Immersive Virtual Reality for Visualizing Flow Through an Artery

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Abstract

We present an immersive system for exploring numerically simulated flow data through a model of a coronary artery graft. This tightly-coupled interdisciplinary project is aimed at understanding how to reduce the failure rate of these grafts. The visualization system provides a mechanism for exploring the effect of changes to the geometry, to the flow, and for exploring potential sources of future lesions. The system uses gestural and voice interactions exclusively, moving away from more traditional windows/icons/menus/point-and-click (WIMP) interfaces. We present an example session using the system and discuss our experiences developing, testing, and using it. We describe some of the interaction and rendering techniques that we experimented with and describe their level of success. Our experience suggests that systems like this are exciting to clinical researchers, but conclusive evidence of their value is not yet available.

1 Introduction

Coronary artery grafts regularly fail for unknown reasons, requiring repeated heart surgeries and often causing heart failure. Medical imaging modalities provide varying views of these arteries, via x-ray angiography, ultrasound, and magnetic resonance imaging, but simulation of the flow of blood in the vessels holds significant potential for understanding why these grafts fail.

We have coupled numerical simulation of graft geometry with an immersive virtual environment for studying the resulting flow data. Doctors reviewing the results are optimistic about using the system to better understand cardiovascular hemodynamics.

In this paper we briefly describe the biological problem, the numerical simulation methodology, and the immersive virtual Cave environment. The subsequent discussion section describes some of the lessons that we learned: what worked and to what degree, and what didn't work. Our long term goal includes understanding how immersive environments such as the Cave are useful for scientific visualization.

2 Arterial Grafts

In a multi-disciplinary effort, we are currently attempting to understand the haemodynamic effects due to three-dimensional modifications of the geometry within arterial bypass grafts. Atherosclerotic lesions tend to develop near areas of flow disturbances such as at arterial branches and bifurcations.

Fig. 1 shows a graft schematically. A new piece of artery is attached to a point in a damaged coronary artery downstream from the damage. This graft brings new blood to parts of the heart that have been starved. Grafts like this tend to fail when lesions form that block the new flow.

Fig. 2 shows one image from an angiogram of a damaged artery. Images like these are current state-of-the-art for how clinicians view blocked arteries. Angiograms are effective for showing the degree of blockage in an artery but do not show why or how future lesions may form.

Although a great deal of flow data has been obtained experimentally, certain flow quantities which are inaccessible to the physician using commonly available clinical techniques can be modeled accurately through the use of numerical simulation. Fig. 5 shows output from tecplot [1], a widespread fluid dynamics visualization package. We believe that an immersive environment can permit more effective visualization of fluid simulation results than conventional desktop display devices.

3 Simulating Complex-Geometry Flows with $\mathcal{N}\varepsilon\kappa\mathcal{T}\alpha r$

The flow solver corresponds to a particular version of the code $\mathcal{N}\varepsilon\kappa\mathcal{T}\alpha r$, which is a general purpose CFD code for simulating incompressible, compressible and plasma flows in unsteady three-dimensional geometries. The major algorithmic developments are described in [2] and [3]. The code uses meshes similar to standard finite element and finite volume meshes, consisting of structured or unstructured grids or a combination of both. The formulation is also similar to those methods, corresponding to Galerkin and discontinuous Galerkin projections for the incompressible and compressible Navier-Stokes equations, respectively. Field variables, data and geometry are represented in terms of hierarchical (Jacobi) polynomial expansions [4]; both iso-parametric and super-

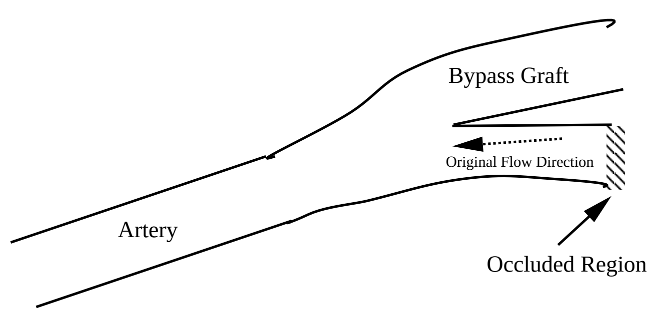

Figure 1: Diagram of a graft.

