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Original Article

The Role of Immersion for Improving Extended Reality Analysis of Personalized Flow Simulations

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Abstract
Purpose—Computational models of flow in patient-derived arterial geometries have become a key paradigm of biomedical research. These fluid models are often challenging to visualize due to high spatial heterogeneity and visual complexity. Virtual immersive environments can offer advantageous visualization of spatially heterogeneous and complex systems. However, as different VR devices offer varying levels of immersion, there remains a crucial lack of understanding regarding what level of immersion is best suited for interactions with patient-specific flow models. *Methods*—We conducted a quantitative user evaluation with multiple VR devices testing an important use of hemodynamic simulations—analysis of surface parameters within complex patient-specific geometries. This task was compared for the semi-immersive zSpace 3D monitor and the fully immersive HTC Vive system. *Results*—The semi-immersive device was more accurate than the fully immersive device. The two devices showed similar results for task duration and performance (accuracy/duration). The accuracy of the semi-immersive device was also higher for arterial geometries of greater complexity and branching. *Conclusion*—This assessment demonstrates that the level of immersion plays a significant role in the accuracy of assessing arterial flow models. We found that the semi-immersive VR device was a generally optimal choice for arterial visualization.

Keywords—Immersive visualization, Coronary models, Arterial simulations, User study.

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INTRODUCTION

Visualization of three-dimensional (3D) biomedical data is critical for understanding complex phenomena and effectively communicating key research findings. To augment biomedical visualizations of 3D data, which have been traditionally confined to two-dimensional (2D) desktops, virtual reality (VR) can be particularly competitive for understanding spatial heterogeneity in complex arterial visualizations.[20] VR has the advantage that it enables a more immersive experience with computational models and simulation data.[19] Experiences in VR can be measured by the degree of immersion, an intrinsic VR property that objectively describes the level of sensory fidelity.[6] In this work, we assess whether the level of immersion influences user interaction with complex intra-arterial physiology derived from computational fluid models of patient-specific vasculature. Such physiological features are important attributes in biomedical research and exhibit particularly complex spatial details.

Study Motivations and Contributions

Immersion is determined by two key metrics: display fidelity and interaction fidelity, which are respectively defined as the degree of exactness that real-world effects and interactions are reproduced in the virtual environment for a given task.[22] Immersion can be especially useful for visualizing arterial vascular models, which are important components of many workflows in biomedical research.[5,8] Such arterial models are often coupled with computational fluid dynamics (CFD) simulations to facilitate the understanding of patient-specific hemodynamic risk factors such as endothelial shear stress (ESS), which have been associated with the progression of disease development.[5,8] However, visualization of important surface parameters such as ESS is complex and time-consuming due to vessel tortuosity, arterial branching patterns, and integration of vector field data.[20,5,39,2] We hypothesize that increased immersion could improve the effectiveness of surface parameter analysis and thus propose the application of a VR environment to test the level of immersion required for both accurate and timely visualization of ESS.

We conducted a quantitative user evaluation with 31 participants who were experts in medical and physical science principles using a visualization platform that supports multiple VR/AR modalities with varying levels of immersion. Since ESS is an important hemodynamic biomarker that is often visualized,[38] we developed a task where users were asked to identify regions of low ESS in patient-specific arterial geometries. This task allowed us to capture user interaction with hemodynamic simulations (Fig. 1). For this task, we evaluated different levels of immersion using the fully immersive HTC Vive head-mounted display, the semi-immersive zSpace fish tank VR device, and a traditional 2D monitor with minimal immersion. The two immersive devices offer differing display fidelity, which can result in differences in spatial judgment and a disparate understanding of spatial heterogeneity when analyzing key surface parameters such as ESS.

There are three main contributions of this study. First, evaluation of how immersion, a key VR metric, intrinsically affects user interaction with patient-specific hemodynamic simulations. Our results demonstrated that the semi-immersive device yielded greater accuracy in identifying physiological crucial regions of ESS than the fully immersive device. Second, quantification of the impact of a semi- vs. fully immersive device on user performance metrics, such as task duration and performance. We obtained similar duration and performance between the two immersive devices. Third, identification of the interplay between spatial complexity and immersion level and the associated effect on accuracy in hemodynamic simulations. This study used patient-specific arterial geometries having varying levels of spatial complexity. Our findings suggest that the semi-immersive accuracy advantage was more pronounced in the case of more spatially complex arterial geometries.

