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Fast-track virtual reality for cardiac imaging in congenital heart disease

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Abstract

Background and Aim of the Study: We sought to evaluate the appropriateness of cardiac anatomy renderings by a new virtual reality (VR) technology, entitled DIVA, directly applicable to raw magnetic resonance imaging (MRI) data without intermediate segmentation steps in comparison to standard three-dimensional (3D) rendering techniques (3D PDF and 3D printing). Differences in post-processing times were also evaluated.

Methods: We reconstructed 3D (STL, 3D-PDF, and 3D printed ones) and VR models of three patients with different types of complex congenital heart disease (CHD). We then asked a senior pediatric heart surgeon to compare and grade the results obtained.

Results: All anatomical structures were well visualized in both VR and 3D PDF/printed models. Ventricular-arterial connections and their relationship with the great vessels were better visualized with the VR model (Case 2); aortic arch anatomy and details were also better visualized by the VR model (Case 3). The median post-processing time to get VR models using DIVA was 5 min in comparison to 8 h (range 8–12 h including printing time) for 3D models (PDF/printed).

Conclusions: VR directly applied to non-segmented 3D-MRI data set is a promising technique for 3D advanced modeling in CHD. It is systematically more consistent and faster when compared to standard 3D-modeling techniques.

KEYWORDS

3D reconstruction, congenital heart disease, surgical planning, virtual reality

1 | INTRODUCTION

Congenital heart surgery is recognized as one of the most challenging surgical disciplines due to the broad spectrum of conditions and high variability of patient anatomies.[1] A deep and extensive understanding of the complex spatial relationship between anatomical structures is mandatory to plan the optimal surgical approach and therefore reduce operative time, morbidity, and mortality. During the past 10 years, we have seen significant advancements in the field of innovative three-dimensional (3D) visualization techniques due to the ever-growing availability of 3D-ready imaging data derived from cardiac nuclear magnetic resonance, cardiac computed tomography (CT) scan, and 3D echocardiography.[2,3] However, the spread of these technologies has been limited by the lack of standardized

equal contribution

approaches, long processing times, high costs, and a lack of dynamic representations of the cardiac cycle without any hemodynamic data.

Volumetric representation in virtual reality (VR) was first applied to interactive real-time visualization of cardiac anatomy in 2001,[4] and it proved to be a promising 3D rendering technique that may answer some clinical needs in the management of patients with complex congenital heart disease (CHD).[5-7] However, VR rendering in this context was based on manual segmentation of 3D data derived from medical imaging, consequently leading to operator variability and relevant time-consumption limitations.

The aims of this pilot study were to evaluate in three patients with different CHD: (1) the appropriateness of cardiac anatomy rendering by a new VR technology directly applied to raw magnetic resonance imaging (MRI) imaging data without intermediate segmentation steps (DIVA software), (2) the differences in comprehension and appreciation of anatomic details between the VR representation algorithm and standard 3D modeling techniques (3D PDF and 3D printing). Differences in post-processing times were also evaluated.

TABLE 1 Comparison between 3D models (3D PDF/3D printed model vs. VR model)

	Patient 1		Patient 2		Patient 3	
	3D[a]	VR	3D[a]	VR	3D[a]	VR
Systemic veins	4	4	4	4	4	4
Pulmonary veins	4	4	4	4	4	4
Atrial anatomy	4	4	4	4	4	4
AV connections	4	4	4	4	4	4
VSD	na	na	3	4	na	na
VA connections	4	4	3	4	4	4
Aorta	4	4	4	4	3	4
Pulmonary artery	4	4	4	4	4	4

Note: Score: 1 = non-visualized, 2 = poorly visualized, 3 = visualized, 4 = well visualized.

Abbreviations: AV, atrio-ventricular; na, not applicable; VA, ventriculo-arterial; VR, virtual reality model; VSD, ventricular septal defect.

[a]3D = 3D PDF and 3D printing.

2 | MATERIALS AND METHODS

We used cardiac magnetic resonance (CMR) data of three patients with different types of CHD to reconstruct 3D models in the standard fashion (STL, 3D-PDF, and 3D printed ones) and to produce VR models. Patient data were fully anonymized so that neither informed consent nor Institutional Review Board (IRB) approval was deemed necessary. CMR imaging was performed using a Philips Achieva 1.5T scanner (Philips Medical Systems, Philips Healthcare). Images were acquired with a 5-channel phased-array cardiac coil. 3D SSFP sequence, electrocardiogram (ECG), and navigator gated in free-breathing, was performed for whole heart acquisition.

