Phoenix Virtual Heart: A Hybrid VR-Desktop Visualization System for Cardiac Surgery Planning and Education

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Abstract

Physicians diagnosing and treating complex, structural congenital heart disease (CHD), i.e., heart defects present at birth, often rely on visualization software that scrolls through a volume stack of two-dimensional (2D) medical images. Due to limited display dimensions, conventional desktop-based applications have difficulties facilitating physicians converting 2D images to 3D intelligence. Recently, 3D printing of anatomical models has emerged as a technique to analyze CHD, but current workflows are tedious. To this end, we introduce and describe our ongoing work developing the Phoenix Virtual Heart (PVH), a hybrid VR-desktop software to aid in CHD surgical planning and family consultation. PVH is currently being integrated into a 3D printing workflow at a children's hospital as a way to increase physician efficiency and confidence, allowing physicians to analyze virtual anatomical models for surgical planning and family consultation. We describe the iterative design process that led to PVH, discuss how it fits into a 3D printing workflow, and present formative feedback from clinicians that are beginning to use the application.

Index Terms: Human-computer Interaction—Immersive Visualization—Virtual Reality—Interactive Data Analytics; Radiology—Surgical Planning—Medical Education—Medical Imaging

1 Introduction

Congenital heart disease (CHD) refers to a pathology of the heart which is present at birth. The most difficult cases are complex, structural defects, in general. Catheter, a mechanism that can be used to dilate / occlude anatomical structures or deliver other device types, and / or surgical interventions are often required during infancy for these complex cases [16]. For both catheter and surgical planning, physicians employ visualization tools for understanding of the spatial relationships of lesions and anatomy.

To reveal anatomical insights and plan clinical interventions, clinicians have traditionally employed desktop-based applications which show medical images as a volume stack of either 2D computed tomography (CT) or magnetic residence (MR) slices [3]. These applications generally limit the viewing to the in-plane image stack and its two corresponding planes that are orthogonal to each other. A drawback to this method is that it can take physicians years to train themselves to "mentally construct" these three orthogonal image planes (called the axial, coronal and sagittal planes) into a 3D-space of spatial knowledge [9]. Alternatively, while image stacks can also be visualized using volume rendering [14] or as 3D models, visualizing 3D anatomy on 2D displays has well-known drawbacks, including lack of depth perception and potential for misinterpretation [3].

Recently, the 3D printing of anatomical models based on CT/MR data has emerged as a strategy for CHD study. Allowing clinicians to hold a physical representation of a patient's anatomy has demonstrated trends for reduced operating room and case length of time [25] and promoting a high degree of engagement and therefore increased memorability [12, 30]. As an example, our collaborator hospital (Phoenix Children's Hospital, or PCH) was one of the first hospitals in the United States to develop a Cardiac 3D Print Lab to create life-size models of hearts from infants with complex forms of congenital heart disease to aid surgeons and physicians in surgical planning and family consultation. While this hospital is one of the first in the United States to support 3D anatomy printing in practice, the current workflow can become tedious (see Figure 1). First, a physician must dictate printing needs (including the identification of the anatomical features to reproduce, where cuts should be made, etc.) to an engineer who uses 3D printer software to produce the anatomical model. If changes are needed, the physician must specify additional print requests which are interpreted by the engineer and printed as additional models. The result is, for the physician, larger gulfs of execution and evaluation [21], as printing can take several hours for complex anatomies, as well as increased cost for using 3D printing material. Further, while the tactile nature of 3D printed models provides certain advantages compared to display on 2D monitors, such as improved conceptual understanding of complex anatomy [19] and informing the appropriate catheter course and device [22], these models also have drawbacks, such as low annotation capacity where only a surface area of interest can be highlighted with a marker pen. We have been interviewing physicians at PCH to learn how issues like these are considered bottlenecks in their 3D printing workflow. For example, instead of relying on engineers to update print requests and having to wait one or more hours every time a change is needed, physicians would prefer to plan first using software and make a print after being able to review the anatomy.

VR provides an attractive modality for this scenario, as it provides stereoscopic perspective of 3D anatomies with the benefit that virtual models can be explored or altered immediately (thus improving physician efficiency) [26]. VR is already being used for CHD tasks, including for treatment planning, training and practice simulation, and educational applications, and rehabilitation [27, 28].