Related Work

Application of Virtual Environments

Virtual immersive environments have been applied to numerous fields, ranging from military and robotic applications, to aerospace and automotive design, and to computational chemistry simulations.[7] The success of VR in each of these domains has advanced spatial understanding of complex structures and enabled virtual training. Therefore, the broad and visually complex domain of biomedical research is especially ripe for the application of immersive displays. VR-based biomedical research has been applied to a variety of tasks, such as cellular understanding[20] and comparing spatial perception techniques for medical visualization.[18] While there are many examples of VR implementation in biomedical research, it remains unclear how increased display fidelity impacts the visualization of arterial vascular models. This problem is further confounded by the availability of different consumer-grade VR devices and the lack of consensus for which VR device is most suitable. To answer both of these research questions, this study investigates the influence of immersion, a key VR metric that varies between different VR devices, within the context of complex arterial simulations.

Vascular Models and Workflow

The accurate and efficient visualization of 3D arterial models is a difficult challenge for biomedical researchers.[5] These vascular geometries are used as the basis for CFD analysis, which produces detailed maps of physiologically relevant quantities such as velocity

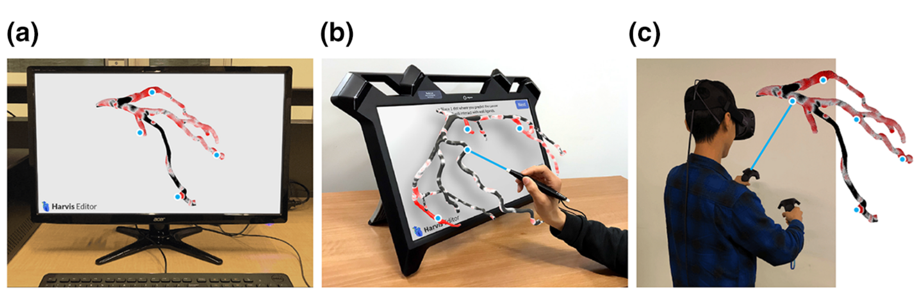

FIGURE 1. Our hemodynamic simulation visualization software is shown running on (a) conventional 2D desktop, (b) semi-immersive zSpace device, (c) fully-immersive HTC Vive device used in this study. This rendering shows interaction with the endothelial shear stress map for a coronary artery and was generated using screenshots of the software.

and pressure.[39,28] For example, the ESS (frictional force exerted by blood in the tangential direction) data from these simulations have been shown to be important for understanding disease localization and progression.[11,34] The geometries used in these simulations are also often modified, involving changes to their vascular or surface topologies. This *in silico* pipeline can be used as the iterative basis for detailed investigations connecting vascular morphology to hemodynamic outcomes.[15,24,36,31] This investigative process often involves several difficult steps of pre and post-processing, spanning multiple software packages.[25,37] Moreover, invasive clinical diagnostic metrics, such as fractional flow reserve, can now be directly and non-invasively derived from CFD simulations and have been approved by the FDA.[33] These examples underscore the increasing clinical acceptance of CFD as applied to arterial models. Our study extends such CFD arterial studies by evaluating the influence of VR-based visualization, which is imperative to advance the current state-of-the-art.

