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Original Article

Three-dimensional patient-specific cardiac model for surgical planning in Nikaidoh procedure

Israel Valverde,[1,2] Gorka Gomez,[3] Antonio Gonzalez,[4] Cristina Suarez-Mejias,[3] Alejandro Adsuar,[4] Jose Felix Coserria,[1] Sergio Uribe,[5] Tomas Gomez-Cia,[3,6] Amir Reza Hosseinpour[4]

[1]Paediatric Cardiology Unit, Hospital Virgen del Rocio; [2]Cardiovascular Pathology Unit, Institute of Biomedicine of Seville, IBIS. Hospital Virgen de Rocio/CSIC/University of Seville; [3]Technological Innovation Group, Hospital Virgen del Rocio; [4]Cardiac Surgery Unit. Hospital Virgen del Rocio, Seville, Spain; [5]Department of Radiology and Biomedical Imaging Center, School of Medicine, Pontificia Universidad Católica de Chile, Santiago, Chile; [6]Plastic Surgery and Burns Unit, Hospital Virgen del Rocio, Seville, Spain

Abstract *Purpose:* To explore the use of three-dimensional patient-specific cardiovascular models using rapid prototyping techniques (fused deposition modelling) to improve surgical planning in patients with complex congenital heart disease. *Description:* Rapid prototyping techniques are used to print accurate three-dimensional replicas of patients' cardiovascular anatomy based on magnetic resonance images using computer-aided design systems. Models are printed using a translucent polylactic acid polymer. *Evaluation:* As a proof of concept, a model of the heart of a 1.5-year-old boy with transposition of the great arteries, ventricular septal defect and pulmonary stenosis was constructed to help planning the surgical correction. The cardiac model allowed the surgeon to evaluate the location and dimensions of the ventricular septal defect as well as its relationship with the aorta and pulmonary artery. *Conclusions:* Cardiovascular models constructed by rapid prototyping techniques are extremely helpful for planning corrective surgery in patients with complex congenital malformations. Therefore they may potentially reduce operative time and morbi-mortality.

Keywords: Rapid prototyping techniques; Congenital heart disease; Nikaidoh procedure

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THE PLANNING OF CORRECTIVE SURGERY FOR complex congenital heart defects may be difficult due to the heterogeneity of the malformations, broad spectrum of anatomical spatial inter-relationships and small size in children. A precise understanding of the anatomical structures of the heart and great vessels is essential for surgical planning in order to avoid unexpected findings, plan the best surgical approach and therefore reduce operative time and mortality.

The stage of surgical planning is where imaging techniques play a key role. Unlike two-dimensional echocardiography and cardiac catheterization, magnetic resonance imaging and computed tomography can reconstruct the cardiovascular geometry in three-dimensions and better expose the spatial inter-relationships between cardiovascular structures. Rapid prototyping techniques are promising tools which can exploit the full three-dimensional potential/features of magnetic resonance imaging and computed tomography scanning. Physical models in three-dimensions have been found to be useful in maxillofacial surgery,[1] craniofacial surgery and other surgical specialties. However, their use has been limited in the field of congenital heart disease.[2–4]

In this paper, we present the case of a 1.5-year-old boy with complex congenital heart disease (transposition of the great arteries, ventricular septal defect

Correspondence to: Israel Valverde, MD, Institute of Biomedicine of Seville, IBIS, Hospital Virgen del Rocío, Avda. Manuel Siurot, s/n. 41013 · Seville (Spain). Tel: +34 955 923 000; Fax: +34 955 923 101; E-mail: ivalverde-ibis@us.es

