

3D Visualization

Brain Blood Behavior, In Vivo meets Virtual Reality

Tony Sun*

University of Missouri-Columbia

Mehrdad Yousefi†

Clemson University
Clemson, SC 29631
yousefi@clemson.edu

Oyewole Oyekoya‡

Clemson University
Clemson, SC 29631
ooyekoy@clemson.edu

Ulf Schiller§

Clemson University
Clemson, SC 29631
uschill@clemson.edu

ABSTRACT

Strokes have been more prevalent in our modern age as people grow older. To combat this, those interested in computation sciences have turned to Computational Fluid Dynamics as a means of quantifying data. These quantifying simulations have undergone many validation studies and are now ready to be visualized in an immersive environment. We did this by combining existing scientific visualizer Paraview with an open-sourced VR environment the HTC Vive. By choosing open sourced software, we were able to build an application that could streamline the large data sources. We came up with figures that could be displayed in the headset to help both doctors and patients intuitively understand the complex dynamics of blood within their middle cerebral arteries. In the future, we would like to expand the segmentations we are visualizing, and combine our work with super computing resources to create a low-cost, non-invasive method for visualizing complex biological systems.

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*None

†None

‡None

§None

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1 INTRODUCTION

Complications resulting from strokes regularly rank amongst some of the top 5 most deadly forces globally. Subarachnoid haemorrhages (SAH) are a class of stroke resulting from bleeding around the brain. There are two types of aneurysms, the fusiform and the saccular. The vast majority (85%) of SAH are caused by the saccular variety. In this case, SAH results from the ballooning and eventual rupture of an intracranial blood vessel due to the weakening of the artery. Prevalence rates of 50-100 per million people have an aneurysm and experience a rupture in their lifetimes, with some 10-15% failing to reach a hospital. An estimated 1 in 20 people carries an unruptured cerebral aneurysm, detected during unrelated scans of the brain. While these ruptures represent a statistically compact subset of all strokes, their mortality rate have been reported to be 50%.

6.7 million people lost their lives to stroke in 2012 with countless others are left with disability. Symptoms of SAH include crippling headaches, sensitivity to light, and a stiff neck. There may also be a loss of consciousness that is commonly experienced.

Current medical procedure for determining rupture risk is based on qualitative CT and MRI scans. After a segmentation process, the calculations are made from rudimentary estimates based on aneurysm size, shape, and location (Coy 2017). For example, a benchmark of 10mm has long been used as a threshold for rupture. However, a study by (Coy [43, 48]) involving 945 patients discovered that 77% of ruptured aneurysms did not fit the criteria for size which is a considerable false-negative rate. Other factors that are considered include familial rates of aneurysms, cardiac disease, and alcohol consumption (Coy [49]). The decision to operate is a culmination of the triad: lifetime prevalence of unruptured aneurysms and life expectancy as mentioned before, along with risk of treatment.

While enacting invasive methods could ensure an accurate diagnosis, there is a significant risk to further complications. Medical personal require a better set of tools in order to perform prognoses and prescribe treatment. Computational Fluid Dynamics (CFD) is a budding field of tools widely applied to an array of biological processes, including rupture risk for aneurysms. The quantitative return parameters of CFD could ingratiate themselves alongside other qualitative measures in decision making. These simulations would compile with existing medical knowledge in order to ease

the difficulty faced by doctors charged with determining an appropriate treatment plan. To display the data, we have chosen to use consumer-available virtual reality headsets. We first delve into the background of CFD before returning to the visualization of our arteries.

2 LITERATURE REVIEW

Computational Fluid Dynamics refer to a multitude of computing-intensive simulations run in order to extract useful biological parameters. This can inform clinicians facing potential surgical interventions; and the study of these parameters could eventually lead to a standardized procedural fix for analyzing rupture risk. Although critics are quick to point out that the informational overload of doctors would not be alleviated in this fashion, implementation of this lofty goal has begun in a multitude of haemodynamic investigations.

An overview of the field of CFD with respect to haemodynamics was required. In order to properly simulate the blood flow through an artery, many factors had to be considered. Recent improvements in the field have made many simulations reliant on a program called HemeLB. HemeLB is a lattice-Boltzmann flow solver which works on complex geometries through the use of high performance parallel processing, otherwise known as supercomputing (Mazzeo 2008). While there are many lattice-Boltzmann flow solvers, HemeLB is great for simulations of a large, complex, time-dependent nature. This makes it great for modeling blood flow in the brain as the time-dependent nature of the cardiac cycle and the intricate geometries of brain arteries can be captured together.