Platforms for Cardiovascular Simulation and Visualization

Several software applications have been developed to integrate the aforementioned hemodynamic visualization steps into a single workflow. SURGEM is a novel software tool that integrates vascular geometry modification and CFD simulation, with support for modeling several types of cardiovascular procedures.[25] SURGEM has received positive user evaluation and seen preliminary usage in the clinic.[25] Another software tool, AView, centers on intracranial aneurysm analysis with integrated flow simulations and has exhibited encouraging results from a pilot study and clinical feedback.[37] Biomedical researchers have recently started supporting immersive displays for cardiovascular visualization, such as building a prototype of integrated software for cardiovascular decision support that utilizes the zSpace VR monitor[17]; another work presents a semi-automatic workflow that takes patient-specific cardiovascular imaging and produces a CFD visualization within a cave automatic virtual environment (CAVE).[27] Such ongoing efforts reflect a steadily growing interest in developing streamlined tools that utilize hemodynamic visualization, with an emphasis on clinical practice. These works helped to inform the VR devices used in our empirical user study. However, existing studies have targeted either conventional 2D monitors or a specific immersive device, e.g., a semi-immersive device or CAVE. By comparing fully immersive to semi-immersive VR, our research provides new findings on how the key VR factor of immersion affects interaction with arterial models. This work helps inform the choice of VR devices for biomedical researchers visualizing CFD data.

Comparisons of Immersive Devices

A VR hardware setup consists of several components: display, input devices, headphones, and a computer.[9] These different components combine to provide a high-fidelity immersive VR user experience. Among these different components, the display is central to the immersive VR experience due to the relative importance sight has on perceptual information and sensory interaction in the real world.[9] VR displays are different from standard displays as they are stereoscopic and provide a sense of depth and solidity. Input devices and other components must all be carefully compared to demonstrate suitability in an interactive VR environment—an active area of research; however, the display occupies centrality and is often the key design choice for a VR application.[10] Therefore, the focus of this study is to assess the impact of different immersive displays on visualizing and interacting with arterial models.

While these studies offer valuable insights into general trends, the performance of immersive devices greatly depends on the particular application being investigated. It may be concluded from these investigations that comparative results of immersive VR devices are confounding at best and that there is no single display that can be used for any given application. Visualization of hemodynamic simulations generally involves parsing unique, sparse, and complex geometries, and thus may result in differential effectiveness from immersive devices offering various levels of immersion. Therefore, this research intends to offer guidance on the suitability of various VR devices for computational scientists interested in integrating VR-based visualizations with physiological vascular models. This requires a unified computational platform that we can use to compare the effect of immersion in these simulations, as well as an empirical study with representative participants.

METHODS

Computational Fluid Dynamic Solver and Immersive Visualization Platform

De-identified CT angiographic (CTA) datasets of left and right coronary arteries were obtained for nine patients under appropriate Institutional Review Board guidelines and approval. This CTA data were segmented using Mimics (Materialise, Leuven, Belgium), a commercial segmentation software. The arterial blood flow simulations were performed using HAR-

VEY, a massively-parallel CFD software using the lattice Boltzmann method, an alternative to solving the Navier-Stokes equations.[36,29,35] Each geometry was simulated using transient physiological inlet and outlet boundary conditions. At the inlet, a pulsatile left and right coronary waveform was applied to the left and right coronary arteries respectively[16]; at the outlet, a lumped parameter model was applied to simulate microresistance at arterial vessel ends.[33] Spatial convergence was achieved at a resolution of 50 microns. Temporal convergence was noted at 20×10^3 time steps, corresponding to two cardiac cycles.[34] Blood was assumed to be Newtonian fluid and blood vessels were modeled as rigid walls, with a no-slip boundary condition on the flow. These simulations were performed on 1024 cores of Intel Xeon E5-2699 processors with 56 Gb/s Infiniband interconnect on the Duke Compute Cluster because of the memory required for the large fluid domain.

For the user study tasks, the simulation results were visualized using a software known as Harvis.[31] Harvis is a cross-platform desktop application built using the Unity engine. In addition to running on traditional 2D monitors, the application supports the zSpace VR display and SteamVR-compatible VR head-mounted displays, such as the HTC Vive. The Harvis software includes two main categories of features: 1. interactive geometry modification and 2. hemodynamic visualization.[31] ParaView, an open-source visualization software with VR support,[3,32] was also considered for this task; however, Harvis allows for more streamlined visualization of cardiovascular data, as well as integrated vascular geometry modification and the ability to run interactive user modules. The focus of this study is to assess optimal VR display for visualizing arterial simulations and identifying critical regions of ESS which is important because ESS promotes atherosclerosis in coronary arteries.[8] Detailed physiological flow field maps, such as the ESS, overlaid on 3D arterial geometries consist of several million points; thus, we use a custom serialization framework to cache these data sets for efficient re-visualization. To conduct the user study, we designed modules—scripts using Harvis—to orchestrate the study tasks for each participant.