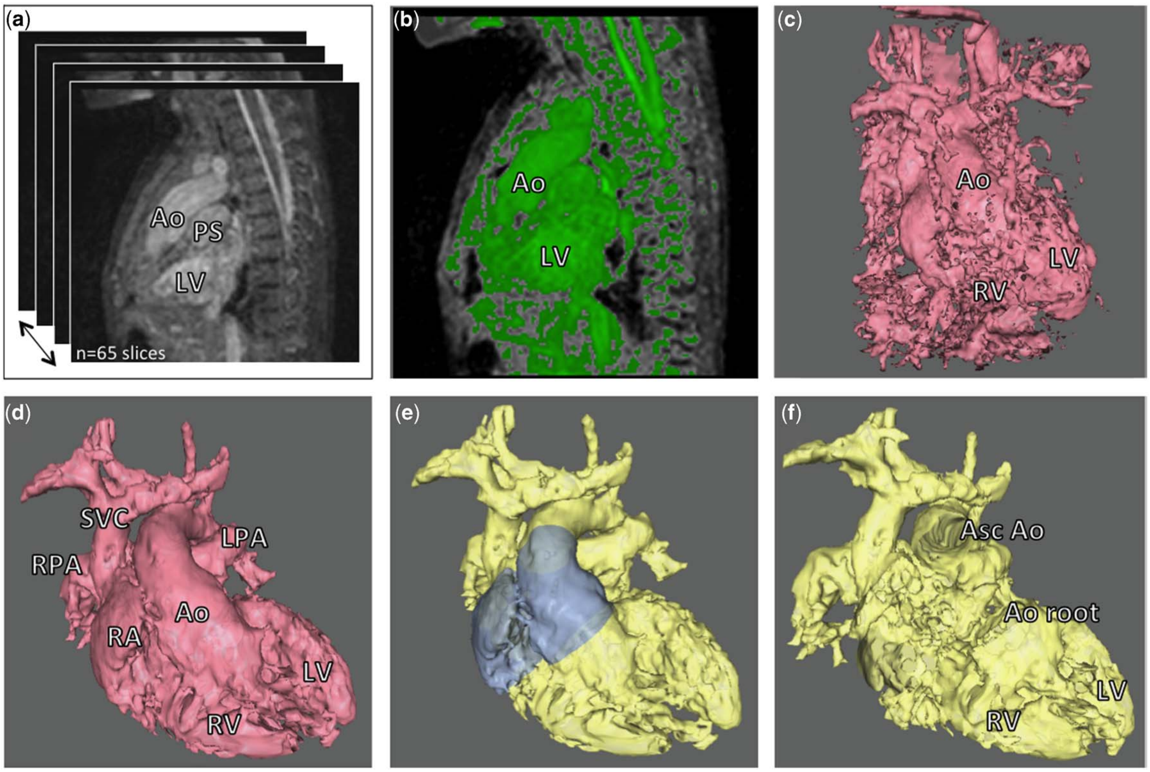

Figure 1.

*Segmentation process of the cardiovascular anatomy (**a**) Raw 3D-ssfp Magnetic Resonance Imaging data containing 65 2D-sagital slices. (**b**) Thresholding process to segment the cardiovascular anatomy. (**c**) Gross segmented cardiovascular anatomy including noise. (**d**) Appropriate 3D segmentation after the cutting and smoothing processes. (**e**) Division of the segmented anatomy into two parts to allow visualization of the intracardiac anatomy. (**f**) Main segmented part view showing the interior of the heart. AO = Aorta; Ao root = Aortic root; AscAo = Ascending aorta; LPA = left pulmonary artery; LV = left ventricle; PS = pulmonary stenosis; RA = right atrium; RPA = right pulmonary artery; RV = right ventricle; SVC = superior vein cava.*

and pulmonary stenosis) in which a low-cost three-dimensional physical model was constructed by fused deposition modelling technique using open-source software and hardware to plan surgical repair. By using this technique, clinical imaging data is converted into patient-specific models that enhance the real cardiovascular anatomy. This has the potential to significantly facilitate the surgical planning of complex congenital heart disease.

