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PICTORIAL ESSAY

# 3D-Printing in Congenital Cardiology: From Flatland to Spaceland

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## ABSTRACT

Medical imaging has changed to a great extent over the past few decades. It has been revolutionized by three-dimensional (3D) imaging techniques. Despite much of modern medicine relying on 3D imaging, which can be obtained accurately, we keep on being limited by visualization of the 3D content on two-dimensional flat screens. 3D-printing of graspable models could become a feasible technique to overcome this gap. Therefore, we printed pre- and postoperative 3D-models of a complex congenital heart defect. With this example, we intend to illustrate that these models hold value in preoperative planning, postoperative evaluation of a complex procedure, communication with the patient, and education of trainees. At this moment, 3D printing only leaves a small footprint, but makes already a big impression in the domain of cardiology and cardiovascular surgery. Further studies including more patients and more validated applications are needed to streamline 3D printing in the clinical setting of daily practice.

Key words: Cardiac surgery, cardiology, congenital heart disease, tetralogy of Fallot, three-dimensional printing

## INTRODUCTION

Medical imaging has changed to a great extent over the past few decades. Advanced two-dimensional (2D) technology evolved to three-dimensional (3D) imaging, which is now powerful and gaining momentum. For surgical implants and prosthetics, 3D printing is already transforming the field of medicine. However, at this moment, it seems that this technology may also have found its way in the world of cardiology and cardiovascular surgery. The complex anatomy of heart and vessels needs to be studied and visualized in three dimensions. Although 3D images can be obtained accurately, 2D flat screens limit the visualization of 3D content. This is often insufficient for obtaining an intuitive understanding of complex anatomical details. Furthermore, cardiac surgeons operate in a 3D world and rely mostly on 2D imaging for preoperative planning of procedure. 3D

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prototyping became a feasible technique to overcome this missing gap and is gaining ground as a clinical tool. Current applications in cardiology imply printing of the left atrial appendage before percutaneous closure, preoperative planning of transcatheter valve replacement, surgical planning in patients with an aberrant cardiac anatomy, and even 3D printing of custom-made heart valves.[1-6] We started to print pre- and post-operative 3D-models of complex congenital and structural heart defects, scimitar syndrome, compressed bronchial tree by extreme heart enlargement secondary to congenital heart disease, complex Fontan circulation with separated systemic venous return to the left- and right-sided pulmonary artery, multiple pulmonary vein stenosis after catheter ablation for atrial fibrillation, stented native coarctation of the aorta and its relationship to the aortic arch branches, and pulmonary arteriovenous fistula. The purpose of these models was first to study anatomical details, to make a surgical or interventional roadmap, and to re-evaluate the post-procedural result. Second, these models were used to explain the complexity of the procedure and to discuss the outcome with the patient. Finally, a collection of printed models will have an added value to educate trainees. We present one complex case as an example.

## CASE DETAILS

An adult female patient born with a complex tetralogy of Fallot consisting of pulmonary atresia and major aortopulmonary collateral arteries (MAPCA's) was referred to our hospital. In childhood, she had undergone a unifocalization of the left- and right-sided MAPCA's, which were connected by a left- and right-sided modified Blalock–Taussig shunt to the systemic circulation. Later at repair, a pulmonary homograft was implanted on the right ventricle outflow tract and connected to the left- and right-sided unifocalized MAPCA's using the previously applied two small Blalock–Taussig conduits. Redo surgery was now required to combat the increasing repercussion of the pressure load on the right ventricle because of the undersized conduits (right ventricle systolic pressure estimated on Doppler echocardiography = 80 mmHg). At referral, the patient carried 2D contrast computer tomography (CT) images of the chest [Video 1]. Since it was very challenging to understand the underlying pulmonary circulation and its relationship with the bronchial tree, a computer 3D-model was created [Video 2]. Three hundred eighty-three 2D CT slices of 1 mm were uploaded in 3D modeling software (Amira 3D software, FEI Corporate, Oregon, USA). As a first step, an isosurface of all CT slices was created, which represents all points of a constant density within a volume. The threshold for preparing the isosurface was chosen in such a way that the pulmonary vasculature was visualized as precise as possible. Unnecessary anatomical structures in the isosurface (mostly bone tissue) were manually removed. As a next step, a surface was extracted (extracting triangles from the module displaying the isosurface) and exported to a stereolithography (STL) file. The final step was to upload the STL file in 3D printing software (Symplify3D, Cincinnati, OH, USA). The 3D model was printed via Leapfrog Creatr dual extruder printer (LeapFrog, Alphen aan den Rijn, The Netherlands). The 3D model itself was printed in a hard plastic (acrylonitrile butadiene styrene). For supportive printing, polylactic acid was used which was later separated from the final hard plastic 3D model. The entire software processing took maximal 30 min. For printing the 3D model, 24 h were needed (scale 1/1, medium quality printing). The model was intended to increase the procedural efficiency. To lower the pulmonary vascular resistance, the surgical plan consisted of replacing the pulmonary homograft and the two undersized conduits and inserting two extra conduits from a new homograft to the distal pulmonary vascular tree. A multidisciplinary team used the printed 3D model to discuss the preoperative procedure in detail and afterward with the patient


**Video 1:** Adult female patient born with a complex tetralogy of Fallot consisting of pulmonary atresia and major aortopulmonary collateral arteries requiring redo surgery to correct increasing repercussion of the pressure load on the right ventricle because of the undersized conduits. Preoperative scroll through two-dimensional slices of computer tomography scan images of the chest. Heart and pulmonary circulation are filled with contrast.