Unfortunately, despite the emerging popularity of VR for cardiac use, there are questions as to the efficiency of such a technology. For example, VR software tend to employ hand-held controllers for interaction, which performs poorly in tasks such as text input and precise selection of small objects, where keyboard-and-mouse interfaces are much more effective [29]. As these are common actions in the 3D printing workflow (loading model and image stack files, manipulating item color and opacity, etc.), relying on VR as the only means of interaction is likely suboptimal compared to

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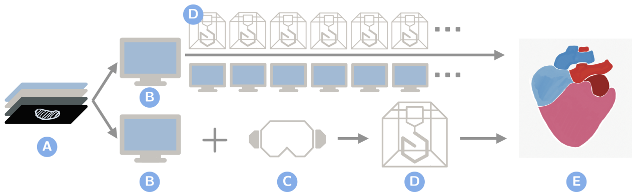

Figure 1: The 3D printing pipeline at PCH includes medical image acquisition (A), desktop data analysis (B) and potentially multiple iterations of 3D printing (D) to obtain a desired 3D anatomical model (E). The PVH software employs both desktop (B) and VR (C) to mitigate the need for multiple 3D prints, by allowing physicians to first virtually assess and modify anotomical models until satisfied. At that point, a print request can be made (D) to generate a 3D print of the model (E).

leveraging both VR and desktop modalities.

In this paper, we report on our ongoing work developing such a cross-device system that combines the strength of both VR and desktop tools to facilitate CHD surgical planning and education within a 3D printing workflow. Our software, called Phoenix Virtual Heart (PVH), is being built in an iterative manner with close collaboration with clinicians at PCH. It consists of two interfaces, a VR interface and the desktop interface, and has been integrated into the hospital's existing 3D printing workflow. Each interface in PVH supports different tasks: spatial manipulations of medical models is done in VR to leverage its stereoscopic perspective and intuitive spatial interactions, while common operational tasks are done on a desktop computer with keyboard and mouse, taking advantage of familiarity of usage for these types of operations. Here, we report on the specific design goals of this system, and how it is being integrated into hospital use. We also report formative feedback from physicians who are beginning to use the tool as a supplement to the hospital's existing 3D printing capabilities.

2 Related Work

2.1 Immersive Analytics in Medical Field

Immersive analytics (IA) is "*the use of engaging, embodied analysis tools to support data understanding and decision making*" [4]. Though the idea behind IA goes back decades [6], it has recently gained attention due to advances in technology platforms [7]. IA applications in medical fields are also emerging. Javaid et al. [13] surveyed applications of VR in the medical fields and identified four major application areas: virtual surgery, operation planning, diagnosis, and physical therapy. He et al. [10] developed a VR technique that creates an exploded view to enable interactive exploration of medical image "atlas"; (expert labeled tissues or structures) so as to enhance understanding of atlas. Pfeiffer et al. [24] proposed a framework that accommodates data of multiple modalities to aid in preoperative planning for liver surgery and enhances spatial understanding. Adams et al. [1] developed an commodity-level simulation where users can simultaneously interact with high resolution and temporal resolution CT and their corresponding 3D structures as well.

2.2 Visualization Technologies for CHD

Traditionally, CHD visualization has been done on the desktop using medical images (such as image stacks from CT or MR data) and/or anatomical reconstruction models to assist CHD procedures [3]. The use of 3D printing, which provides benefits such as tactile feedback and life-size reconstruction of anatomical models, is increasingly being used as a way to provide morphological information during surgical planning and medical education [17]. For example, Moore et al. [20] have demonstrated a clinical outcome benefiting from digital reconstructions and 3D printed model and a discussion on how the advancement of virtual surgery and 3D printing will enhance decision making in CHD treatment.

Likewise, VR is a well-known technique in medicine, due to the fact that VR offers high embodiment, immersion, and realistic depth perception of the 3D-space occupied by human anatomy. Salavitabar et al. [26] recently surveyed existing VR applications in CHD and summarized them into four categories: teaching, predicting, planning, and guiding. Our work lies in the line of using VR as a means of planning, with intended future usage in educational scenarios (such as family consulation and student education). Regarding the latter, VR is heavily used in medical education. For example, Maresky et al. [18] explored the usability of teaching cardiac anatomy to undergraduate students using VR, and Erolin et al. [5] ran a pilot study to test the usefulness of VR in various anatomies such as cranial structures. Silva et al. [27] provide an overview of most recent commercialized VR technologies in cardiovascular medicine such as the Stanford Virtual Heart that provides intuitive interactions for users to gain straightforward understanding of heart anatomy and Echopixel that employs stereoscopic techniques to simulate 3D volumes realistically to enhance surgical planning. Ong et al. explore the role of VR in CHD in [23] where they design interactions such as magnification and see-thru to facilitate exploration of 3D heart models in immersion. While we employ some of the same techniques as in these papers, our work differs in that we focus on a hybrid ecology specifically situated for integration into a 3D printing workflow.