Materials and methods

Patient and data acquisition

A 1.5-year-old-boy of 9 kg diagnosed of transposition of the great arteries, subaortic ventricular septal defect and severe pulmonary stenosis was referred to our unit for preoperative assessment. He had a previous palliative Blalock-Taussig shunt operation at the age of one month. He was cyanotic and the oxygen saturations were 80%. The study was approved by the local institutional review board and informed consent was obtained.

The patient underwent a cardiac magnetic resonance imaging scan by using a 1.5-T clinical Magnetic Resonance Imaging unit (Intera, Philips Healthcare, Best, The Netherlands). A single-phase three-dimensional balanced steady-state free precession whole-heart sequence with respiratory navigator gating and electrocardiographic triggering was acquired using the following parameters: repetition time/echo time = 3.4/1.7, flip angle 90°, 80 sagital sections, isotropic resolution 1.5 × 1.5 × 1.5 mm, acquisition window 72 msec at end-diastole, parallel imaging with sensitivity encoding factor = 2) (see Fig 1a). The image data was stored in DICOM format.

Segmentation

Multi-slice two-dimensional DICOM images of the patient are segmented to reconstruct the three-dimensional model with AYRA. AYRA is an open-source software tool designed and developed under a research, development and innovation project funded by the Andalusian Health Service since 2005. It is a tool used to plan and optimize the surgical interventions using virtual reality technology. To generate the three-dimensional models, first the radiological image is pre-processed, then it is segmented and

Figure 2.
*3D rapid prototyping technique. (**a**) The scheme of the stereolitotraphy. (**b**) The process of depositing fused polylactic acid layer by layer. (**c**) The manufactured plastic biomodel.*

finally reconstructed. In the pre-processing phase, the image is standardized and filtered to eliminate noise. Then an enhancement of the contrast is applied to increase the intensity difference between the blood pool (white) and the myocardium and vessel wall (grey). This grey-scale intensity threshold difference between these two boundaries is used to segment the interface between blood pool and myocardium (endocardium) and that between the blood pool and vessel wall (endothelium).

After preprocessing, the image is segmented.[5,6] Segmentation is the process that allows users to select a region of interest within a tissue, retain the key anatomical structures and discard unnecessary data. Thresholding and region growing methodologies are implemented in AYRA for segmentation and can be easily perfomed by clinicians (paediatric cardiologists, surgeons, radiologists) after a brief training. Thresholding methodology was used in this work whereby clinicans use a toolbar that represents the different grey levels (tissue density) within a broad spectrum of shades of grey in the radiological image. The selected tissue is painted in green (Fig 1b). Once the tissue of interest has been selected, AYRA builds a three-dimensional image using a marching cube algorithm. This permits joining the voxels that composed the image using polygons. It is possible to interact with this mesh – cutting, smoothing, copying – to get an appropriate three-dimensional image of the cardiovascular anatomy. The model was partitioned in two independent pieces (Fig 1e and f). The small piece comprised the ascending aorta and the small main pulmonary artery, and could be detached from the main piece to allow better visualization of the interior of the heart and the area of main surgical interest.

Three-dimensional rapid prototyping

After segmentation of the biomodel mesh, this is stored as a stereolithography file format (.stl) widely used for rapid prototyping and computer-aided design and manufacturing. The mesh obtained from AYRA cannot be printed directly. It requires further manipulation with computer-aided design tools in order to create a wall thickness of 1 mm, correct various defects and orientate the mesh to improve the printing process. Once the computer-aided design is finished, the stl file is processed with a three-dimensional printer software that transforms the three-dimensional mesh file into a machine-code file. The machine code is a list of commands that indicate all the actions (heat printig head, move home, all axis moves, stop, pause, etc.) necessary to print the biomodel.

Fused deposition modelling is an additive manufacturing technology that works by depositing fused polylactic acid layer by layer (Fig 2). The polymer is melted in an extrusion nozzle that is moved under the machine code commands. Each layer is deposited over the previous solidified layer building a three-dimensional structure. The Z axis thickness is 0.25 mm, so the printer needs about 600 layers to build a 150 mm biomodel.

