# 3D Printing and 3D Virtual Models for Surgical and Percutaneous Planning of Congenital Heart Diseases

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Abstract: Despite increasing evidence of their utility, 3D models have never been extensively tested so far in pediatric cardiac surgery planning. 3D models may offer advantages over traditional imaging examinations: 1) a deeper understanding of 3D anatomy in complex defects allowing visual and tactile inspection from any point of view, 2) the possibility to interact with a tangible replica of the real organs, 3) the surgical planning and simulation maneuvers on the printed and virtual model, and 4) interaction with anatomical structures thank to Virtual Reality technologies. The work aims to test and compare the accuracy and the incremental diagnostic value of 3D printed and virtual models in patients undergoing cardiac surgery for CHDs.



## 1 INTRODUCTION

In the last years, the interest in 3D printed models is increased in numerous medical fields (Vukicevic et al., 2017) both for the operative planning of different surgical approaches and the development of custom devices based on the patient-specific cases (Kurenov et al., 2015)(Sun et al., ). Congenital heart diseases (CHDs) are an ideal field to test the potentialities, accuracy, reproducibility and clinical effectiveness of 3D technologies due to the complexity and diversity of cases, the need for a complete representation of intra/extra-cardiac anatomy, and of personalized interventional approaches and size materials (Cantinotti et al., 2017). In complex CHDs the understanding of the 3D spatial relationship in an unusual anatomical arrangement is certainly a major difficulty. Currently medical imaging is able to provide functional and anatomical detailes with hight resolution and accuracy (Burchill et al., 2017) (Greil et al., 2017) (Celi et al., 2017) and are used as starting point for several advanced studies based on integration with numerical models (Celi and Berti, 2013) (Celi et al., 2013) (Capellini et al., 2018). Despite all these advances in the research field, currently, for the routinely diagnosis of CHDs there is a strong need to introduce interactive tools in clinical practise. In fact, all current 3D imaging modalities are not interactive and don't allow to manipulate the 3D image or the projected images. The standard volume rendering applications included in the image processing workstations are not able to provide tangible surfaces and edges; it refers to a technique for generating a visual representation of data that is contained in a three dimensional space. Even if volume rendering is an important graphics and visualization technique and several techniques and algorithms have been developed to provide high quality visualization (El Seoud and Mady, 2019), this approach is not able to produce a mathematical model useful for additional clinical evaluation and planning. Reconstructed 3D models

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can reproduce anatomical details with high accuracy and permit both virtual and physical manipulation of the model offering the advantage to simulate surgical interventions in a real physical environment in terms of spatial relationship with an adjunct tactile sense.

The key problems in complex CHDs are the small and often the non conventional dimensions and spatial relationships (Triedman and Newburger, 2016) (Stout et al., 2019). With this in mind, in addition to the physician's knowledge, and his/her experience, an important role is played by the spatial intelligence, defined as "a capacity for mentally generating, rotating, and transforming visual image" (Park et al., 2010). This kind of intelligence is crucial to the effectiveness of CHD physicians (Gardner, 2008) and is considered a fundamental element in medical education (Hegarty, 2014) and more in particular for anatomy education of the cardiovascular system (Kumalasari et al., 2017). In this context, research results (Sajid et al., 1990) have shown the benefits of three-dimensional approaches for learning. Indeed, physical interaction with a 3D model allows to understand the physical structures of the organs and obtain familiarity with them (Cooper and Taqueti, 2008). In the study presented by (Maresky et al., 2018) students who were exposed to VR demonstrated significant improvement in their understanding of cardiac anatomy. The learning advantage of VR technology has been proven useful also in the training of minimally invasive surgical procedures (Konietschke et al., 2010). Given its complex three-dimensional structures, cardiac anatomy may be challenging to grasp. In this context, VR technologies offer immersive and intuitive experiences that allow appreciating the size differences of such structures and at the same time to contextualize their relationships. Several VR applications in cardiovascular medicine education are currently being explored, for instance, the one developed in the Stanford Virtual Heart Project (2017) where such technology is used in the context of pediatric patients' parents' education to allow them visualizing their child's congenital heart disease. These kinds of applications contributed to the research in cardiovascular intervention by assisting the physicians in learning and interpretation of cardiovascular anatomy and pathology, increasing the precision and reducing the invasiveness of the interventions (Silva et al., 2018). 3D models may provide to pediatric surgeon/interventionalist a direct visualization of complex intra-extra-cardiac anatomy. Moreover, the combined use of 3D virtual and printed models may help to plan more accurate surgical/interventional strategies and to choose materials of proper size (i.e. conduit, ballon, prosthesis, etc) (Moore et al., 2018). Immersive bimanual exploration of virtual models will complement the understanding and planning capabilities of the printed model, without requiring complex haptic devices. In a recent study, some advantages of VR technique respect to the 3D printing approach have been depicted (Ong et al., 2018), however, according to our knowledge, there are no studies in the literature that investigate the effectiveness of these two approaches on the same populations of cases. Furthermore, virtual models, combining immersive visual and vibrotactile feedback, have been scarcely tested for pediatric cardiac surgery (Izard et al., 2018), and no specific comparison between the 3D virtual model and 3D printed anatomies have been proposed. This work aims to perform a comparison of the adoption of 3D printed and 3D virtual models for complex CHDs defects in terms of the satisfaction of physicians. To extend our investigation, both surgical and endovascular planning have been investigated.