2.1 | 3D printing and 3D rendering

Images were segmented and reconstructed using the Mimics™ in-Print™ software (Materialise NV) and the resulting models were post-processed using the Meshmixer™ software (Autodesk Inc.). The segmentation was aimed at the volumes filled with contrast medium, to create a 3D reconstruction of the patient blood pool, including the heart chambers and the great vessels. The resulting 3D anatomical models were 3D printed in a 1:1 scale on a Formlabs™ Form2™ (Formlabs Inc.) 3D printer using a clear resin, also provided by Formlabs. The 3D PDF files were generated from the same STL models used for 3D printing.

2.2 | Virtual reality

The VR models of the patient's anatomy were generated using the DIVA software.[8,9] It was developed by using the popular Unity game engine and it includes two native interfaces: a desktop mode for volumetric viewing on a standard computer monitor and a VR mode to interact with medical images in an artificial environment through the use of a VR headset. The patient's imaging data were loaded directly from DICOM files and the volumetric renderings of the MRI are generated instantaneously by the software, without any human intervention.

All models were realized by a multidisciplinary team composed of a pediatric cardiologist expert in noninvasive cardiac imaging (Francesca Raimondi) and by an engineering expert in cardiac modeling (Charlotte Godard). The main anatomical features of the heart models were analyzed according to a 4-level scoring by a senior pediatric heart surgeon blinded to the patient's anatomy (Vladimiro Vida) (Table 1).

3 | RESULTS

3.1 | Case 1

The main diagnosis included {S,D,S} heart topology, dextrocardia, and partial anomalous pulmonary venous drainage of the middle and lower lobe of the right lung into the inferior vena cava (scimitar syndrome).

Both 3D and VR models showed appropriately the relationship between the anomalous pulmonary venous drainage (scimitar collector), the inferior vena cava, and the diaphragm. It was possible to measure the distance between the scimitar vein collector at its junction with the inferior vena cava and the left atrium as well as the position of the heart in the right hemithorax to plan the correct mini-invasive surgical access (Figure 1).

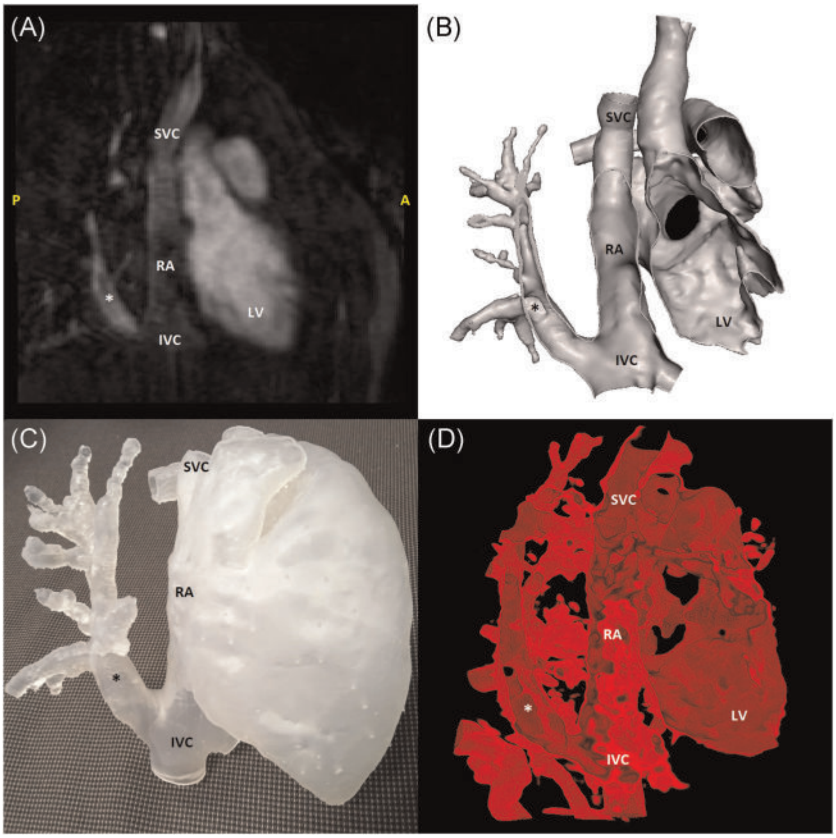

FIGURE 1 Images of patient 1: CMR scan (A), 3D PDF reconstruction (B), 3D printed model (C), a screenshot of the DIVA software (D). *Scimitar collector. CMR, cardiac magnetic resonance; IVC, inferior vena cava; LV, left ventricle; RA, right atrium; SVC, superior vena cava

3.2 | Case 2

The main diagnosis included {S,D,D} heart topology, ventricular D-loop, double outlet right ventricle with hypoplasia of the left ventricle, hypoplasia of the mitral valve, pulmonary valve atresia, and subaortic ventricular septal defect (VSD) (Figure 2). The patient underwent two previous surgical interventions including right ventricle-to-pulmonary artery (RV–PA) conduit and bidirectional cavo-pulmonary shunt (BCPS).