Results

The construction of the model including segmentation and printing required ~14 hours of work: 2 hours of segmentation, 2 hours of engineer design for rapid prototyping preparation and 10 hours of automated printing where no supervision is necessary. The estimated cost is 350 US dollars. The case was presented in the joint paediatric cardiology/surgical meeting where, in addition to the routine clinical information and images (echocardiography and magnetic resonance imaging), the three-dimensional-model was used to illustrate the anatomy (See Fig 3 and Supplementary Video S1).

Two-dimensional echocardiography helped delineate the anatomy. However, all the information required to understand the anatomical spatial relationships between the ventricular septal defect, outlet septum and great vessels could not be imaged in a single plane; several views were required. Magnetic Resonance Imaging reconstructions suggested that

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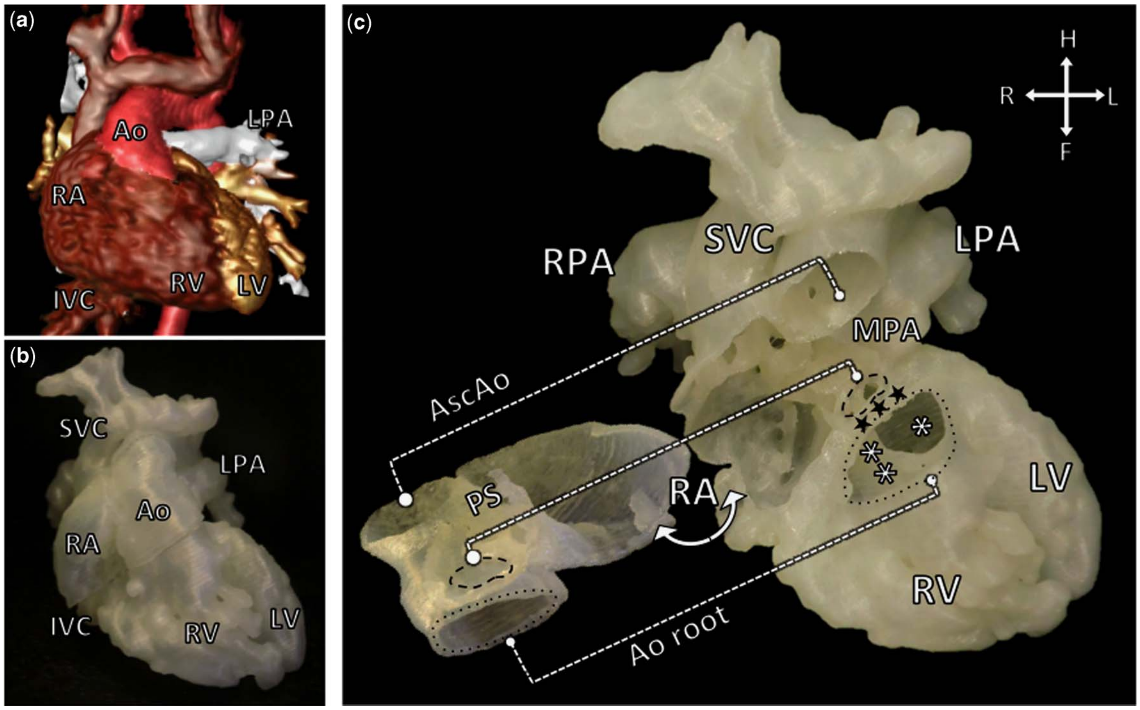