## 2 MATERIALS AND METHODS

The workflow of this study is reported in Figure 1. It starts from the segmentation of clinical images to create the 3D model of cardiac structures affected by CHDs. The 3D models are printed with different 3D printing techniques and materials and used as virtual models in a virtual environment and a VR platform. Depending on the case, the clinical team investigates the most suitable surgical or catheter-based procedure on both the printed and virtual models. This workflow is illustrated for two CHDs cases: aortic coarctation (CoA) and heart with a complex CHD.

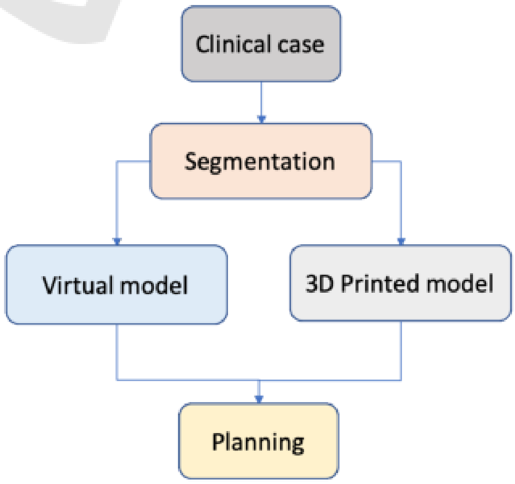


Figure 1: Diagram of the procedural phases of the presented approach.

### 2.1 Image Processing

Twelve Magnetic Resonance (MR) and eight Computed Tomography (CT) volumetric datasets of CHDs patients scheduled for surgical repair were analyzed. In order to obtain a 3D model of cardiac structures of interest, segmentation was performed by adopting different techniques. Semi-automatic segmentation algorithms such us threshold, active contours, and region growing algorithms were adopted when possible, together with manual segmentation slice by slice for more complex regions of interest.

After the segmentation phase, a process of mesh refinement was necessary to obtain the final model without imperfections and a constant thickness was assigned. The resulting 3D shell models were both printed and used in the virtual environment. Figure 2 depicts, as example, the three main phases of this process in case of a MR dataset: the medical volume rendering (Figure 2a), the segmentation process (Figure 2b) and the final 3D result (Figure 2c).

### 2.2 3D Printing

In this study, two different 3D printing strategies were tested: the fused deposition modeling technique (FDM) and the stereolithography technique (SLA). A thermoplastic polyurethane material (TPU Elasto85) with shore A85 (Standard, 2005) was used in the FDM approach. A hydrosoluble support polymer (SSU04) was used due to the presence of cavities in the models. The models were printed with a layer thickness of 0.25 mm on a 3ntr A4v4 3D printer. For the SLA technique, a Form2 3D printer was adopted with a clear elastic resin with shore A50 (Standard, 2005) and a layer thickness of 0.1 mm. The internal and external supports were manually removed.