3.3 | Case 3

The main diagnosis included {S,D,S} heart topology, ventricular D-loop, atrio-ventricular concordance, ventriculo-arterial concordance with normally positioned aorta.

The patient underwent two previous surgical interventions including (1) coartectomy with end-to-end anastomosis and (2) ventricular septal defect closure. The patient presented with severe aortic valve regurgitation (on the bicuspid aortic valve) and multiple aneurysms of the distal aortic arch.

Both 3D and VR models showed the exact position and dimension of the aortic arch aneurisms, their extension and their relationship with the brachiocephalic vessels (Figure 3).

The comparison between 3D models (3D PDF/3D printed vs. VR) in all three cases is shown in Table 1. Ventricular-arterial connections and their relationship with the VSD were better visualized by the VR model in Case 2 when compared to 3D PDF/printing. Aortic arch anatomy with aneurysm anatomical detail was better visualized by the VR model in Case 3 if compared to 3D PDF/printed. All other anatomical structures were equally visualized in VR models and 3D PDF/printing models.

The median post-processing time to get the 3D PDF and the 3D printed model was 8 h (range 8–12 h) including printing time, while the VR model using DIVA took 5 min in each case.

4 | CONCLUSIONS

Virtual reality provides a natural means to visualize 3D structures through the integration of immersion, motion tracking, and stereoscopic vision. Its use is spreading due to the easy access to new low-cost mass-produced commercial headsets. In its medical applications, VR offers an advanced representation of anatomical structures, easy navigation, and interpretation of medical images. In VR, tomographic image stacks are represented as “physical objects” that users can grasp and explore via physical manipulation using VR controllers included with VR headsets. VR representations are generated using ray casting, while pixel appearances are controlled through transfer functions that determine the optical properties of the voxels.

In this paper, we propose a promising new technique based on VR directly applied to raw data without any preliminary segmentation process. This allowed the visualization of anatomical structures and navigation within the hearts of the three patients from their respective

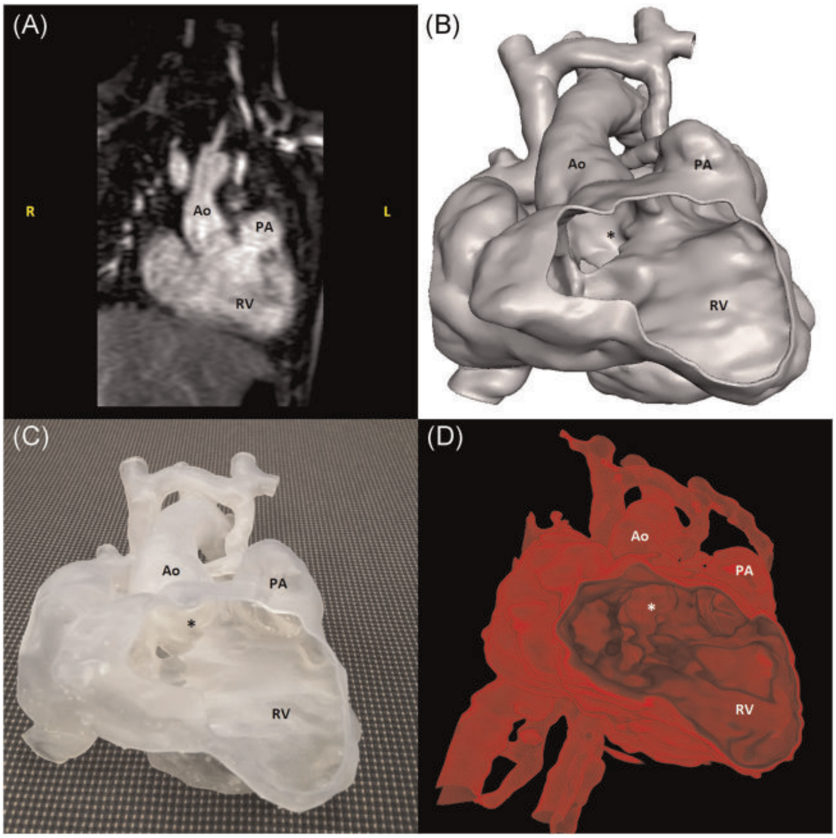

FIGURE 2 Images of patient 2: CMR scan (A), 3D PDF reconstruction (B), 3D printed model (C), a screenshot of the DIVA software (D). *Ventricular septum defect. Ao, aorta; CMR, cardiac magnetic resonance; PA, pulmonary artery; RV, right ventricle