Figure 3.
*Comparison between 3D Magnetic Resonance Imaging and the 3D-model. Using Magnetic Resonance Imaging 3D reconstruction (**a**) a 3D-cardiovascular model (**b**) is created which is an exact replica of the patient's anatomy. The 3D-model is separated into two parts with the front section rotated to show its internal aspect and to allow inspection of the cardiovascular structures as detailed in Figure 5. AO = Aorta; Ao root = Aortic root; AscAo = Ascending aorta; Dashed-line circle = pulmonary stenosis root; Dotted-line circle = aortic root; Inn = Innominate vein; IVC = Inferior vein cava; LPA = left pulmonary artery; LV = left ventricle; PS = pulmonary stenosis; RA = right atrium; RPA = right pulmonary artery; RV = right ventricle; SVC = superior vein cava; *left ventricular side of the interventricular septum; **right ventricular side of the interventricular septum; ★ outlet septum; Orientation arrows (H = head; F = feet; R = right; L = left; A = anterior; P = posterior).*

the patient would benefit from the Nikaidoh rather than the Rastelli procedure. This was even clearer with the hands-on 3D-model. Nikaidoh was considered to be a better repair than Rastelli as it may achieve a more laminar flow, more efficient haemodynamics and less potential for left ventricular outflow tract obstruction (Fig 4).

The 3D-model was to corroborate the surgical decision of undergoing a Nikaidoh repair, and also to facilitate the technical planning of this particular intervention. It allowed visual and tactile examination of the malformation helping to visualise the extent of the subaortic septum that needed to be cut in order to translocate the aorta posteriorly, and where to place the intraventricular patch to close the ventricular septal defect (Fig 5).

The patient underwent the Nikaidoh procedure. The precise spatial relationship between the ventricular septal defect, the origin of the aorta and stenotic pulmonary artery were found to be identical to those that had been reproduced by the 3D-model (see Fig 6). No unexpected findings were encountered during the operation. The patient had an uneventful postoperative course and remains well 6 months after the operation with no left ventricular outflow tract obstruction and good systolic function.

Discussion

The importance of preoperative planning, particularly in complex congenital heart disease, is well established and needs no further emphasis: it allows better precision, avoids improvisation, saves intraoperative time and therefore allows better outcome. Patient-specific cardiovascular three-dimensional models may contribute significantly to this goal because surgeons do not need to reconstruct and imagine in their minds the three-dimensional cardiovascular anatomy from several two-dimensional images such as those obtained by echocardiography. Distances, dimensions and spatial relationships may be better appreciated with a three-dimensional model than with echocardiography or Magnetic Resonance Imaging volume renders displayed on a screen. Holding a model in one's hands allows the surgeons to examine the exact replica of the organ, better plan the surgical correction and anticipate the problems that may arise during the intervention. It allows planning

