redefining the best surgical approach in 19 cases (47.5%, confidence interval 29.6–61.5%). In 9 cases, 3D models prompted only small modifications of the surgical approach. These included adjustment in biventricular repair (8 cases) and adaptation of the UVH physiology approach (1 case).

Remarkably in 10 cases (25%), inspection of the 3D model resulted in significant modifications of the surgical plan. It should be emphasized that in up to 3 cases, patients who were thought not to be surgical candidates were surgically corrected achieving a successful biventricular repair in 2 of them (Cases 10 and 11) and palliated with UVH physiology in 1 patient (Case 12). Also important, in 4 cases initially considered for UVH physiology palliation (Cases 25–28), evaluation of the 3D model changed the surgical decision to biventricular repair which was successfully achieved. It is also notable that in 3 cases, 3D models permitted the clinical team to reassess their initial plan and adopt an approach perceived to reduce risk (Cases 29, 30 and 40). In 2 cases considered initially for biventricular repair (Cases 29 and 30), UVH-staged palliation was preferred after consideration of the 3D model. This demonstrated that the VSD was too large for septation. Had the 3D model not been considered, this insight may have gone unnoticed and resulted in a difficult or unsuccessful biventricular repair. This observation is reflected in the survey questionnaire: 96% of surgeons agreed or strongly agreed that 3D models helped reduce the potential for surgical complications. As several surgeons stated, '3D models eliminate the subjective part prone to error which is the

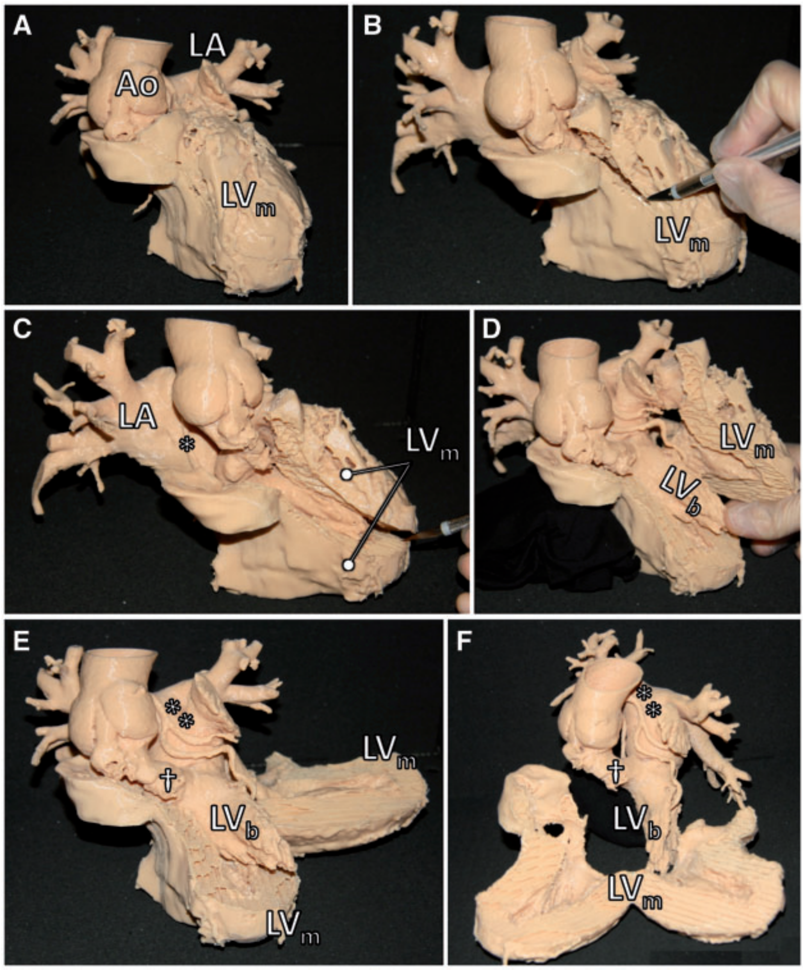

Figure 7: 3D printed model of Case 34. The 3D model of the left heart anatomy comprises: the left ventricular myocardium (LVm) and associated blood pool (LVb), left atrium (LA) and aorta (Ao). The myocardium can be dissected (**B–D**) revealing the LVb, LV to Ao baffle stenosis (†), right coronary artery (*) and left coronary artery (**).

surgeon imagination to interpret the size and relationship of anatomical structures (such as the VSD) in multiplanar reformatted images displayed on a flat screen'.

Surgical planning and decision-making informed by 3D models were successfully accomplished in 29 of the 30 cases undergoing surgery. This implicitly suggests that there was good geometrical agreement between the 3D model and patient-specific anatomy. This is supported by the non-clinically significant diametric bias of only -0.27 ± 0.73 mm between medical images and the 3D models.

Patient-specific anatomical geometries were derived from either CT or MRI (3D bSSFP acquisition) depending on institutional preference. Our experience favours the use of MRI 3D bSSFP [11, 16], particularly during diastole as it most closely resemble the form of the arrested heart, as it would be encountered surgically.

While the 3D models in this study have made significant contributions to surgical care, they lack potentially valuable anatomical information that may enhance their utility. This includes valve morphology and dynamic changes in geometry that occur during the cardiac cycle. Some preliminary studies have used 3D echocardiography to print atrial septal defects and valve leak [17, 18]. Each of image acquisition, segmentation and additive manufacturing technique affects the accuracy and cost of 3D printed models. These factors have been discussed previously [1–3] and are expanded on in the Supplementary Material. The cost of printing ranges from $300 to $1000, depending on the software, printing technology and materials [19]. The use of open-source software and low-cost fused deposition 3D printer in this study was motivated by a desire to reduce cost below 500$ while maintaining model accuracy.