**Video 2:** Adult female patient born with a complex tetralogy of Fallot consisting of pulmonary atresia and major aortopulmonary collateral arteries requiring redo surgery to correct increasing repercussion of the pressure load on the right ventricle because of the undersized conduits. Preoperative three-dimensional reconstruction of the heart and pulmonary circulation shows a left and right Blalock–Taussig conduit originating from the pulmonary homograft and respectively cross over the left and right main bronchus.

[Video 3]. After surgery [perioperative Figure 1], a second 3D model was created [Video 4], and printed [Figure 2] to evaluate and discuss the surgical outcome within the team and with the patient. The methodology to print the second 3D model was similar to the first one with the only difference that 84 2D CT slices of 3 mm were used for reconstruction. It was clear that all conduits were well connected to the distal pulmonary circulation, albeit one conduit was inserted to a slightly narrowed distal vessel. However, pressure load on the right heart decreased significantly (right ventricle systolic pressure estimated on Doppler echocardiography = 50 mmHg) and the patient's functional capacity improved markedly.

## CONCLUSIONS

Patient-specific 3D models may have multiple applications, as in this case. Better understanding of complex heart or vessel anatomy may result in shorter operation time and perhaps overall better treatment. Simulating complex surgical steps in advance using 3D prototypes may limit possible complications. Second, a postoperative model allows re-evaluation of the procedural result in a thorough manner. Moreover, it enhances patient-clinician interactions. 3D printed models can be used as didactic tools to educate trainees by easier explaining aberrant anatomical heart and vessel structures. Finally, further shortening of the software processing and printing time might open the way for the use of 3D printing in widespread clinical practice.


**Video 3:** Adult female patient born with a complex tetralogy of Fallot consisting of pulmonary atresia and major aortopulmonary collateral arteries requiring redo surgery to correct increasing repercussion of the pressure load on the right ventricle because of the undersized conduits. Preoperative three-dimensional print of the heart and pulmonary circulation shows a left and right Blalock–Taussig conduit originating from the pulmonary homograft, respectively cross over the left and right main bronchus.

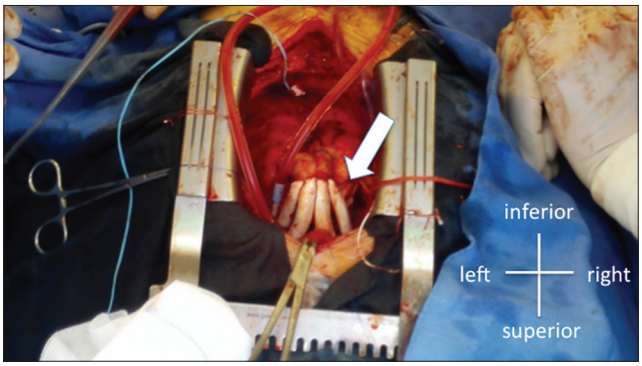


**Figure 1:** Adult female patient born with a complex tetralogy of Fallot consisting of pulmonary atresia and major aortopulmonary collateral arteries requiring redo surgery to correct increasing repercussion of the pressure load on the right ventricle because of the undersized conduits. Perioperative image of the (surgical field) chest shows two new left-sided conduits and two new right-sided conduits originating from the replaced homograft (white arrow).

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## Conflicts of interest

There are no conflicts of interest.


**Video 4:** Adult female patient born with a complex tetralogy of Fallot consisting of pulmonary atresia and major aortopulmonary collateral arteries requiring redo surgery to correct increasing repercussion of the pressure load on the right ventricle because of the undersized conduits. Postoperative three-dimensional reconstruction of the heart and pulmonary circulation shows two new left-sided conduits and two new right-sided conduits originating from the replaced homograft, respectively cross the left and right main bronchus and are inserted distally into the native pulmonary circulation.

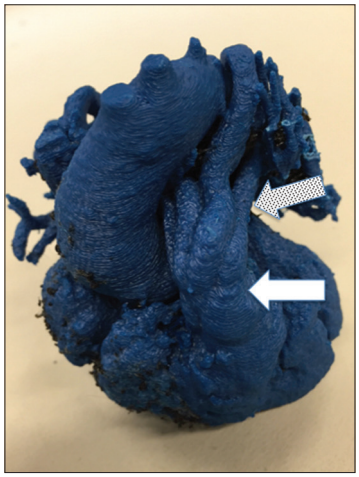

**Figure 2:** Adult female patient born with a complex tetralogy of Fallot consisting of pulmonary atresia and major aortopulmonary collateral arteries requiring redo surgery to correct increasing repercussion of the pressure load on the right ventricle because of the undersized conduits. Postoperative three-dimensional print of the heart and pulmonary circulation shows two new left-sided conduits and two new right-sided conduits (black dotted white arrow) originate from the replaced homograft (white arrow).

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