2.3 Cross-device interaction

Cross-device interactions aim to facilitate users by combining the strength of different devices. In our case, this is motivated by the ease of some tasks when using traditional desktop peripherals such as mouse and keyboard, compared to VR where both the peripherals and the user's hands are not visible [15]. Despite the overhead required in physically switching between devices, the idea of combining VR and desktop to take advantage of both interfaces is not new [2, 11]. To the best of our knowledge however, it has not yet been employed in CHD usage scenarios. In Section 3, we note how the hybrid desktop+VR system supports our design goals by providing different affordances to support different tasks. In other words, we take advantage of VR's immersion, depth perception, and spatial interactions when visualizing and directly interacting with anatomical models, but utilize the familiarity and efficiency of the desktop for operational tasks.

3 Design Goals

To our knowledge, a systematic analysis of the design goals for incorporating VR into CHD usage scenarios has not yet been conducted. To understand how VR could help our collaborators, we conducted interviews with clinicians at PCH to understand how a VR software could be implemented to augment their existing 3D printing workflow. In particular, we honed in on the fact that engineers were required to "drive" the 2D desktop displays to analyze and position the anatomical models prior to 3D printing. A customized VR software application could have two advantages at this point in the workflow: (1) It could be tailored specifically to clinician expertise and requirements, allowing physicians to directly analyze and manipulate anatomies instead of relying on engineers. (2) By utilizing VR as a visual and interaction modality, clinicians will have realistic depth perception of the 3D anatomy, resulting in increased confidence when physicians analyzing the spatial relationships between lesions. Our discussions with our collaborators therefore led us to focus on supporting four design goals.

(G1) Separate controls for desktop and VR for different tasks. During our initial development, we quickly realized that a VR-only solution would be insufficient, and that a hybrid VR+desktop application would better serve our collaborators. For example, an early prototype of PVH offloaded all functionality into the VR platform's paddles. While physicians like the immersive viewpoints and intuitive manipulations afforded by VR, they had trouble with operations that were traditionally "desktop-based tasks," such as precisely manipulating the intensity of medical images or navigating through the computer's file system to load additional objects into the software. As a solution, PVH separates operations based on whether they are considered better suited for the VR or desktop modality.

(G2) Spatial manipulation of computer generated models. CHD diagnosis and treatment relies heavily on understanding the 3D spatial relationships of heart lesions. Physicians often rotate and translate computer generated models to gain different views of the heart so as to synthesize a holistic view of the heart structure. Additionally, some surgeries rely on implanting artificial devices to replace malfunctioning heart tissues; planning for these operations require spatial knowledge which can be gained through spatial manipulation of different cardiac structures. The takeaways is that the heart's anatomy is not considered a single object, but is instead composed of multiple subcomponents, which should be individually selectable and manipulatable within the VR space.

(G3) Alignment of models with medical images. When planning for an operation (e.g., a surgery or a catheter procedure), physicians need to know what the inside of the heart looks like. CT and MR image slices are common techniques for obtaining structural information of a target organ and the surrounding anatomy (traditionally viewed as three orthogonal image planes). Surgeons planning for an operation and physicians planning for catheter interventions sometimes combine 3D computer generated models with images of three imaging planes to get situated knowledge of the patient's heart [3]. It was therefore important to our collaborators that PVH includes functionality to superimpose CT and MR image slices within the VR space on top of the anatomical model.

(G4) Integrating devices into heart models. Implantation is a common CHD-related procedure where physicians need to implant a medical device in the patient's heart. The ability to study the heart's structure first and preview a post-implantation heart is essential to the surgeons because it offers an immediate realistic feedback of how the heart structure will look after an operation; physicians can use this knowledge to evaluate and adjust implantation strategies. A major drawback of 3D printed anatomical models can be that it is difficult to simulate implantation, due to model rigidity and occlusion. The virtual, stereoscopic anatomy afforded by a VR space better supports this.