User Study of Arterial Visualization

Using the Harvis visualization interface, we conducted a quantitative user study to understand how different level of immersion relates to performance for arterial visualization. Users were tasked with identifying regions of low ESS on the surface of coronary artery geometries because low ESS is a commonly investigated pro-atherogenic risk factor.[5,8,35] The user placed dots on a surface to mark regions of low ESS. Low ESS regions were defined as contiguous areas of the lowest ESS for a particular geometry, color-mapped to bright red in the visualization. This mirrors the common research task of reading a parameter map on the surface of a 3D geometry.

To render arterial simulations using Harvis, we chose three display devices offering varying levels of immersion: a traditional 2D monitor, the zSpace 200 3D VR monitor, and the HTC Vive VR headset. The 2D monitor was a 21-inch diagonal 1920 by 1080 pixel desktop monitor. The zSpace 200 has a 23.6-inch diagonal 1920 by 1080 pixel monitor, which allows for stereoscopic 3D with integrated head-tracking. The zSpace is also accompanied by a stylus controller, which is tracked in 3D as well. The HTC Vive VR system includes a headset with two 1080 by 1200 pixel displays, as well as two motion-tracked controllers that appear as avatars in the VR environment. When the study was performed, the HTC Vive was chosen over the Oculus Rift, a similar VR platform, due to a more reliable headset and controller tracking. We expect both the Vive and zSpace to have similar interaction fidelity due to their wand-style interaction mechanisms.

The 2D monitor offers minimal immersion, while the zSpace and Vive are semi-immersive and fully immersive, respectively. Since the focus of this study is comparing levels of immersion and given the overwhelming amount of experience users have with the traditional 2D format, the results and analysis focus on comparing the zSpace and Vive; the 2D data is used as a baseline standard rather than a direct comparison.

In contrast, the zSpace has higher display fidelity, and thus greater immersion, than the Vive. This is because the Vive, while higher in resolution, suffers from the screen door effect, with fewer pixels fitting into the visual field.[9] The 2D display version of Harvis relied on mouse controls with pan, zoom, and trackball inputs emulating conventional CAD software. Mouse buttons were used to place dots and click interface buttons. For zSpace, a wand-style control setup was implemented for the 3D-tracked stylus, using a screen-rendered ray emanating from the stylus tip to click on interface elements and place dots. The stylus was also used to move, rotate, and scale the on-screen geometry. The Vive controller was utilized in the same wand-style setup as the zSpace; only one of the Vive controllers was needed for the interface to operate.

Cohort Planning and Participant Demographics

Using a pilot study, we estimated the target study size to be 28 participants with an $\alpha = 0.05$, a power of

0.8, and an effect size of 0.5.[31] We thus recruited 31 participants as part of the study population. Among these, 24 participants were experts in physical science disciplines and biomedical research, and 7 were medical trainees. Such a study population is a desirable mixture of backgrounds because it captures the audience for this study: clinical and physical science researchers with a keen interest in biomedical visualizations. We had 18 (58%) male and 13 (42%) female participants. In terms of prior experience with VR: 8 (26%) users reported having no prior experience, 18 (58%) users reported having used VR once or twice, 3 (10%) reported using VR 3-5 times, and 2 (6%) reported having used VR more than 5 times. The level of experience with VR was consistent with the recent growth of VR gaming and usage among research institutions. Participants were initially screened for normal and corrected vision and monetarily compensated upon completion of the study.

Study Procedure

The study involved performing a common interaction task for arterial visualization on multiple devices. Each user began the study by taking a pre-survey, which collected basic demographic information and details about prior experiences with virtual reality.

