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Role of virtual reality in congenital heart disease

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Abstract

Objective: New platforms for patient imaging present opportunities for improved surgical planning in complex congenital heart disease (CHD). Virtual reality (VR) allows for interactive manipulation of high-resolution representations of patient-specific imaging data, as a supplement to traditional 2D visualizations and 3D printed heart models.

Design: We present the novel use of VR for the presurgical planning of cardiac surgery in two infants with complex CHD to demonstrate interactive real-time views of complex intra and extracardiac anatomy.

Results: The use of VR for cardiac presurgical planning is feasible using existing imaging data. The software was evaluated by both pediatric cardiac surgeons and pediatric cardiologists, and felt to be reliable and operated with a very short learning curve.

Conclusions: VR with controller-based interactive capability allows for interactive viewing of 3D models with complex intra and extracardiac anatomy. This serves as a useful complement to traditional preoperative planning methods in terms of its potential for group based collaborative discussion, user defined illustrative views, cost-effectiveness, and facility of use.

KEYWORDS
cardiac surgery, congenital diaphragmatic hernia, congenital heart disease, truncus arteriosus, ventricular septal defect, virtual reality

1 | INTRODUCTION

Virtual reality (VR) is broadly defined as a three-dimensional (3D) simulation of the real-world, with the ability for a user to interact directly with the simulation.[1,2] VR integrates imaging data and user input into a unified graphical output, often onto a wearable technology like a headset.[1–3] Originally, VR flourished in the gaming community, though its use in medicine dates back to the early 1990s.[2] In its earliest applications to biomedicine, VR was largely applied to the behavioral sciences,[2] though the advent of "controllers," or sensors that track hand position and movements in real time have vastly expanded the ability to interact with the virtual space and thus its applications to surgery. Presently, VR is widely used in medicine, from stroke rehabilitation,[4] to tools for trainees to learn how to perform laparoscopic surgery.[2,5]

This interactive rendered 3D environment of VR lends itself well to congenital heart disease (CHD), as surgical planning involves careful presurgical discussion of often widely varying and nuanced structural heart disease. Planning of surgical patch or baffle placement, conduit sizing, placement of surgical cannulae, or approach (in cases of cardiac malposition) can vary by patient. Utility of a 3D modality beyond traditional echocardiographic and cross-sectional imaging is currently underscored by the rise in 3D printing.[6–8] In pediatric cardiology and cardiac surgery, the use of VR is emerging. In published literature, VR was used to construct a training tool for minimally invasive surgery.[9] However, this method lacked the ability to interact with the heart nor could it provide interactive sectioning or 4-chamber views.

Juan R. Garcia and Lasya Gaur contributed equally to this study.

Beyond surgical planning, VR has also been utilized as a training tool for residents and medical students.[2,5] Simulators can incorporate VR to immerse trainees in a virtual rendering of a range of different procedures, particularly with laparoscopic procedures.[2,5] Previous studies have shown that trainees who use these VR simulators in their surgical curriculum face shorter times to completion of their learning tasks compared with their counterparts who did not use VR.[2] The use of VR for surgical planning has been demonstrated in plastic and orthopedic surgery[10] wherein surgeons created VR models of their surgical sites and simulated the planned procedure.

We present the novel use of VR in CHD, to create a virtually rendered high fidelity 3D VR model of the heart, viewed via a VR headset and controller platform for visualization and manipulation. We used high resolution cardiac multidetector computed tomography (CT) source data to reconstruct 3D virtual models from two patients: one with truncus arteriosus type IV with arch anomalies and another with large ventricular septal defect and congenital diaphragmatic hernia (CDH) causing cardiac malposition; cases selected to demonstrate common periprocedural concerns regarding intra and extracardiac anatomy. The models, controlled in real time by the end user allow customized and real time immersive viewing This technique has the potential to aid in the presurgical planning of complex cardiothoracic surgical procedures by assisting in visualization of complex spatial anatomy.