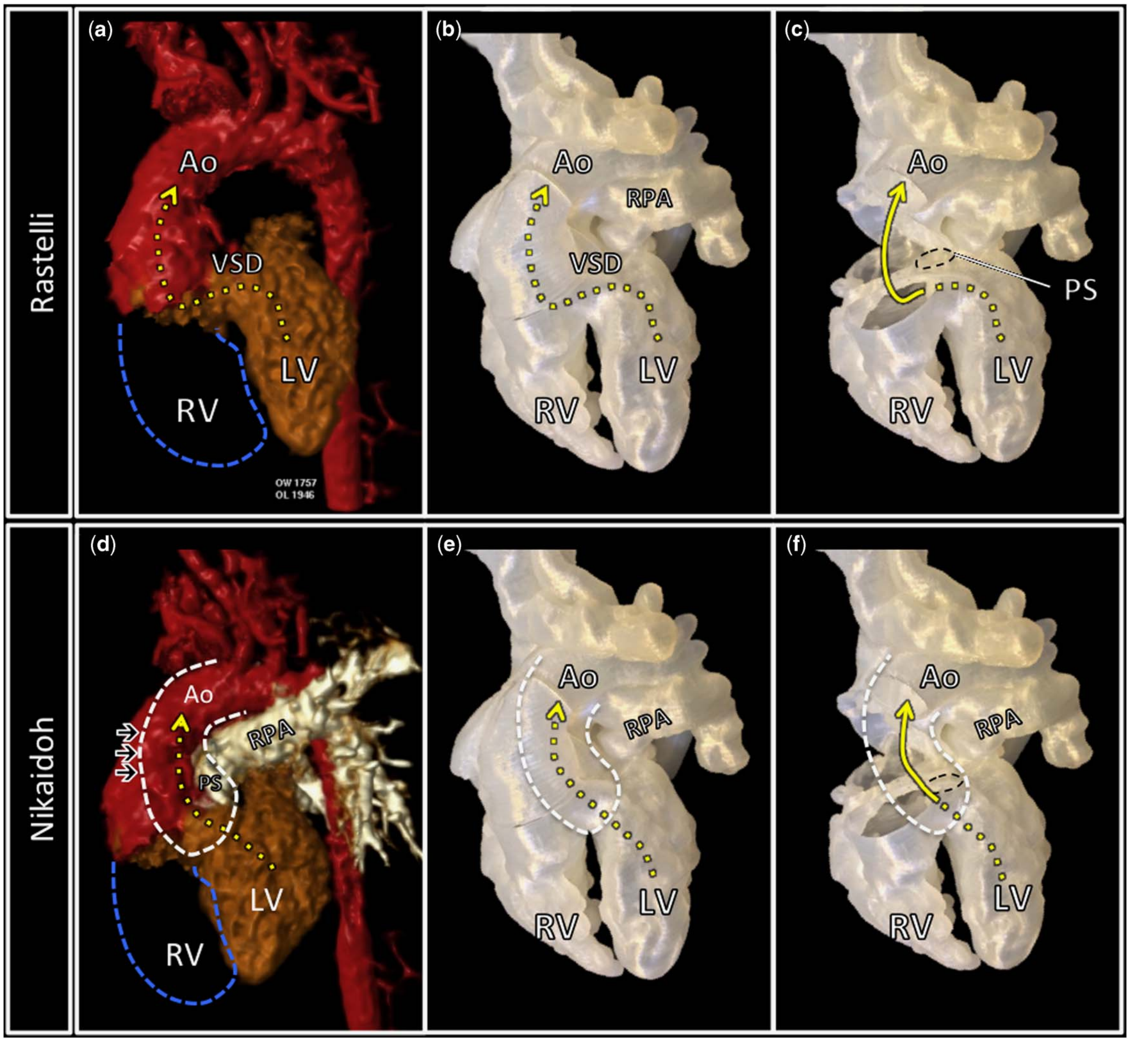

Figure 4.
*Comparison of the surgical options: Rastelli versus Nikaidoh operation. The Rastelli operation (**a**, **b**, **c**) may result in inefficient haemodynamics as suggested by the Magentic Resonance Imaging reconstruction (**a**). The potential for left ventricular outflow tract obstruction through the ventricular septal defect was clearly confirmed by the biomodel (**b**, **c**). On the other hand, the Nikaidoh operation (**d**, **e**, **f**) may achieve a more laminar flow to the aorta as suggested by the virtual Magentic Resonance Imagingreconstruction (**d**) by translocating the aorta posteriorly. This theoretical option was confirmed by the hands-on three-dimensional model (**e**) which allowed to plan the intraventricular resection of the outlet septum (**f**). AO = Aorta; Inn = Innominate vein; LPA = left pulmonary artery; LV = left ventricle; PS = pulmonary stenosis; RA = right atrium; RPA = right pulmonary artery; RV = right ventricle; SVC = superior vein cava; Orientation arrows (H = head; F = feet; R = right; L = left; A = anterior; P = posterior).*

the surgical intervention more accurately as the surgeon can visualize with precision where and how the various surgical maneuvers are to be carried out, or try various patch orientations within the model in order to ascertain the most haemodynamically efficient placement as demonstrated in Figure 6. In the opinion of the surgeons involved in the intervention (ARH, AG, AA), the three-dimensional model provided a degree of comfort that cannot be matched by other imaging modalities as it enables to better anticipate the problems that may arise during the intervention.

