A Summary of My Summer Work, 2023

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As a student researcher at Baylor College of Medicine, I worked in the Rusin Lab at Texas Children's Hospital on computational analysis of blood flow in vessels. In a normal human circulatory system, deoxygenated blood flows from the veins into the heart before entering the lungs for oxygen. In patients who have undergone the Fontan procedure, the deoxygenated blood flows directly to the lungs, skipping the heart. To learn more about the effects of the Fontan circulation on major vessels such as the aorta, I developed a system to compute, analyze, and visualize shear stress on the walls of the aorta in Fontan patients. Wall shear stress is the force exerted by a vessel wall on the blood inside, slowing the velocity of the blood closest to the wall. Given the inputs of blood flow velocity data from a patient MRI and a triangulation mesh of patient aortic geometry (created in SimVascular and 3DSlicer), my system computes wall shear stress at each vertex on the aortic mesh and produces both vector and scalar visualizations (displayed in VisIt).

I developed a suite of functions to compute an orthonormal frame at each vertex of the mesh, relative to the surface and structure of the mesh itself, as the basis of my system. I implemented the Navier-Stokes equations to solve shear stress along the vessel walls analytically. My system was prototyped in Matlab. I built synthetic datasets, which I used extensively in algorithm development, testing, and data analysis. After the system proved functional, I ported it into C++ and integrated it into the pre-existing codebase the project team was building. In C++, I determined the most efficient data structures to store information and conduct computations. I also developed a library of functions to easily generate synthetic data based on user input parameters for further testing. Finally, I used my system to evaluate and visualize wall shear stress on real patient data; for each vertex on the mesh, it produced a bundle of data, including the orthonormal frame, components of shear stress with respect to the frame, and the shear stress vector itself. Results from this system may be useful in furthering medical studies on the structure of the aorta.

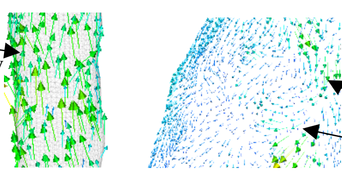

Figure 1: Shear stress vectors on each point of the aortic mesh along a section of the ascending aorta (left) and descending aorta (right)

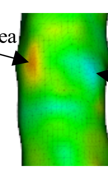

Figure 2: The component of shear stress parallel to the centerline of the vessel, at each point on the mesh along a section of the descending aorta

$$w = \mu(\nabla u + (\nabla u)^{\top}) \cdot n$$

Derivation of shear stress from the Navier-Stokes equations

w: shear stress $\quad$ μ: viscosity constant

u: velocity $\quad$ n: local unit normal vector

One challenge of the project was interpolating the input velocity data onto the input aortic mesh. While the velocity data came from MRI scans, where sample data had regular intervals, the aortic mesh was manually generated in 3DSlicer from another data source, and the Delauney triangulation that the mesh was built upon was neither regular nor registered onto the velocity data. I solved the problem by developing an interpolation function that mapped velocity data correctly onto the corresponding parts of the mesh.

This project provided opportunities for me to tie multiple domains of knowledge together: linear algebra, differential equations, algorithmic concepts, fluid dynamics, and image processing. I also gained experience in software development cycles: requirements/research, prototyping/design, development and debugging, testing, visualization, communication with team members, etc. As a bonus, I now also have a handy self-written library of common mathematical operations for future convenience.