For investigating the formation of an aneurysm, one integral factor is on the characteristics of blood interaction with the wall of the artery. Researchers in the area call this interaction Wall Shear Stress (WSS). WSS has been highly correlated with vascular pathologies (Bernabeu [6-8][9-11]) including aneurysms. They tested WSS under different physical models of Newtonian fluids and found that although there is an impact, both models did quite fine in regards to the middle cerebral artery. These findings were used in the following work on modeling the brain's blood flow in regards to aneurysms.

Much of the existing work on cerebral vasculature CFD had been done on a limited number of geometric sections. A large study was done by Cebal et al that incorporated 128 patients and 210 different vessel geometries containing aneurysms through CFD simulations. Aneurysms were classified based on radiological and medical rupture records across many locations in the brain. Inlet velocities were measured to derive inflow boundary conditions and paired with the structural information to obtain WSS values. The final product was analyzed by two observers in double-blind trials. The flows were then independently categorized as "simple" (single recirculation zone) or "complex" (hierarchical division of flows), "stable" (time dependent) or "unstable" (dependent upon the cardiac cycle), and "concentrated" or "dispersed" flows. Finally, "flow impingement", as a measure of the interaction between blood flow and the wall of the artery, was classified as large or small depending on the proportion of the aneurysm located in the "flow impingement zone". Their findings indicated that ruptured aneurysms had complex, unstable,

and concentrated flows within small impingement zones. This statistically significant discovery showed that there was potential for CFD to model haemodynamic forces in aneurysms.

Bernabeu et al demonstrated that it was possible to reconstruct haemocentric-geometric models directly from samples of retinal vasculature. Not only did these models contain high-detailed rendering in three dimensions, but it was also possible to combine them with existing lattice-Boltzmann algorithms to obtain the haemodynamic parameters that would interact with the structure. A proposed model under the HemeLB flow solver proved to be effective in matching the known flow rates with simulated results. This was huge as it meant that vasculature that imaging provided could be matched with accurate haemodynamics despite difficulties in obtaining the flow measurements experimentally.

The blood flow velocities were also validated through transcranial Doppler (TCD) measurements. Work by Groen et al used a multiphase modeling setup to match clinical findings with simulation results. Their work builds on that of Marzo et al (Groen [10]) who demonstrated that patient-specific flow measurements with the MRI results have a limited scope with their boundary conditions. Transcranial Doppler can only be applied on a limited number of cerebral arteries, but the more accurate detection of peak velocities works well to capture the fluid pulses of the cardiac cycle. Groen and his team showed that when comparing simulation data to clinical patient-specific TCD inflow measurements as the boundary condition, they were able to estimate flow rates with great precision. This again reduces the need for invasive flow measurement procedures and reinforces previous work on the validity of CFD.

An issue with the TCD data was the lack of fidelity under lower velocity inflow conditions, such as those in otherwise healthy subjects. Itani et al looked at the impact of heart rate on the HemeLB data and also concluded that a studying a range of heart rates can elucidate new pathways to study cerebrovascular flow properties. They did this by building a multitool program that combines existing CFD research into one flow solver which can be automated and run in parallel. In conjunction with supercomputing units, we are able to minimize the human effort in conducting simulations of a larger scale and with more resolution. Both of these are valuable assets to our project as they validate the findings of previous studies on the reliability of CFD simulations and provide a framework for which we can build our visualization.

3 MATERIALS AND METHODOLOGY

We took medical images from MRI and CT scans and segmented them using VMTKLab to obtain the geometries of the brain. Then using HemeLB we predicted the blood flow using patient-specific boundary conditions. These flow rates were validated through a series of tests, including TCD. Finally, the interaction between artery walls and the haemodynamic forces were compiled to obtain WSS values. Now we have data on the geometries, blood flow, and on the wall of the arteries with methods of classification. The resulting file containing the data was immensely large.

With our simulation data in place, we now looked at appropriate methods to visualize our data. Paraview is a popular open-source program commonly used for scientific visualization. It was developed by Kitware and was recently awarded the 2016 HPCwire