### 2.3 Virtual Technique

Given the fact that there is no necessity for the data to be produced in real-time, the virtual techniques involve the production of 3D models and textures that could take several hours and days. One of the objectives of the VR visualization presented here is instead that of producing a textured 3D model that is possible to visualize as soon as possible thus introducing a trade-off between the accuracy of the representation and immediate availability of the model. For this reason, the 3D model segmented from MR and CT scans are passed to a pre-processing step where the models are optimized for visualization and the texture coordinates for each vertex are generated. A preliminary texture, not reflecting the real organic texture but with realistic rendering, is produced and applied on the model on the fly. This allows us to reduce the timing for the VR simulation to be used, and this is extremely important giving the time at disposal for pre-operation analysis. The VR interaction with the generated 3D model will give the surgeons some tools to manipulate the 3D scene. In particular, the user can rotate the view to analyze the 3D structure at its best. A virtual cutting feature has been implemented to enable performing some cuts on the 3D model surface to explore the internal cavities and plan possible surgical exploration of the models. A second implemented tool allows using simple 3D shapes (like cubes and sphere) to perform a real-time clipping on the 3D model thus showing internal elements in a non disruptive way. Examples of these two types of operation are shown in figure 3 and 4. The Unity engine was used to develop both a desktop VR application and an immersive VR visualization for the Oculus rift Head Mounted Display (HMD).

### 2.4 Pre-operative Planning

Every case under exam has been discussed by a multidisciplinary team (cardiac surgeons, pediatric cardiologists, anesthetists) in two different steps: firstly, based on conventional imaging and, secondly, with the support of the 3D printed and virtual models. The planning strategies were compared and the added value of the two additional methods was evaluated. For this study, the same team has evaluated all the 3D printed and virtual models.

## 3 RESULTS

The image segmentation was feasible for all datasets and the corresponding 3D shell models were generated for all patients. For the subjects with a CT dataset an automatic segmentation was practicable due to the high spatial resolution. The segmentation of the MR datasets was more complex to be performed. It is worth to point out that the complexity of this process was due to the presence of breath and motion artifacts and, in general, due to the absence of the contrast medium.

*Case of Coarctation -* In Figure 5 an example of planning for a percutaneous procedure for an artery affected by CoA is reported. Starting from an MR dataset (Figure 5a), the model was 3D printed with the SLA technique and used by the clinician to simulate the endovascular procedure during the pre-planning phase.

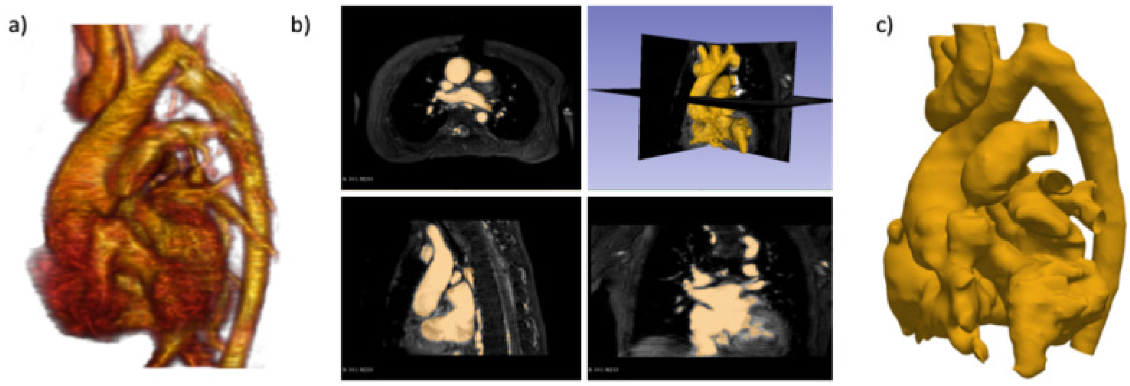


Figure 2: An example of standard volume rendering (a), images segmentation (b) and the final 3D model (c).

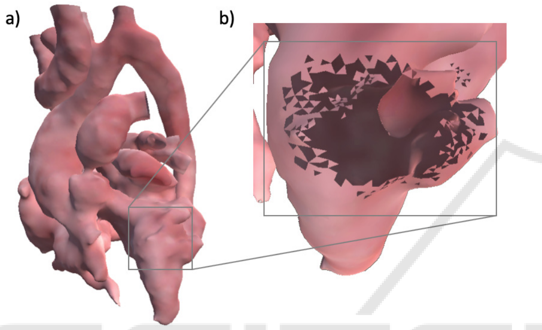


Figure 3: Rendering in VR of a virtual heart model with a custom texture (a) and example of cut applied on the mesh enabling the display of internal structures (b).