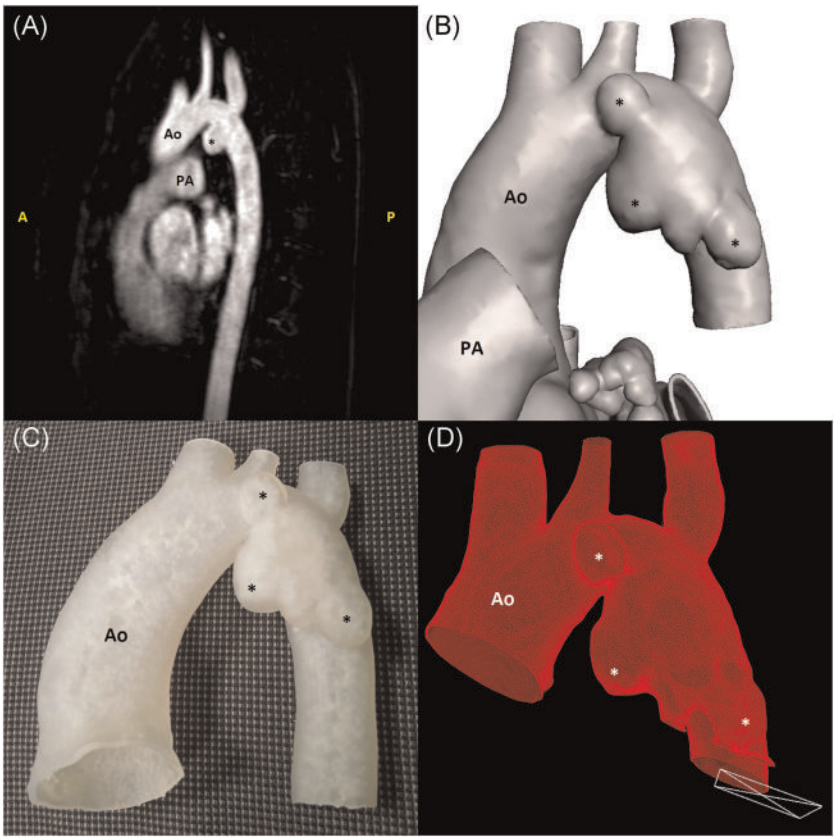

FIGURE 3 Images of patient 3: CMR scan (A), 3D PDF reconstruction (B), 3D printed model (C), a screenshot of the DIVA software (D). *Aneurysms. Ao, aorta; CMR, cardiac magnetic resonance; PA, pulmonary artery

CMR 3D data. In fact, data are loaded directly from DICOM files and this leads to a very short post-processing time. Of note, while the CT scan is the most used technique for advanced 3D modeling,[10] we successfully used CMR 3D data, avoiding any ionizing radiation exposure.

All cardiac segments were appropriately visualized both in 3D PDF/printed and VR models, demonstrating that our technique is at least not inferior to current technical approaches while being reliable, compared to MRI scan-based 3D modeling, easy to manage and generating highly reproducible results. Moreover, our data show the potential of automatic VR model generation to better reproduce intracardiac anatomy in complex CHD if compared to 3D PDF/printed models.

In conclusion, we propose a promising new approach to CHD visualization and analysis based on volumetric rendering in VR directly applied to DICOM data without preliminary segmentation processes. Based on these initial results, we assessed the use of VR models that has all the advantages of the other 3D modeling techniques but with the significant advantages of being easy to manage, reproducible, faster, and less prone to human errors. In specific cases, it allowed a better visualization and comprehension of the intracardiac and vascular anatomy. Future studies and a large sample size are certainly needed to explore the usefulness of routine utilization of VR in the setting of CHD surgery.

CONFLICT OF INTERESTS

The authors declare that there are no conflict of interests.

AUTHOR CONTRIBUTIONS

Conceptualization: Francesca Raimondi and Vladimiro Vida. *Data analysis and interpretation*: Charlotte Godard, Vladimiro Vida, and Nathalie Boddaert. *Drafting article*: Francesca Raimondi. *Critical revision of the article*: Francesco Bertelli and Mohamed El Beheiry. *Data collection*: Francesco Bertelli and Elena Reffo. *Critical revision of the article*: Vladimiro Vida and Jean-Baptiste Masson.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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