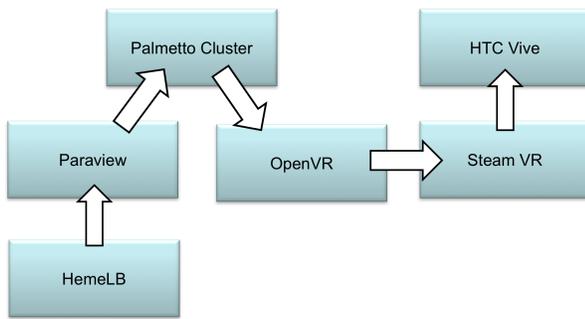


Figure 1: Workflow

Reader's and Editor's Choice Award for Best HPC Visualization Product or Technology. Awarded for a number of reasons, of primary importance was the vibrant community that helps to develop Paraview. Many of its users work to contribute to a vast repository of plug-ins and this has allowed researchers across varied disciplines to employ Paraview for their benefit. Not only was it built for multi-platform data-analysis and visualization, its capabilities extend to benefit both qualitative and quantitative researchers through the 3D interactions. It can handle larger scale supercomputing jobs through batch processing or smaller data sets to be done on a personal computer. Utilized in laboratories, universities, and industries around the world, Paraview is an obvious choice for our applications.

Since we had a method of reading in our immense data file, we now needed to look at Virtual Reality (VR) displays. There are several popularized options, the most widely known to be Oculus Rift. While the Oculus has long been developed for a multitude of display purposes, it did not directly support the open-sourced application Paraview that we were using, so another option had to be found.

The HTC Vive is another well-known VR headset. Developed in conjunction with HTC and Valve Corporation for immersive environments and have already made an impact in the gaming community. For their setup, they have a headset that goes on around your glasses in addition to controllers and room sensors called the Lighthouse base. Together, they can track head motion, body movement, and hand gestures through a 5x5 foot space. The main attraction to the Vive, beside the added comfort for bespectacled users, was the direct interface with SteamVR due to the overwhelming support for that application. Valve has released a software development kit called OpenVR which works with the HTC Vive. OpenVR updates the SteamVR API and contains documentation on building software that supports the Vive.

Due to the open-sourced nature of both Paraview and SteamVR's extension OpenVR, we were able to build Paraview with the OpenVR plugin to interface our scientific visualizer to the Vive. This results in being able to transfer the large simulation data, through to an image in Paraview and then projecting that image into the virtual reality headset to be controlled through the controllers.

4 RESULTS

When standing in the immersive environment the first thing one notices is the clipping plane. The plane is placed just a few inches in front of the user's face. What this does is allow the user to look within a structure simply by moving the figure closer to them. This can be accomplished by the controller or by moving forward into the direction of the figure. Never before has it been so easy to look within a structure, not simply at the outside. Adjusting the opacity is another option to do such a task, but again, the remaining structure of the figure does remain on the outside. The immersive environment has great advantages in this aspect.

The time dependent lapse figures can be obtained by individually projecting the images into the virtual environment. This is effective for freezing the frame at the exact moment in the cardiac cycle to point out particular morphologies. Oftentimes the wall shear is highest midway through the cardiac cycle, thus prompting the greatest difference in the unstable concentrated portion of blood flow we have previously identified to be a risk factor for aneurysms.

The glyph filter allows one to see the velocity of the blood flow. Placing the glyph filter on in the immersive environment is helpful because without animations, it would be tough to see the actual motion of the blood. The vectorial glyphs can indicate both the direction and magnitude of blood flow in a qualitative manner that is more intuitive than the color legend.

One issue with the current state is the boundary problem. When using the controller's joystick to access the figure, there are certain motions that cause the figure to fly away rapidly and without recovery. The only solution thus far is to exit the environment and recalibrate it. Another issue we found is with the scope of the clipping plane. The plane does cut off a few inches in front of the user so the immersion is slightly broken when moving through. We wanted to use animation but the software did not support it at this moment. If animation is possible, we would like to have tried following a streamline of a voxel in order to path the motion of the user.

5 CONCLUSIONS

The use of Computational Fluid Dynamics has been shown to be very useful in simulating various biological functions. With the present state of CFD and medical imaging, we have collect reliable simulation data on the structure of the middle cerebral artery, the blood flow, and the interaction between the two, known as Wall Shear Stress. We move to incorporate all these data points into a singular visual representation. We wanted to find an intuitive method to do so, that would help both doctors and patients alike understand the ramifications of aneuristic behavior. We accomplished this from incorporating virtual reality environments into our work.

To do so, we looked at open source softwares because of their proclivity towards building interactive applications. We found that Paraview can be integrated with the HTC Vive headset through SteamVR and OpenVR. The result is the best picture of a middle cerebral artery yet. With it, one is able to accurately intuite the current state of an aneurysm, in both the relative size and in the interaction of blood. This is tremendously helpful for doctors to decide whether or not they would like to operate and for patients to understand possible risk factors.