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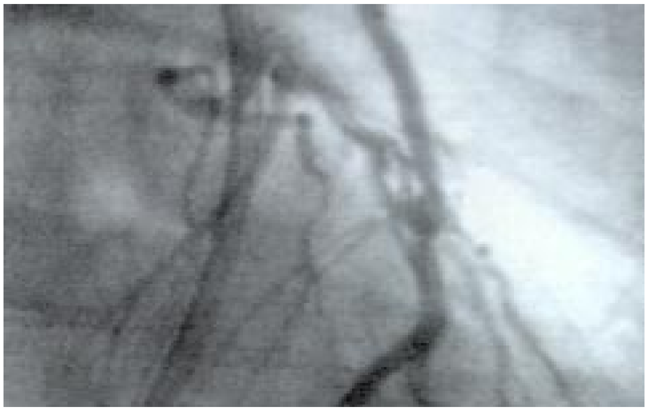

Figure 2: One image from an angiogram showing the "bird's eye" view that doctors are typically limited to. These angiograms give an excellent image of where problems lie, but are not very reliable indicators of the genesis of lesions.

parametric representations are employed. These expansions are ordered in vertex, edge, face and interior (or bubble) modes. For the Galerkin formulation, the required C^0 continuity across elements is imposed by choosing appropriately the edge (and face in 3D) modes; at low order expansions this formulation reduces to the standard finite element formulation. The discontinuous Galerkin is a flux-based formulation, and all field variables have L^2 continuity; at low order this formulation reduces to the standard finite volume formulation. This new generation of Galerkin and discontinuous Galerkin spectral/hp element methods implemented in the code $\mathcal{N}\varepsilon\kappa\mathcal{T}\alpha r$ do not replace but rather extend the classical finite element and finite volumes that the CFD practitioners are familiar with [4]. An additional advantage is that convergence of the discretization and thus solution verification can be obtained without remeshing (h-refinement) and that the quality of the solution does not depend on the quality of the original discretization.

4 A Virtual Cardiovascular Laboratory

An example user scenario in the virtual cardiovascular laboratory describes its functionality. The scenario is shown in the accompanying video, with a few frames in this submission illustrating the main points.

The session begins with an overall view of the bifurcated artery, which shows both the originally blocked artery, and the newly grafted segment into which the blood now flows.

Since the vascular geometry is the primary determinant of the flow field, the researcher begins by examining the reference geometry. Here, the reference geometry is manipulated using a combination of hand gestures. A 3D tracker locates each hand and pinch gloves [5] provide information about relationships between fingers. The user places himself at the entrance of the bypass graft by gesturally pulling himself through space and begins to examine the artery structure and moves further down the artery to investigate the area of the bifurcation, shown in Fig. 3.

The user selects tools from a virtual tool-belt around his waist and controls these tools using both voice commands and hand gestures. Tools can be retrieved from the tool-belt when the user looks down, as he is demonstrating in Fig. 6. To orient himself to the flow conditions, the researcher uses two different particle advection widgets. The first, a dust widget, allows the user to throw particles into the flow just as if he were throwing chaff into the wind.

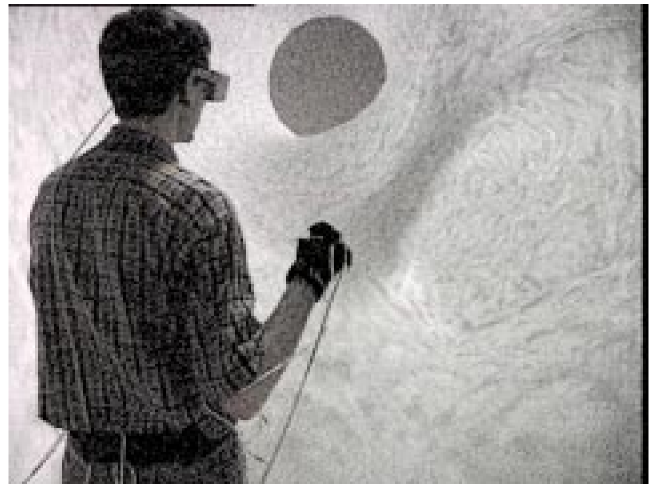

Figure 3: A view of the immersive artery visualization looking at the bifurcation where the graft enters the original artery. The visualization is within a 4-wall Cave (3 walls and a floor), with head-tracked stereo. A gestural interface provide easily-learned interaction techniques for navigating through the environment and for studying the flow.