Rapid prototyping technology was originally used in engineering to manufacture prototype models and has been recently transferred to medicine, mainly in maxillofacial and orthopedic surgery.[1] It has been shown that using stereolitography models for surgical planning significantly reduces operative times.[1,7] Transferring this technology to the field of congenital heart disease has only been shown in a few case reports.[2–4]

The rapid prototyping technique is a simple process for the production of three-dimensional models. We encourage the use of magnetic resonance imaging, particularly in children, due to its non-ionizing and non-invasive nature,[8] but depending on institutional preferences there are other data formats which

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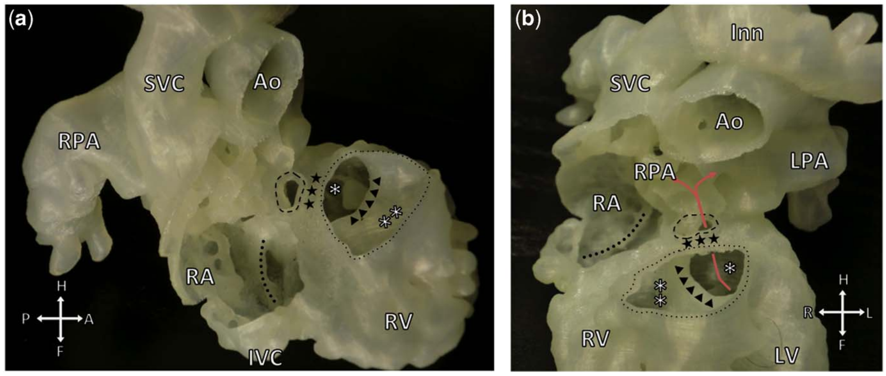

Figure 5.

*Intracardiac anatomy and surgical planning using 3D-model. Right-sided (**a**) and left-anterior (**b**) view of the 3D-model without the front section to allow visualization of the pulmonary annulus rim (Dashed-line circle) and the subaortic infundibulum (dotted-line) separated by the outlet septum (★). Through the subaortic infundibulum the intracardiac anatomy is easily revealed allowing visualization of the ventricular septal defect crest (triangles), which separates the LV (*) and the RV cavity (**). The red arrows (**b**) show the direction of the flow from the left ventricular cavity (*) through the stenosed pulmonary valve to both pulmonary arteries. The 3D-model shows how to plan the intervention, visualising the division of the subaortic septum that allows the posterior translocation of the aorta, and how to orientate the intraventricular patch to close the ventricular septal defect. AO = Aorta; Inn = Innominate vein; LPA = left pulmonary artery; LV = left ventricle; PS = pulmonary stenosis; RA = right atrium; RPA = right pulmonary artery; RV = right ventricle; SVC = superior vein cava; Orientation arrows (H = head; F = feet; R = right; L = left; A = anterior; P = posterior).*

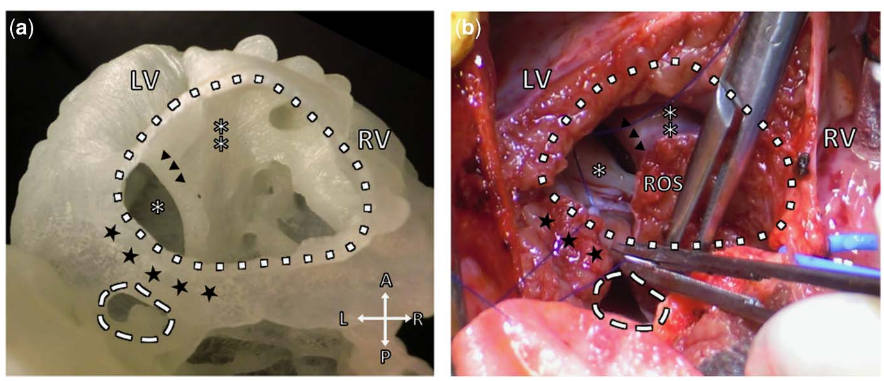

Figure 6.