For the study task, users were instructed to locate regions of low ESS on patient-derived coronary artery geometries. This was chosen as the study task due to its clinical relevance; as previously discussed, low ESS is a pro-atherogenic risk factor.[8] Moreover, the identification of low ESS regions with diverging color maps on 2D desktops was also previously investigated by Borkin *et al*.[5] and was found to be more accurate and efficient than a rainbow color map. A diverging red to black color map was used to represent the ESS data for the 9 reconstructed left and right arterial models, generated from CFD simulations using HARVEY. The resulting ESS maps were overlaid on corresponding arterial geometries and then displayed to the user in Harvis (Fig. 2).

Each participant was assigned 3 coronary geometries, chosen at random from the total pool of 9. The user would be cycled randomly through all 3 display modalities and be shown the same 3 geometries on each. Within a device, the geometries appeared in random order to reduce learning effects. As such, each user would see every geometry 3 times, thus facilitating a within-subjects comparison. For each geometry on a device, the user would be given on-screen instructions to place dots to mark large regions of low ESS. These dots would adhere to the surface of the geometry. The duration was measured as the time taken from when the task was presented to when the user clicked a button indicating they were ready to proceed. We quantified accuracy by first dividing the number of regions correctly identified by the number of total low ESS regions for that geometry, which was determined by cardiologists and a computational fluid modeling expert. This ratio was then multiplied by the number of dots placed in correct regions divided by the total number of dots placed, to penalize for incorrect dot placement; doing so allowed us to counter a user who could potentially identify all the correct regions just by placing many dots over the entire surface. The number of low ESS regions per coronary ranged from 2 to 3. Dots were deemed correct if they were placed inside the bounding box for a particular region; some regions with more complex topologies required several bounding boxes to define completely.

Bias Minimization

Several measures were taken to minimize bias in the design of the study. To ensure a consistent experience for all participants, the use of each device was preceded by an interactive tutorial where the user would learn all the navigational controls for the device and how to place dots. Before starting the task, the user would first read a written document that explained the background and specific instructions for the task. Experimental conditions were kept consistent, with the lighting and room setup being the same for all devices and participants. Instructions for tasks were displayed on-screen, and quantitative metrics such as accuracy and duration were recorded using the software itself. Users were extensively trained on controller usage. We employed a simplistic interaction method of dot placement and used the same wand-style navigation for both immersive devices. To control for the effect of arm fatigue, each session on a device was designed to take between 5 and 10 minutes, and fatigue was addressed on the post-survey.

RESULTS

From the visualization user study, we obtained three quantitative metrics—accuracy, duration, and performance. We collected 279 trials (31 participants $\times$ 3 tasks $\times$ 3 devices). Participants took between 45 and 65 minutes to complete the study and all associated surveys.

We base our statistical procedures on fair practices for HCI, using confidence intervals and effect sizes.[13] Each metric is aggregated by participant ($n = 31$) before computing the confidence intervals. For all metrics (accuracy, duration, performance), we compute