2 | METHODS

2.1 | Data acquisition and 3D segmentation

CT of the heart performed following administration of intravenous contrast and was exported using Carestream Vue (Rochester, New York). The 3D segmentation was performed using DICOM to Print (D2P) software (3D Systems, Rock Hill, South Carolina) using auto-segmentation and/or thresholding by Hounsfield unit to identify the blood pool. A 3D volumetric mask was first created, and processed using cutting and Boolean subtraction tools. Finally, the 3D mask was converted into a 3D surface mesh for VR visualization. Depending on the complexity of the case and the experience of the operator, this 3D segmentation process can take less than 30 min, or up to several hours.

2.2 | VR visualization

VR visualization was performed at the Johns Hopkins Carnegie 3D Printing and Visualization Facility using a VR platform (Figure 1A), consisting of a VR headset with two controllers (HTC Vive, New Taipei City, Taiwan). An area of 12 feet by 12 feet was designated for VR, and two base stations were used to detect the exact spatial location of the VR user and the two controllers. The 3D segmented mesh (Figure 2) was visualized into VR using D2P software (3D Systems). The VR user can magnify, handle and rotate the entire 3D heart model using the left controller (Figure 1B), and section the 3D heart model using the right controller acting as a clipping plane for intracardiac or intraluminal viewing (Figure 1C-E). To examine the sections at various angles, the VR user can walk either around or closer to the 3D heart model visualized in VR, or move, magnify and rotate the object using the left controller. Open Broadcaster Software Studio (Version 20) was used to capture the VR views (Figure 1B-E, Supporting Information Video 1).

2.3 | Clinical Experience

2.3.1 | Case 1

A 2.95 kg baby girl was delivered at full term with a prenatal diagnosis of truncus arteriosus, ventricular septal defect (VSD) and aortic arch hypoplasia. The initial postnatal echocardiogram on day of life (DOL) 1 demonstrated truncus arteriosus type A4 (Van Praagh classification) with ascending aortic arch hypoplasia with coarctation versus arch interruption. A CT angiogram (CTA) of the chest was performed on DOL 2, confirming the diagnosis of hypoplastic aortic arch without interruption.

The CTA dataset was segmented and processed to create a 3D model which was projected into VR. The 3D visualization and dynamic manipulations (Figure 1B), live sectioning of the 3D heart model to

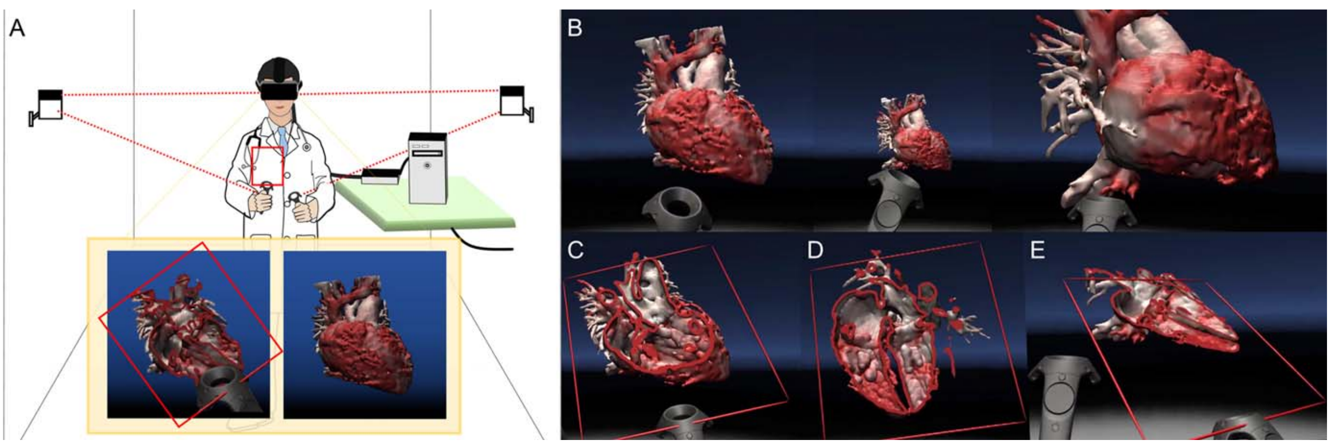

FIGURE 1 VR visualization of the heart. (A) Schematic diagram demonstrating the VR set-up. (B) Various magnifications. (C) Persistent truncus arteriosus. (D-E) Apical 4-chamber view