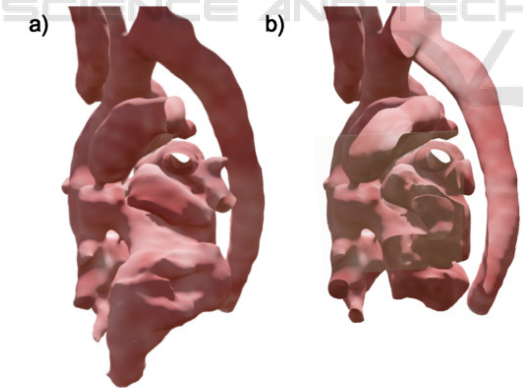


Figure 4: Virtual 3D model (a) and example of model manipulated through the use of a clipping plane (b).

Due to the complexity of this CHD, two different devices were required (Figure 5b): one to occlude a pseudo-aneurysm at the aortic arch level and one to recover the lumen of the CoA. Figure 5c depicts the intra-operative image according to the planning procedure. In this case the 3D virtual model (Figure 5d) was used to take the measurements to define the proper size of devices.

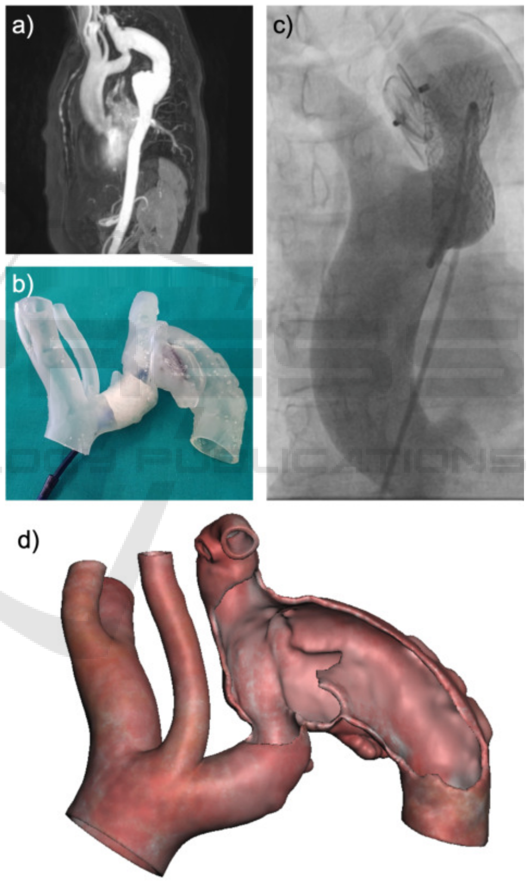


Figure 5: Case report of CoA from images to intervention: MR image (a), simulation of endovascular treatment on 3D printed model (b), angiographic image acquired during procedure (c) and 3D virtual model (d).

*Case of Complex CHD* - In Figure 6 the planning for a heart CHD is reported. The surgeon tested the selected plan on the 3D printed model by cutting in the defined region from the same view that he would have in the operating room and he explored the heart inside

(Figure 6a-b) to better understand which parts could be seen and reached thank to the possibility to interact with the real patient dimensions. Also the possible surgical strategies were investigated by implementing a virtual planning (Figure 6c).

Regarding the 3D printing techniques, it has always been possible to obtain 3D models with high accuracy by using the FDM approach. This technique permitted to have 3D deformable heart models to simulate the operative incisions by the surgeons as reported in Figure 6.