This type of normal action allows the user to comfortably acclimate himself to the flow conditions. Although convenient, this widget is not very precise. For a more precise and persistent stream of particles, the metaphor of a fizzing "alkaseltzer tablet" is used. Using this widget, the researcher interactively places particles precisely in areas of interest and watches as the particles are advected along by the natural flow of blood. This type of interactive investigation gives the researcher an initial indication of the flow patterns within this complex system.

Leaving the alkaseltzer tablet in place, the user places an interactive rake widget in the region of the advecting fluid particles. Here, streamlines at one instant of time are examined. Streamlines are lines which run tangential to the velocity at any given point. Hence streamlines give to the researcher an idea of the currents of blood flow through which the particles are traveling.

The researcher switches to a single streamline widget for investigating a particular region of interest. The streamline dips near the bifurcation, indicating a flow disturbance. The researcher then uses the streamline as guide, just like a rope, as he traverses down the bypass past the graft and into the original artery.

Rotating himself 180 degrees with two-handed interaction, the researcher sees the blockage that the bypass is intended to alleviate.

Low flow velocity can lead to regions with long particle "residence times". Regions like these are correlated with thrombus formation and to possible plaque formation which can lead to graft failure. To investigate regions of slow flow, three widgets are used. First, the researcher uses a reverse streamline widget to examine the region of the blockage. The fact that this streamline at first bends significantly, and then ends abruptly as the user moves it into the blocked region demonstrates what the researcher suspected, that the fluid between the blockage and the graft entrance is stagnant.

It may be possible to use automatic algorithms for displaying features of interest such as low flow velocity, but one risk is that they tend to produce binary results. Choosing regions only where pressure is above some threshold may miss regions with pressure lower that the threshold that are still of interest. If a user can see the

Figure 4: Wall shear stress is encoded in wall color (see color plate), with blue showing low values, green midrange values, and red high values. Regions of low shear stress tend to be correlated with sites of future lesions.

gradations of pressure, they can make the decision, which is most important where thresholds have not been reliably determined.

The researcher then uses the alkaseltzer widget to place particles around the stagnation area. What becomes immediate apparent is the relative stagnation of the particles placed within the blocked artery as opposed to the particles flowing through the newly grafted artery.

A gray cube isosurface microphone widget creates isosurfaces which help expose the gross features within the flow region. Low order isosurfaces increase interactivity; high order isosurfaces are available to show greater flow detail. Isosurfaces are computed at interactive rates by the NOISE isosurface extraction system developed at the University of Utah's Center for Scientific Computing and Imaging [6].

The researcher then examines wall shear stress mapped to the color of the vessel walls. Shear stress is essentially frictional force tangential to the wall and is a quantity which was previously unavailable using either clinical or experimental techniques (see Fig. 4). Quantities like wall shear stress can give important insights into flow behavior [7, 8, 9, 10]. Since the bypass graft is much larger than the original diseased artery, the flow velocity within the bypass graft is slower than that of the flow downstream of the bypass in the smaller diameter artery. This naturally implies a lower relative shear stress in the bypass compared to the original diseased artery. Also of interest to the researcher are anomalous regions of shear stress. The researcher notices a region of extremely high mean shear stress immediately downstream of the bypass entry point. Just as if you were pointing a garden hose of running water at the floor, we see a region downstream of the graft in which the shear stress is much higher than what the original unblocked artery had experienced. The examination of these types of anomalies within the bypass flow system are regions of interest to both flow researchers and physicians.

5 Feedback

Over the course of about 8 months 6 users interacted with the visualization system and an additional 15 observed it at work. Users and observers were asked to provide feedback on specific interaction techniques and also gave undirected feedback on any aspect of the system they wished. This anecdotal evidence is summarized and discussed in Sec. 7.