CONCLUSION

In conclusion, we have objectively investigated the impact of 3D models on the surgical decision change of 40 patients with complex CHD. To date, this is the largest multicentre study of this emerging clinical technique. We have shown that 3D models are accurate replicas of the cardiovascular anatomy. In the majority of the cases, 3D models supported the surgical decision with no changes in the surgical approach. However, in 19 of the 40 complex cases, consideration of a 3D model redefined surgical management.

SUPPLEMENTARY MATERIAL

Supplementary material is available at *EJCTS* online.

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REFERENCES

[1] Loke T, Krieger A, Sable C, Olivieri L. Novel uses for three-dimensional printing in congenital heart disease. Curr Pediatr Rep 2016;4:28–34.
[2] Cantinotti M, Valverde I, Kutty S. Three-dimensional printed models in congenital heart disease. Int J Cardiovasc Imaging 2016;33:137–44.
[3] Martelli N, Serrano C, Van Den Brink H, Pineau J, Prognon P, Borget I *et al*. Advantages and disadvantages of 3-dimensional printing in surgery: a systematic review. Surgery 2016;159:1485–500.
[4] Schmauss D, Schmitz C, Bigdeli AK, Weber S, Gerber N, Beiras-Fernandez A *et al*. Three-dimensional printing of models for preoperative planning and simulation of transcatheter valve replacement. Ann Thorac Surg 2012;93:e31–3.
[5] Valverde I, Gomez G, Gonzalez A, Suarez-Mejias C, Adsuar A, Coserria JF *et al*. Three-dimensional patient-specific cardiac model for surgical planning in Nikaidoh procedure. Cardiol Young 2014;25:1–7.
[6] Farooqi KM, Gonzalez-Lengua C, Shenoy R, Sanz J, Nguyen K. Use of a three-dimensional printed cardiac model to assess suitability for biventricular repair. World J Pediatr Congenit Heart Surg 2016;7:1–3.
[7] Kiraly L, Tofeig M, Jha NK, Talo H. Three-dimensional printed prototypes refine the anatomy of post-modified Norwood-1 complex aortic arch obstruction and allow presurgical simulation of the repair. Interact CardioVasc Thorac Surg 2016;22:238–40.
[8] Hermsen JL, Burke TM, Seslar SP, Owens DS, Ripley BA, Mokadam NA *et al*. Scan, plan, print, practice, perform: development and use of a patient-specific 3-dimensional printed model in adult cardiac surgery. J Thorac Cardiovasc Surg 2016;153:132–40.
[9] Farooqi KM, Nielsen JC, Uppu SC, Srivastava S, Parness IA, Sanz J *et al*. Use of 3-dimensional printing to demonstrate complex intracardiac relationships in double-outlet right ventricle for surgical planning. Circ Cardiovasc Imaging 2015;8:e003043.
[10] Jacobs S, Grunert R, Mohr FW, Falk V. 3D-imaging of cardiac structures using 3D heart models for planning in heart surgery: a preliminary study. Interact CardioVasc Thorac Surg 2008;7:6–9.
[11] Hussain T, Lossnitzer D, Bellsham-Revell H, Valverde I, Beerbaum P, Razavi R *et al*. Three-dimensional dual-phase whole-heart MR imaging: clinical implications for congenital heart disease. Radiology 2012; 263:547–54.
[12] Yushkevich PA, Piven J, Hazlett HC, Smith RG, Ho S, Gee JC *et al*. User-guided 3D active contour segmentation of anatomical structures: significantly improved efficiency and reliability. Neuroimage 2006;31: 1116–28.
[13] McDonald PJ, Kulkarni AV, Farrokhyar F, Bhandari M. Ethical issues in surgical research. Can J Surg 2010;53:133–6.
[14] Hernández-Díaz S, Hernán MA, Meyer K, Werler MM, Mitchell AA. Case-crossover and case-time-control designs in birth defects epidemiology. Am J Epidemiol 2003;158:385–91.
[15] Valent F, Brusaferro S, Barbone F. A case-crossover study of sleep and childhood injury. Pediatrics 2001;107:E23.
[16] Potthast S, Mitsumori L, Stanescu LA, Richardson ML, Branch K, Dubinsky TJ *et al*. Measuring aortic diameter with different MR techniques: comparison of three-dimensional (3D) navigated steady-state free-precession (SSFP), 3D contrast-enhanced magnetic resonance angiography (CE-MRA), 2D T2 black blood, and 2D cine SSFP. J Magn Reson Imaging 2010;31:177–84.
[17] Faganello G, Campana C, Belgrano M, Russo G, Pozzi M, Cioffi G *et al*. Three dimensional printing of an atrial septal defect: is it multimodality imaging? Int J Cardiovasc Imaging 2016;32:427–8.
[18] Farooqi KM, Sengupta PP. Echocardiography and three-dimensional printing: sound ideas to touch a heart. J Am Soc Echocardiogr 2015; 28:398–403.
[19] Gómez-Ciriza G, Hussain T, Gómez-Cía T, Valverde I. Potential of 3D-printed models in planning structural interventional procedures. Interv Cardiol 2015;7:343–50.

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