4 The Phoenix Virtual Heart

PVH is developed using the Unity platform for HTC Vive Pro VR headsets via an iterative prototyping methodology [8] in close collaboration with several physicians at PCH. The system is being frequently tested by physicians and radiologists, who are providing immediate feedback for quick refinement, which allows us to adapt and change designs as difficulties are identified and new requirements emerge. We briefly describe the design of PVH as it reflects the four design goals listed in Section 3.

4.1 Separate Controls for Desktop and VR

A well-known drawback for extended reality devices, both VR and AR, is their inability to provide fast text entry and precise selection, which results in inefficiency of conducting 2D UI-based tasks [29]. In our initial development of PVH, the system was designed solely as a VR platform, however feedback from an early prototype quickly led us to realize that, in the context of the 3D printing workflow, a hybrid modality made the most sense. For example, physicians regularly must make precise adjustments to the intensity of CT and MR image slices when performing analysis, which was difficult to do in VR using paddles and much easier to do with numbers on a keyboard.

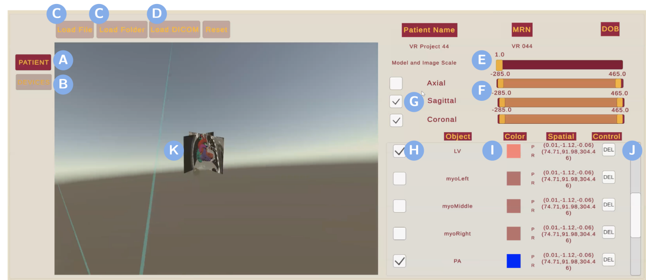

Figure 2: PVH's desktop interface supports operations that are efficient in traditional desktop UIs and inefficient in VR. The user can toggle between (A) the heart model (B) and any loaded devices (B). For the selected item, available interactions include (E-F) resizing the models, (G) toggling medical image planes, (H) toggling the visibility of model subcomponents, (I) changing color intensities, and (J) deleting model subcomponents. (K) The VR scene is also mirrored for coherence.

As a result, we decided to offloaded operations that were more natural with mouse-and-keyboard operations to a desktop modality (shown in Figure 2), such as file selections and slider bar interactions, as opposed to requiring these interactions via the use of paddles within the VR space. The desktop interface is used by physicians to load and delete models (or model subscomponents), and can be used to efficiently change image intensity, model color, and model size, and model opacity via the use of traditional UI affordances (checkboxes, sliders, input boxes, etc.) and windows, icons, mouses and pointers (WIMP) interactions. The physicians switch between desktop and VR control by mounting / unmounting the VR headset. Though such a setup – switching between modalities whilst using the application – temporarily breaks the user's 3D immersion, the ultimate objective of PVH is not total or increased immersion and presence, but rather enhanced 3D intelligence and work efficiency. While we plan to conduct extensive empirical evaluations of this setup to understand the advantages and drawbacks of this approach in terms of task efficiency, insight, and cognitive load, the initial feedback from PCH personnel regarding this hybrid design is promising.

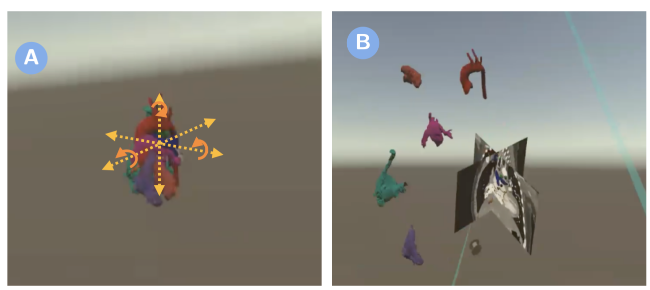

Figure 3: (A) Within the VR space, a user can select a heart model or device and then translate, rotate, or resize it. (B) Selecting a model allows the user to subsequently select its individual subcomponents, which can be further be moved around the space.

4.2 Spatially Manipulating Computer-Generated Models

Compared to using a mouse and keyboard on a desktop, VR supports more intuitive spatial manipulations of objects [3], such as allowing a user to virtually "grab" an object and translate it around by moving the user's hand, or slice a model to simulate a cut plane. In PVH, the user can raycast to select a model with a paddle. Once selected, a model can be manipulated with six degrees of freedom (DOF) by moving, rotating, or twisting the paddle to translate and rotate the model (see Figure 3(A); rotation and toggling a slice plane are additionally supported by scrubbing a control on the paddle.