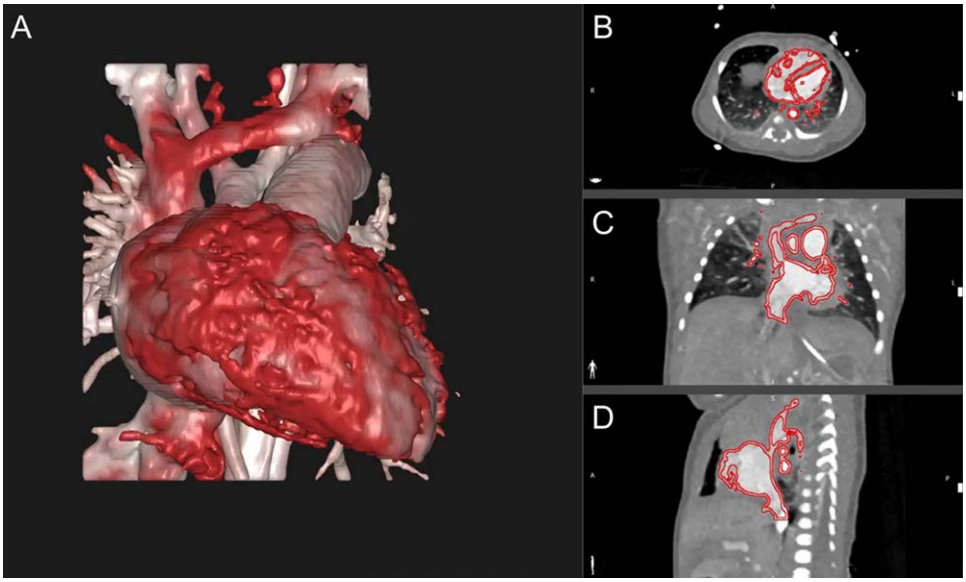

FIGURE 2 The 3D segmentation of the heart. (A) 3D heart model postsegmentation; (B) Axial view; (C) Coronal view; (D) Sagittal view

view the VSD as well as the hypoplastic aortic arch (Figure 1C-E) was performed successfully in the VR space.

The patient subsequently went to the operating room on the third day of life for complete repair with an aortic arch reconstruction using PA homograft patch, patent ductus arteriosus division, 10 mm RV-PA conduit (femoral vein graft), patch repair of the VSD, and ASD partial closure. The patient made an uneventful recovery. The anatomy was accurately represented in the VR space, with improved visualization of the arch for surgical planning.

2.3.2 | Case 2

A 5-month-old, 35 week premature infant with a large VSD and right-sided CDH was transferred from an outside hospital for surgical management following CDH repair and history of extracorporeal membrane oxygenation (ECMO).

Initial transthoracic and transesophageal echocardiograms revealed a large inlet type VSD with anterior extension to the paramembranous septum. CT scan performed for assessment of cardiac malposition and lung fields revealed extreme dextrocardia with rightward rotation in the setting of severe right lung hypoplasia and left lung hyperinflation. VR model of the patient's anatomy allowed user guided manipulation to envision the VSD margins (including relationships to the great vessels) beyond the planes of traditional imaging (Supporting Information Video 2). Median sternotomy at the time of surgery revealed an anteriorly located dilated main pulmonary artery with no visualization of the right atrium due to posterior shift. Initial venous cannulation was performed in the main pulmonary artery and then converted to right atrial cannulation following cardiac decompression. After physical leftward rotation of the heart, surgical patch closure of the large VSD via transatrial approach was performed with no residual defects on follow up imaging. The child tolerated the procedure including weaning of pulmonary hypertensive medications over the next few days postoperatively. The VR model accurately represented surgical findings, including VSD visualization in relation to cardiac shift and rotation as well as outflow tracts.