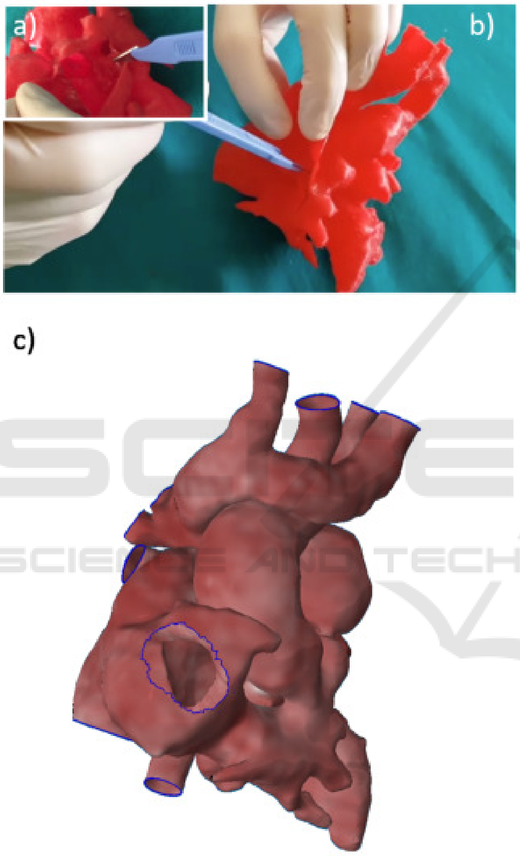


Figure 6: Surgical planninig on printed model (a-b) and on 3D virtual model (c).

The models printed with SLA were required in case of device insertion and expansion (Figure 5).

In Figure 7 an example of VR application is reported. A user can visualize the organic tissues in 3D within an HMD, thus exploring the model in the first person. This enables changing the viewpoint in a natural manner reproducing an immersive experience for the practitioner. Special tools enable the user to visualize both the surface properties and the internal cavities, thanks to the virtual culling of the 3D mesh.

The preliminary results of clinicians' feedback showed that the use of the 3D model in a virtual environment is the better choice to investigate the eligible CHDs repair strategies due to the possibility to investigate more sites of access for the operation by reversibly editing the model. The 3D printed models allowed the in vitro surgical and percutaneous planning simulations in time with clinical timing.

## 4 CONCLUSIONS

Despite recent advances in current imaging techniques for the diagnosis and management of CHDs, several limitations in 3D visualization remain. The 3D printing technique and the deployment of a virtual environment for the CHDs models improve the surgical and percutaneous planning for the pathology treatment. 3D virtual models have proven to be a useful instrument to assist the clinical team and the surgeon in the decision-making procedure for the patient-specific best intervention strategy in the case of surgical approach.

The 3D printed model is used to test the feasibility of the determined surgical technique by giving clinicians the appropriate level of confidence, also related to the real dimensions of patient anatomic structures, not reached with biomedical images visualization and 3D virtual models (Batteux et al., 2019).

Regarding the time costs, the segmentation process affected all approaches and ranging from less than an hour for CT datasets with contrast medium to several hours for some MR datasets. The 3D virtual simple model is available from the 3D shell model without any additional times except for the texture assignment, if required. The VR implementation allowed us to navigate in an immersive context with an intuitive manipulation of the 3D model. The inclusion of 3D model in a virtual reality environment made possible the model rotation in the 3D space, measurements on the model to get the real distance and relationships between the different regions of the heart or arterial models, the variation of model dimensions and the option to cut a specific portion of surface model to analyze internal cavities in a non-destructive manner. This last aspect is particularly important due to several surgical cuts can be tested on the same model. Even if a simple texture has been adopted, this approach reveals an increase of confidence from the clinical team with respect to a single color model. This same comment has been reported by clinician comparing the VR model with respect to the 3D printed one. In fact, it is worth to point out that the 3D printed model were in a single color with a low range of color available from the 3D printer manufac-

Figure 7: Example of VR application.

turer. Regarding the 3D printing approach, the time cost for the 3D printing technique included the printing time and the supports removal time and increases with the model size and complexity ranging from ten to twenty-five hours. The SLA technique presented the main drawback of internal supports removal that it resulted in impossible in the cases of the whole heart model. The supports removal was feasible for the artery models and in these cases, a simulation of endovascular procedure for the CHDs treatment was easily performed. 3D printed models with FDM was more suitable for a surgical procedure, while the use of the elastic resin turned out to be the most suitable to simulate endovascular procedures involving device expansion.

Moreover, the VR platform and 3D printing models seemed suitable for medical students' education thanks to the possibility to navigate inside the model and better visualize CHDs (Figure 7). With specific attention to the VR environment, usability assessment of different interaction metaphors is the focus of future work, testing different VR setups including a classical monitor visualization, an immersive simulation trough an HMD and the use of a tablet for navigation and display of 3D virtual content.

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