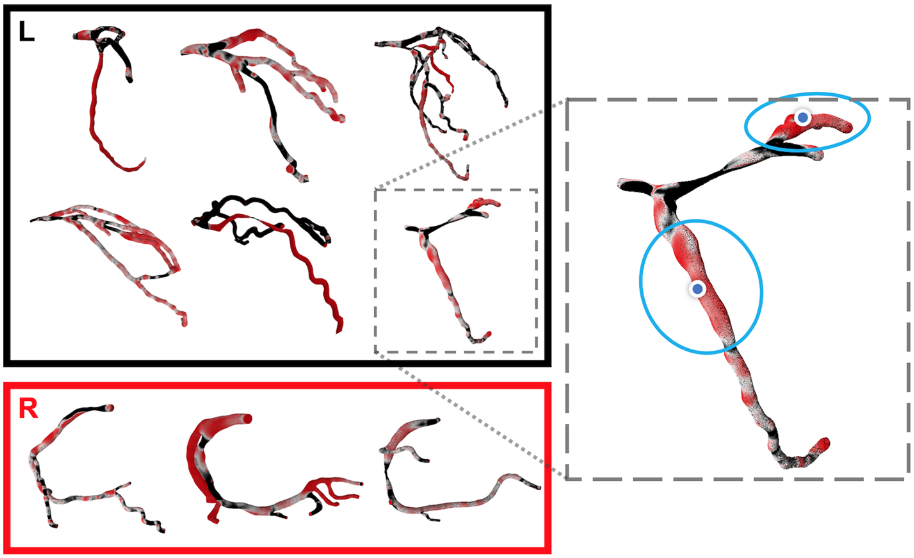

FIGURE 2. Overview of the study task. On the left are the 9 coronary geometries used in the study, grouped as left coronary artery (LCA) and right coronary (RCA) coronaries. The geometries are color-mapped such that red, white, and black indicate low, medium, and high ESS, respectively. In the inset view on the right, we see the correct task result for one of the geometries. The two circled regions are the contiguous regions of low endothelial shear stress and the two user-placed blue-and-white dots indicate examples of correct dot placement—anywhere inside the region. Note that the circles are only for reference and did not appear in the actual task.

the mean and the 95% bootstrapped pivot confidence interval, presented in the following format:

mean [*CI lower bound*, *CI upper bound*]. To facilitate the comparison of devices, we report and plot the within-subjects pairwise difference (PD) for each metric. Unless otherwise specified, PD is calculated per participant as semi-immersive - fully immersive. The plotted data is shown as violin plots to better capture the density distribution. Abbreviations used are *SI* semi-immersive, *FI* fully immersive, and *PD* pairwise difference. A summary of reported metrics is shown in Table 1.

Task Accuracy

We compared the accuracy of the SI and FI devices. PD results are shown in Fig. 3. A PD greater than zero indicates that SI is more accurate. For the overall accuracy, there is good evidence that the SI device results in greater accuracy than the FI device: PD = 12.4% [5.0%, 18.6%]. We note that SI demonstrates greater accuracy than FI with a PD = 9.4% [2.3%, 16.8%].

Task Duration and Performance

For the duration metric, we measured the time taken (seconds) to complete each region identification task, averaged over all such tasks per user. This does not include any of the time spent in tutorials or training. PD values are displayed in Fig. 3. PD values less than zero indicate that SI is faster. The difference in speed is not conclusive and is likely to be small (PD = −2.3 [−11.0, 7.0]). Furthermore, we define the performance metric as accuracy divided by duration, since it allows us to quantify the relationship between accuracy and duration on a per-task basis. The performance PD results, in units of inverse seconds (s^{-1}), are shown in Fig. 3. PD values greater than zero indicate that SI is more performant. The performance is very similar between the devices (PD = −0.002 [−0.012, 0.009]).

TABLE 1. Summary of reported metrics, organized by groupings and devices.

Metric	Grouping	Device	Value
Accuracy (%)	Overall	2D	68.5% [61.0%, 76.4%]
		SI	69.6% [62.8%, 76.3%]
		FI	60.2% [53.4%, 67.2%]
	Left	SI	70.8% [63.7%, 77.9%]
		FI	59.3% [49.2%, 69.5%]
	Right	SI	67.2% [57.5%, 76.7%]
		FI	62.0% [50.5%, 73.8%]
Duration (s)		2D	21.4 [16.6, 25.6]
		SI	31.6 [26.6, 36.2]
		FI	33.9 [26.3, 40.6]
Performance (s^{-1})		2D	0.052 [0.040, 0.062]
		SI	0.031 [0.025, 0.036]
		FI	0.033 [0.023, 0.041]

Values are displayed as means with 95% bootstrapped confidence intervals. *SI* semi-immersive, *FI* fully immersive.