6 Related Work

User interfaces used in production environments have not evolved significantly since the introduction of the windows, icons, menus, and point-and-click (WIMP) interface metaphor over two decades ago. We have incorporated 3D widgets [11] and gestural interfaces [12], [13].

The Virtual Windtunnel [14] visualizes air flow around geometric objects such as the space shuttle. Our system differs in terms of the actual application– blood flow versus air flow visualization.

The combination of the Virtual Director[15] VR interface and the CAVE5D[16] visualization system is one of the few virtual reality-based scientific visualization applications that uses multimodal input. However, their system combines voice and wand input which limits the naturalness of their interface since users will typically only interact with one hand. By combining voice and whole-hand input using Pinch Gloves instead of a wand, our system allows users to interact with two hands which has been shown to be beneficial for many interaction tasks [17].

7 Discussion

The coupling between the medical application, numerical simulation, and visualization was tight and productive. We feel as if the active participation of researchers at each point in this cycle has kept the applicability of the visualization high.

7.1 Simulation/Visualization Coupling

Maintaining a common data format for the numerical simulation software and for the visualization software helped us to iterate more quickly and experiment with more interaction and rendering techniques. In an early prototype of our system the simulation data had to be reformatted significantly before the visualization system could process it. We found that significant time was spent doing this reformatting. In our second visualization system, we built a library to access the simulation data directly. Although the library took some time to implement, the increased coupling between simulation and visualization more than paid off with faster iterations and less wasted time on data conversions. It also helped keep the thrust of the work at a higher level where we could concentrate more on the science and less on the data.

7.2 Interaction Methods

Overall, the post-WIMP gestural navigation was reported to be intuitive and easy to learn. Within a few minutes, most users were able to successfully navigate to regions of interest. As users became more proficient, they began to report that navigation seemed somewhat laborious, particularly when moving over longer distances or when moving between a handful of landmark views. We are looking into modifications of the navigation strategy to address these concerns.

Users found voice commands useful because their hands remained free for other interaction activities. The audible feedback was surprisingly effective. Voice recognition systems are not perfect, and in early versions we found that errors often led to unexpected and hard-to-understand behavior of the software. When the current system errs, it very quickly reports back what it "heard," and the user can then confidently either proceed or understand the misinterpretation. Even though the computer was just as confused, users were less so and able to proceed with confidence more rapidly.

In one of our interaction techniques a user would mimic throwing a dart to indicate the start of a streamline. Most users complained that this metaphor was difficult to learn and were not able to use it as accurately as other methods. We postulate that the unfamiliarity of darts coupled with the need for motion through a particular starting point together contributed to the difficulty. This metaphor was not used in the second system.

7.3 Rendering Methods

We rendered the vessel walls both with and without texture. With texture (as shown in Fig. 3), users reported a better sense of depth. This is consistent with perceptual studies showing that texture provides the visual system with important cues for optical flow and therefore for depth perception. However, users also reported that the surface of the vessel seemed rough, which was not the case. Without texture, the surface appeared smoother, but was more difficult to interpret three dimensionally. We are exploring textures that will enhance 3D shape perception without indicating surface roughness that is not present.

One of the smooth wall rendering methods used wall shear stress magnitude to color the vessel surface. Low wall shear stress is correlated with the formulation of lesions that can lead to failure. Clinical users were interested in this quantity.

Some complaints were voiced about difficultly in determining the location of particles in the flow. Particles were drawn in stereo, but with only a single color. We believe that experimentation with using more shape and location cues for the particles will permit better localization.

8 Conclusions

We have presented a virtual environment for visualization of fluid flow through a simulated arterial graft. Our prototype system has been used only by a small set of researchers who have provided anecdotal feedback. As we respond to their feedback and refine the system, we expect that further use may lead to measurably increased productivity and other important discoveries. The preliminary feedback we have received indicates the environment shows good potential for helping to develop our understanding of failure modalities for these grafts and, hopefully, for reducing their failure rate. Doctors speculated that they would potentially be able to combine the currently available external knowledge with information discovered in the Cave to pose new hypotheses about lesion genesis and progression.

The interaction and rendering lessons we learned during this work and describe in this paper are likely to be applicable not only to our application but also within other virtual environments. This work is a prototype and we expect that it will stimulate ideas for new and different visualization and interaction techniques.