3 | DISCUSSION

The use of VR to generate accurate, patient-specific heart models for immersive anatomical assessment in a neonate or young infant is feasible. User defined controllers allow for spatial manipulation and segmentation of the heart model in real time, suggesting a vital role as a complement to existing imaging modalities in complex CHD.

The conventional and emerging modalities in cardiothoracic presurgical planning are computer based 3D modeling, computer-aided design (CAD) models, and more recently, 3D printed models.[11,12] We believe that our described method of presurgical planning using interactive VR with controllers provides several advantages in the growing paradigms of preoperative planning.

3.1 | VR versus 2D visualizations of 3D heart models (from CT, MRI, or 3D ultrasound)

Modalities such as CT, magnetic resonance imaging (MRI), and 3D ultrasound are increasingly used in CHD for 3D spatial demonstration; however, these remain limited by 2D monitor-based visualization of 3D models, limited realism and depth perception, as well as inability for user specific manipulation. In VR, the user can move themselves or move the model, allowing for dynamic inspection of the patient's anatomy for visualization from a "surgeon's perspective" while preserving the perception of a 3D space. The surgeon's understanding is also increased by displaying views with VR that cannot be achieved in the OR such as the proximity to "unseen" surrounding structures. Additionally, the adjustable cutting planes allow for visualization of how surgical tools might interact with the anatomy, aiding preparedness for the procedure.

VR also offers an advantage over the current presurgical or interventional planning conference format. Traditionally, imaging for each patient is selected and displayed by the noninvasive imaging pediatric cardiologist to surgeons, inteventionalists, cardiologists, anesthesiologists, and other relevant providers, including trainees. By shared viewing and real time manipulation of the anatomy by both the cardiologist and surgeons, a better dialogue and shared mental model may be achieved. With advancing technology, this shared viewing experience can be potentially projected onto multiple VR screens or other increasingly affordable mixed reality headsets.

3.2 | VR versus 3D printed heart models

Like 3D printed heart models, VR technology allows for the physical manipulation of complex anatomy, while offering depth perception and visualization with a binocular field of view. VR does offer some specific advantages over rapid prototyping. Visualization of anatomy is malleable, not limited to a single cutting plane or viewing window on a physical model, since 3D masks and meshes can be edited and revisualized using VR as often as necessary. Planning and expertise for material support apparatus for fine structures is precluded on a virtual model. Finally, the resolution of the VR heart models is not limited to the capabilities of a printer, unlike 3D printed heart models. Using VR, a model can be used to reconstruct all relevant structures with utmost fidelity, with the added benefit of being able to be magnified or minimized to a wide range of sizes to the operators' preference. The use of high resolution source data is critical for both modalities and fastidious attention to accurate segmentation allows reconstruction of all relevant structures. A preclinical translational study has shown that with sufficiently high image resolution initially, images based on VR can be fused with the intraoperative imaging environment with good alignment and may even guide intraoperative interventions.[13] VR models control costs and upkeep necessary for 3D printing,[14] making VR a cost-effective alternative in the long term. Although VR incurs start-up costs such as the purchase of VR equipment (VR headsets, hardware, software, appropriate viewing monitors, etc.), arguably there are comparable start-up expenditures involved for 3D printing as well, such as start-up costs to purchase 3D printing equipment and materials, or fees to use a 3D printing facility. The actual costs vary widely, depending on the quality of the VR equipment and 3D printing equipment/facility. There are equivalent personnel costs for 3D segmentation by specialized technicians for both 3D printing and VR, as 3D segmentation is common to both technologies. However, after initial costs, VR may reduce costs compared with 3D printing, as there is no need to regularly purchase 3D printing material or incur costs pay to use a 3D printing facility. Also, magnification in VR allows for clearer visualization of internal and external structures, which may be otherwise expensive to print. Proper storage and disposal of 3D printed models is of growing relevance, and VR models may provide a more environmentally and fiscally sustainable form of presurgical planning. While digital imaging and communications in medicine (DICOM) storage of VR models is not an insignificant concern, it also offers the advantage of inclusion into the patient's medical record for future reference as well.