Manipulation of individual parts that make up an anatomy is enabled by switching to a subcomponent manipulation mode. Individual features that make up the heart can be freely moved within the virtual space (see Figure 3(B)), allowing the user to examine them in detail. Subcomponents can be moved back to their original position i.e., inside the heart model via a trigger on the VR paddle.

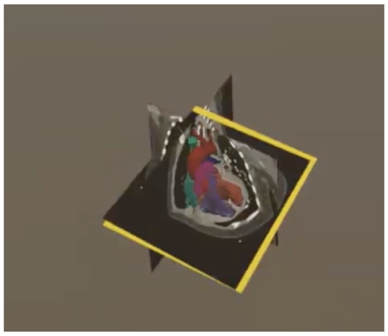

Figure 4: CT and MR image data can be overlaid onto the heart's 3D anatomy, shown as three orthogonal image planes. The user can select and scroll individual planes along their axes.

4.3 Aligning Heart Models and Image Slices

In addition to 3D models, CT and MR-based medical images act as a major source of spatial insight into the heart's anatomy. PVH supports overlaying this data onto the 3D heart model inside the VR space. The medical image stack is shown as three orthogonal planes (axial, coronal, and sagittal) that intersect the heart model's geometry. Each plane can be selected via paddle raycasting and moved along its axis.

PVH supports overlaying image slice data onto anatomy models in VR space — the user load an image stack CT or MR slices using the desktop interface, which are then spatially aligned with the 3D models as shown in Figure 4. Individual image planes can be selected and manipulated via the VR paddle to adjust the depth of each of the three orthogonal planes (up and down, left and right, back and forth).

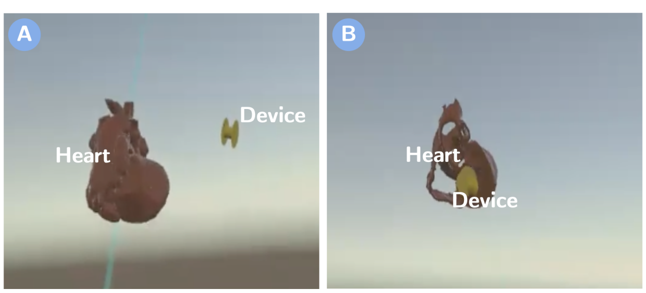

Figure 5: In these images, (A) the user is inserting a 3D model of a device into the VR space, and (B) moving it inside the heart's geometry to assess if a device fits the heart anatomy. The user has also toggled off several subcomponents of the heart model for better visibility.

4.4 Integrating Devices into Heart Models

Finally, PVH supports adding additional medical devices into the VR space to simulate implantation scenarios. Devices can be loaded from the desktop interface and manipulated within the VR space. Figure 5 shows an example of inserting an Amplatzer ventricular septal occluder device into the interventricular septum of the heart. To provide additional visibility, the user has toggled off several subcomponents of the heart, so they can better see how the device fits into the anatomy.

5 Discussion and Conclusion

PVH is an ongoing project, and this paper primarily focuses on highlighting a set of four primary design goals that were considered while implementing this tool. While we plan to conduct extensive evaluations with PCH physicians to learn in detail about how the system supports surgical planning, family consultation, and educational training, a formative survey with three clinicians (one interventionalist and two pediatric radiologists, all with working experience in CHD of more than 24 years) has provided positive feedback about PVH's tailored user experience.

For example, the hybrid VR+desktop interface was well-regarded, and the physicians are planning to expand their use of PVH in their own clinical work. General system usability was rated as high, and all participants felt confident using the system, though as expected, there was a higher learning curve for the users who lacked prior experience in VR. Despite this, during demonstrations all were able to use the software to find pathologies in patient anatomies. We also plan to investigate the design and use of novel affordances and interactions to support physicians using the tool.

In terms of integrating PVH into the 3D printing workflow at PCH, the potential to mitigate scenarios where multiple prints are done, thus requiring multiple consultations between physician and engineer, as well as several hours of wait time, is significant. As PVH is designed specifically to sit inside the 3D printing workflow, we see it as an example of how interactive visualization tools provide exploratory and sensemaking insights without having to create expensive and time-consuming 3D prints. However, if desired, users can export analyzed and manipulated models (both anatomies and devices) to 3D prints and receive additional benefits not offered in VR such as tactile response. We expect our future empirical studies will also shed light into how PVH can act both as an alternative and a precursor to 3D printing of models, and better characterize the types of situations that are best served in the VR space as compared to the 3D printed space or by using a combination of both modalities.

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