*Comparison of the 3D-model (**a**) and the live operative findings (**b**). The figure shows the correlation between the 3D-model and the surgeon's operative view. It demonstrates the accuracy of the 3D-model in replicating the cardiac anatomy from the surgeon's view after the exposure of the subaortic infundibulum (dotted line) and pulmonary annulus rim (dashed line). The 3D-model helps visualising in advance the intraoperative findings and planning the division of the outlet septum (stars) which is shown in Figure 1B (ROS). LV = left ventricle; ROS = resection of the outlet septum; RV = right ventricle; (triangles) ventricular septal defect crest (triangles), (*) left ventricular cavity, (**) right ventricular cavity. Orientation arrows (H = head; F = feet; R = right; L = left; A = anterior; P = posterior).*

can also be used such as computed tomography. A three-dimensional b-SSFP sequence at end-diastole was chosen in order to evaluate the intracardiac anatomy at its maximal size and also because it does not require administration of any contrast. However new dual-phase b-SSFP sequence could be used in order to evaluate the intracardiac anatomy in both systole and diastole.[9] Other imaging alternatives could be magnetic resonance contrast-enhanced or computed tomography. We acknowledge that, although this segmentation algorithm is not a limitation in the reproduction of the vessel wall, it does not truly represent the myocardial wall thickness but the ventricular cavity. This study limitation might be overcome with future implementations of the segmentation algorithm to segment and print the whole myocardial wall thickness.

The data is stored in a universal DICOM format which can be easily shared on-line or stored on a hard drive. Uploading data files on the Internet opens a door for future collaboration between centers. The production of the models requires approximately four hours of segmentation and processing and around 10 hours of printing. Therefore models can be ready within 24 hours and may be handled and shipped. The novelty of this case is that is based on open-source software and therefore the costs are reduced immensely as compared to hiring the services of private companies.

As a proof of concept, we evaluated the case of a child with transposition of the great arteries, ventricular septal defect and pulmonary stenosis. The three-dimensional model complemented the information provided by echocardiography and magnetic resonance imaging supporting the surgical decision to proceed to a Nikaidoh operation. But more importantly, it clearly helped to improve the surgical planning by allowing to understand better the anatomical spatial relationships and distances.

We acknowledge that this technology might contribute significantly only in complex cases. Further models of other complex cardiovascular malformations are mandatory to fully evaluate the usefulness of this technology in the field of congenital heart disease. Rubber-like urethane models may be an even better option to solid resin models, as they may allow simulative surgical operations in congenital heart disease. Another option is to print the models in different colors for the different anatomical segments to improve understanding particularly for trainees and teaching purposes.

In conclusion, this paper illustrates the utility of three-dimensional-models to plan cardiovascular surgery in patients with complex congenital heart disease, particularly in children. This technique holds the great potential to be incorporated into the routine clinical practice in selected cases and provides practical advantages for research and teaching.

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Conflicts of Interest

The sterolithographic models were produced at the FAB_LAB HUVR laboratory (Virgen del Rocio University Hospital). There was no additional funding necessary to perform the study. The authors developed and evaluated this new technology freely and independently and had full control of the design of the study, methods, outcome measurements, analysis of data and production of the written report. IV, AG, AA, JFC, SU and ARH have no conflicts of interest. GG, CS and TG work for Digitalica Salud.

Ethical Standards

The authors assert that all procedures contributing to this work comply with the ethical standards of the relevant national guidelines on human experimentation (please name) and with the Helsinki Declaration of 1975, as revised in 2008, and has been approved by the institutional committee at Hospital Virgen del Rocio in Seville, Spain.

Supplementary material

To view supplementary material for this article, please visit http://dx.doi.org/10.1017/S1047951114000742

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