3.3 | Limitations

Use of our software for VR relies on CT, MRI, or cone beam computed tomography (CBCT) data to construct the VR model. Echocardiography, the standard imaging modality used for pediatric patients, was not used for VR; however, this may be an emerging technology. The incremental use of 3D echocardiography in congenital heart disease and its burgeoning application to 3D printing[15–17] will likely extend to VR as well. Current limitations to the use of 3D echocardiography for rapid prototyping are the lack of standardized image acquisition protocols, and variability in image processing software capabilities and optimization of the 3D dataset, for accurate and convenient segmentation.

An alternative workflow solution is use of a third-party product that allows for accurate STL generation from source 3D echocardiographic data for importing of STL models for VR interaction. Also, upgraded 3D echocardiography machines and updated 3D echocardiography software may potentially allow for the export of 3D STL models directly. The lack of high-resolution data such as CT or MR may provide a limitation to the use of VR for presurgical planning in some pediatric cases. However, when imaging is available, whether in adult or pediatric cardiothoracic cases, VR may contribute potently to presurgical planning.

In addition, while VR may be relatively cheaper for multiple 3D segmentations and multiple VR 3D visualizations, a single 3D printed model offers the convenience of portability, without the need for a headset and other specialized equipment. This is important if the model will be referred to in the OR setting. While video recordings of VR (Supporting Information Videos 1 and 2) can also be conveniently saved and projected onto existing OR computer screens with relative ease, the interactivity with the model is lost in prerecorded videos. A 3D print can be shared for device planning as well. Other limitations include VR equipment and software start-up costs, the lack of existing standards and insufficient evidence so far to support value (the latter two may reflect the limitations of new technology in general). Ultimately, some products allow a shared workflow for DICOM segmentation of both visualization techniques, and use of VR may complement the application of 3D printing.

4 | CONCLUSIONS

We present our preliminary use of virtual reality in two cases of CHD to illustrate the feasibility and potential advantages of this new technology as a complement to traditional imaging modalities. Both cases were selected to demonstrate complex intra and extracardiac spatial relationships commonly encountered in structural heart disease and were accurate representations of intraoperative findings. Specific advantages of VR in complex CHD include: (1) an immersive environment preserving 3D viewing similar to the operative environment; (2) customizable visualization in any arbitrary plane by the end user in a preserved 3D viewing space; and (3) cost containment and storage over 3D physical prints, in some cases. Shared viewership may provide the additional important benefit of enhanced trainee education and improved communication amongst providers. While we have represented our use of this technology on two infants, application of VR naturally extends to the growing population of adult congenital patients with complex, sometimes traditional surgical repairs of previous eras, and need for future interventions. For both infants and older patients, the models also facilitate discussion of anatomy and planned interventions as well as expected outcomes in a tangible format. Future studies are necessary to assess the impact on surgical decision making, training and cost containment.

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CONFLICT OF INTEREST

None.

AUTHOR CONTRIBUTIONS

Concept/Design: CSO, JRG, LG
Data analysis/interpretation/Critical revision of article: CSO, PS, LV, NH, JRG, LG
Drafting article: CSO, AK
Illustration: CYH

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SUPPORTING INFORMATION

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

VIDEO 1 VR visualization (Case 1)
VIDEO 2 VR visualization (Case 2)

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