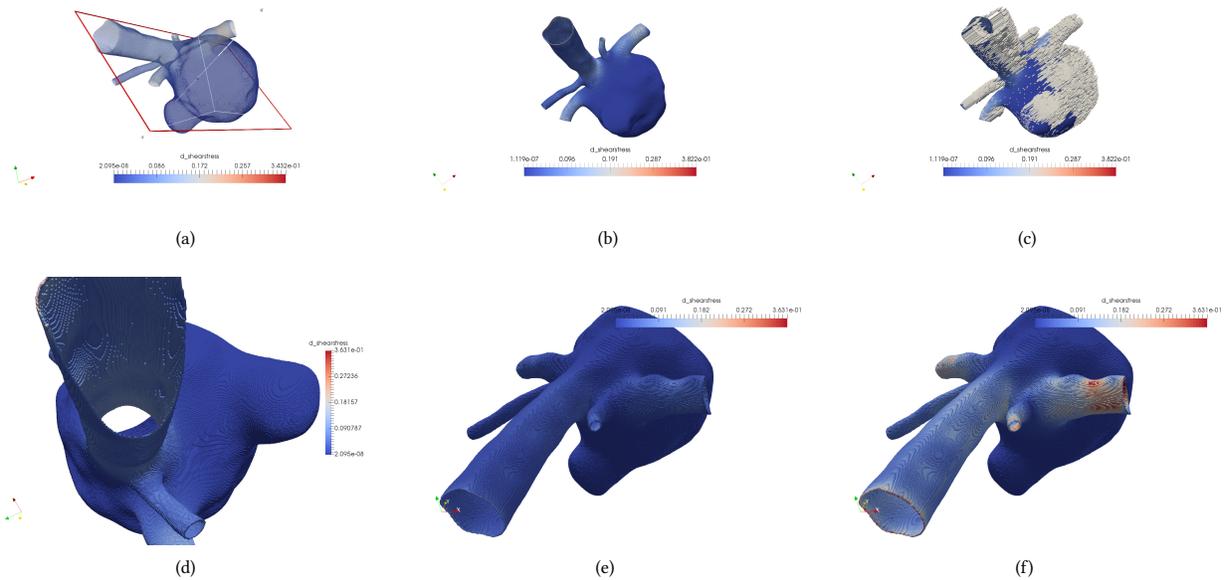


Figure 2: Results.

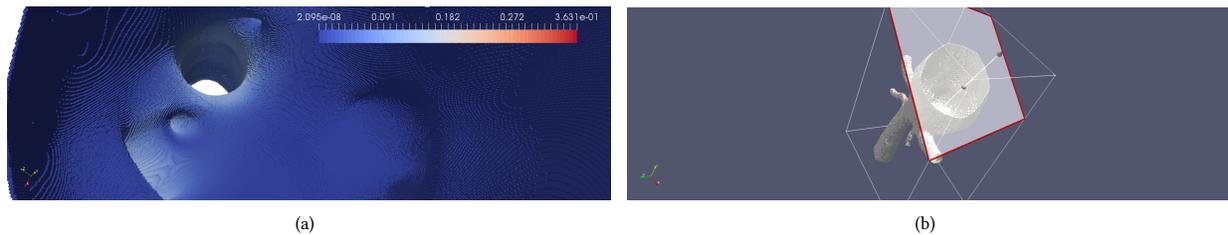


Figure 3: Clipping.

In the future, we would like to incorporate the use of animation in our work. We have done preliminary research on a method and found that Unity3D could be a possible platform. We would use the animation to show the time-dependency of the cardiac cycle, as well as simulate the path of blood through the artery. The clipping plane would need to be extended at a certain point in order to preserve the immersion while pathing. A boundary issue was found, but would also be solved by the animated motion.

The hope for the future is for clinicians to have a powerful tool to learn from. They would be able to put on a headset and see the aneurysm from multiple scales. Both the operating table scale and the intercranial scale would be captured, giving doctors a micro and macro look at the patient they would be operating on. We also hope to use real-time patient data in order to prompt interventions at a greater degree. The popularity of fitbits and of other health tracking applications makes it possible to be able to look at arteries at any time and signal to a medical professional when there are issues. We also hope it will help patients understand the ramifications of their current medical status.

Of course, visualization doesn't stop at the brain. In the future, we are also looking to visualize other critical organs and systems that would require noninvasive procedures. We have shown that it is possible to immerse oneself in the data provided by imaging and CFD and that it will reduce the informational overload of the data. There is great promise in the virtual medical environment of the future. The use of supercomputing resources will help tremendously with all of these large data sets.

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