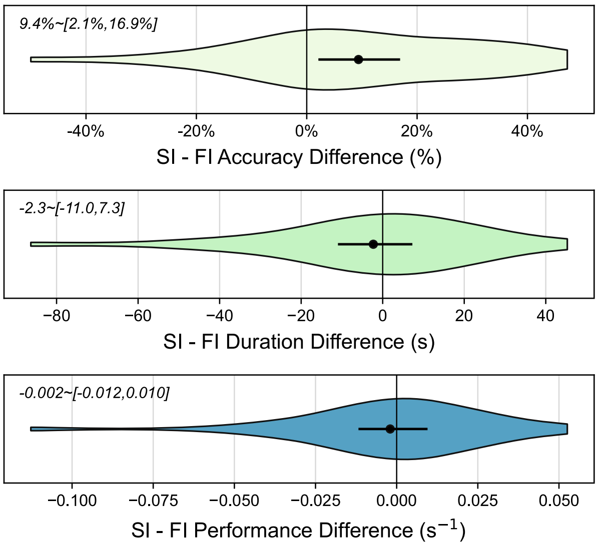

FIGURE 3. Pairwise differences for accuracy, duration and performance. For accuracy, values greater than zero indicate that SI is more accurate. Accuracy was measured as the percentage of correctly identified regions multiplied by the percentage of correctly placed dots. For the duration, values less than zero indicate that SI is faster. For performance, differences greater than zero indicate that SI is more accurate. Error bars represent 95% confidence intervals.

Accuracy for Geometries of Differing Complexity

We tested whether spatial complexity influences task accuracy. Left coronaries exhibit more branching and therefore greater spatial complexity than right coronaries. PD results are in Fig. 4. For the left coronaries, SI appears to be more accurate than FI (PD = 11.5% [−0.7%, 23.2%]); however, it is possible that this difference is small. With the right coronaries, the two devices seem to have similar accuracy results (PD = 5.1% [−6.3%, 17.5%]).

Comparison with Traditional 2D Desktop

We compared the results of the more performant semi-immersive device with those of a traditional 2D desktop. For this section, PD is reported as 2D-SI. The accuracy results (PD = −1.1% [−9.1%, 6.7%]) seem to be very similar between the two devices. 2D was faster than SI (PD = −10.2 [−15.2, −4.9]) and more performant (PD = 0.021 [0.010, 0.031].

DISCUSSION

With the advent of consumer-grade VR technologies, there exists a wide range of devices that can be utilized for different applications. However, few studies evaluate the effect of using VR devices in the analysis of arterial flow simulations. Furthermore, literature remains limited and inconclusive on the selection of the appropriate type of immersive display for arterial simulations, which are gaining increasing clinical acceptance.[33] Therefore, this study evaluates the application of VR devices with varying levels of immersion toward complex patient-derived arterial simulations. Our results demonstrate that for identifying regions of interest in arterial visualizations, a semi-immersive VR environment leads to more accurate outcomes than fully immersive VR, with similar duration and performance.

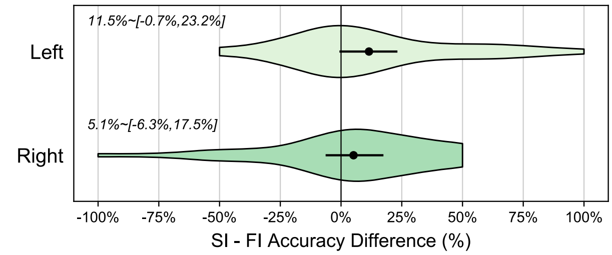

FIGURE 4. Pairwise accuracy differences for geometries of differing complexity. Left coronaries are more complex; right coronaries are less complex. Values above zero indicate that SI is more accurate than FI. Accuracy is quantified as the percentage of correctly identified regions multiplied by the percentage of correctly placed dots. Error bars are 95% CI.

It was previously shown that the higher display fidelity of semi-immersive devices contributed to higher user accuracy when assessing spatial features such as shape, density, and connectivity for complex volume visualization problems.[26] We believe that this effect would similarly influence user accuracy when interacting with hemodynamic visualizations of higher spatial complexity. We tested the effect of display fidelity on user accuracy in both tasks. In studying user interaction with surface data, spatial complexity was presented in the form of branching and tortuosity within the arterial geometries. Our findings suggest that display fidelity, which is a key differentiator between the SI and FI devices, is the driving metric in identifying spatial features for visualization studies that offer high spatial complexity.