The simulation solution had 3,562 spectral elements with 5th order polynomial expansions in each element. To increase interactivity at this time we only used 50,000 triangles to represent the reference geometry, however we plan to explore hierarchical methods for directly displaying the hierarchical numerical results to a defined tolerance, which should help better balance the need for accuracy against the need for interactivity.

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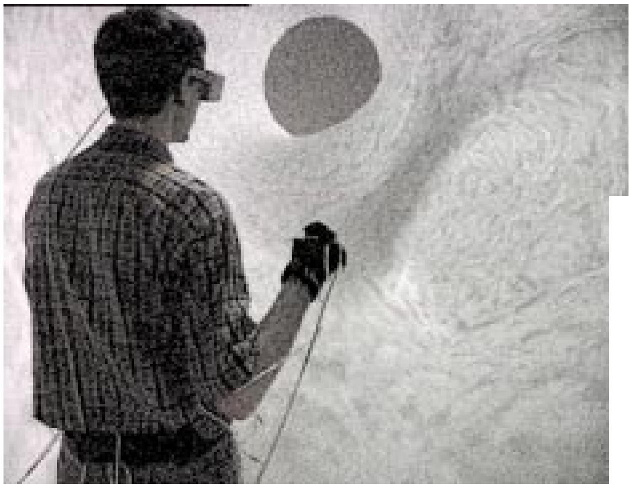

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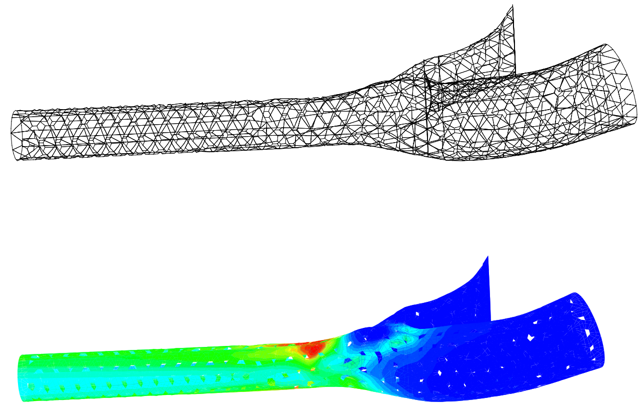

Figure 5: Image created in tecplot showing a typical visualization that might be used to explore simulated flow data within an artery. The top image shows the geometry in wireframe while the bottom image shows wall shear stress magnitude mapped to the vessel surface Note that the larger graft artery is below the original artery, in contrast with Fig. 1. Exploration using tools like tecplot are less interactive than the immersive visualization environment we describe.

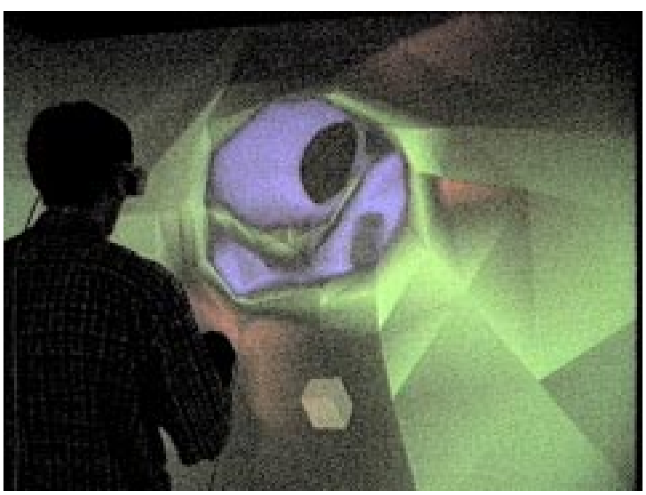

Figure 4: Wall shear stress is encoded in wall color, with blue showing low values, green midrange values, and red high values. Regions of low shear stress tend to be correlated with sites of future lesions.

Figure 6: When the user looks down a toolbelt appears. Tools include dust, for advecting particles through the flow; a widget for choosing wall coloring; a round alkaseltzer widget for creating a persistent source of advecting particles; an isosurface "microphone" widget (the square cube here); and a streamline and rake widget.