We note that higher spatial complexity, exhibited by arterial branching and tortuosity patterns such as those seen in left coronary arteries, influences the accuracy of identifying regions of interest in different virtual immersive displays. For the case of these more complex left coronary arteries, the semi-immersive displays yielded greater accuracy than the fully immersive display, and a minimal difference was seen for the right coronary arteries. While these findings are reported in different immersive environments, an analysis reported by Borkin *et al.*[5]] for a 2D desktop found similar differential accuracy patterns for spatial complexity in left and right coronary arterial trees.

These parallels of accuracy and performance for vascular models concur with the empirical study design and findings presented in this work. Our findings extend the understanding of visualizing arterial complexity to different immersive platforms, showing that the effect of immersive device choice is more pronounced in complex geometries due to improved spatial and angular assessment. Another avenue that may benefit from greater spatial assessment in semi-immersive environments is cardiovascular streamline analysis, which would allow for a more detailed understanding of vector quantities such as WSS,[14] and perhaps a greater difference in the SI and FI results.

As a baseline assessment, we compared the more performant SI device to a traditional 2D desktop for assessing hemodynamic visualizations. First, we demonstrated comparable accuracy results between the 2D desktops and SI displays in terms of accuracy in identifying surface parameters. The accuracy results of ESS region identification on 2D desktops reported by this study, 68%, is in close approximation to 71% reported by Borkin *et al.* in their paper investigating the role of dimensionality and color mapping for ESS region identification.[5] Similar to other studies,[4,21,30] we saw a reduced duration, and subsequently performance, with the 2D monitor. The user's comfort level and experience with such conventional devices is likely a strong contributing factor.

In order, to assess the effect of immersion, we focus specifically on the AR/VR devices. The task duration of the semi-immersive and fully immersive devices was similar. We hypothesize that this is due to the similar wand-style controller setup of the devices. With the task of manipulating a complex cardiovascular geometry and placing markers, it would seem that immersion fidelity is more important than display fidelity for task completion time. In the fast-paced environment of a procedural hospital department, the duration of a visualization task becomes increasingly important. Especially in contrast to the 2D display, which is more performant than both immersive devices, it appears there is a gap to be closed in terms of training time and familiarity with the device. With the increasing utilization of virtual reality in surgery[12] and medical education,[23] the amount of total VR exposure in the medical field is growing; however, whether this training gap can be closed would require further study.

We note that there are some limitations to our study. To study the role of immersion in assessing biomedical interactions, we used arterial simulations as a representative subject. While we assert that the identification of hemodynamic risk factors is an important task for arterial visualization, we acknowledge that there are other types of interactions potentially not captured in these test cases. Low ESS identification is one task of particular clinical relevance; however, there are other cardiovascular visualization tasks that could be investigated, including but not limited to the analysis of ESS ranges, ESS vector fields, and velocity isosurfaces. Our findings are therefore limited in scope to this interaction. Also, we focused on the role of immersion, determined by display fidelity, as a central VR metric in understanding vascular models. We selected our hardware based on prior studies.[26,1]

Overall, this study focused primarily on the effects of immersion in biomedical research, given the increasing acceptance of hemodynamic simulations in clinical practice, we expect that these visualization environments could also be translated into the clinical space.[15,33] We expect FI devices may outperform SI display under test conditions with greater interaction such as geometry modification, which is required for treatment and surgical planning.[25] Thus, future work would investigate the application of immersive virtual devices in implementing vascular surgical procedures such as stents and conduits, in collaboration with experienced physicians and vascular surgeons.

CONCLUSION

This study compares two different immersive virtual environments for visualizing vascular simulations. Within this representative visualization context, we conducted an empirical study with domain experts using real patient-derived geometries, which allowed us to create realistic visualization scenarios for biomedical research. The findings of this study suggest that display fidelity strongly influences the accuracy and duration of arterial hemodynamic visualizations. This result led us to identify the semi-immersive VR device as a generally optimal choice for arterial visualization.

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CONFLICT OF INTEREST

The authors have no conflicts of interests or competing interests to declare.

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