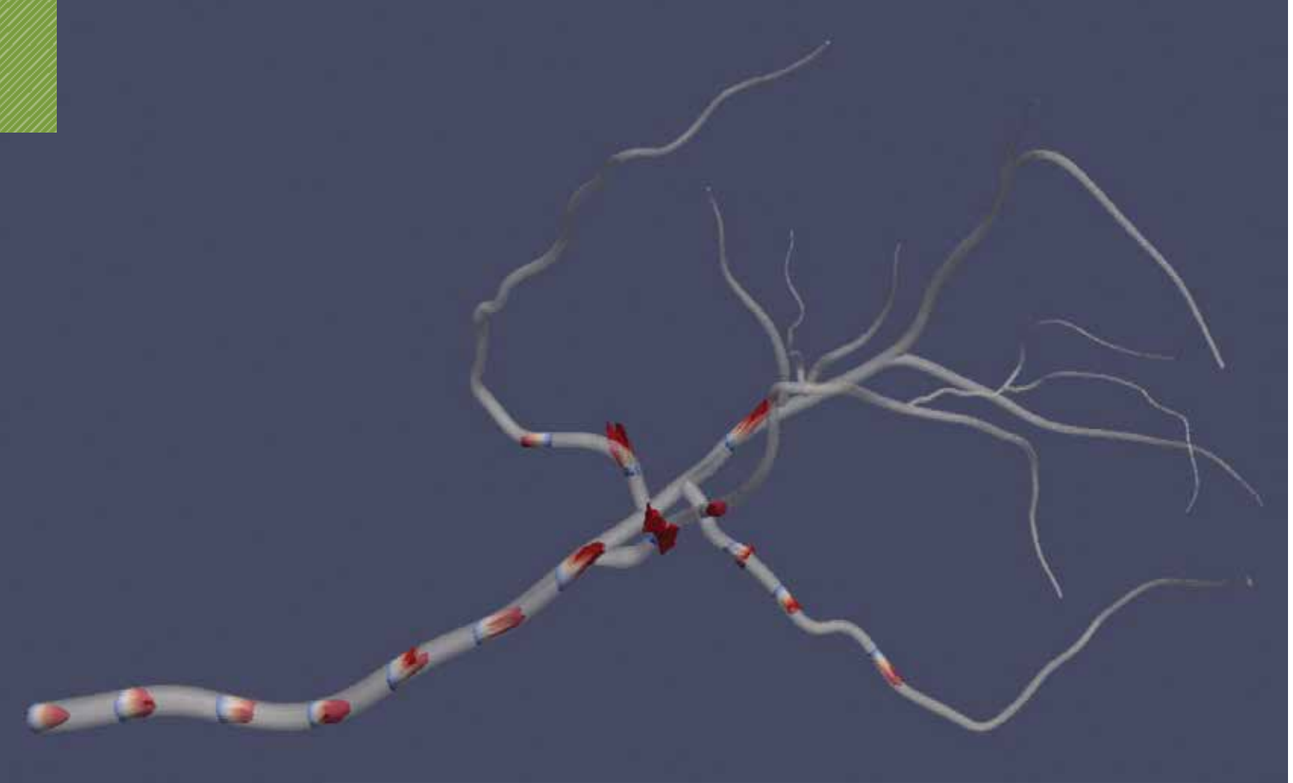

VARIATIONAL MULTISCALE METHOD FOR BLOOD FLOW SIMULATION IN PATIENT-SPECIFIC ARTERIAL GEOMETRIES

FIGURE 3: Instantaneous flow field in the arterial tree.

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EXECUTIVE SUMMARY

In this project, we extended and applied our variational multiscale method [1-7] for non-Newtonian blood flow modeling to account for material and geometrical uncertainty in patient-specific models shown (Figs. 1, 2). Blood is modeled as a non-Newtonian shear-rate dependent viscous fluid, and artery walls are modeled as nonlinear viscoelastic material with relaxation time of the arterial tissue.

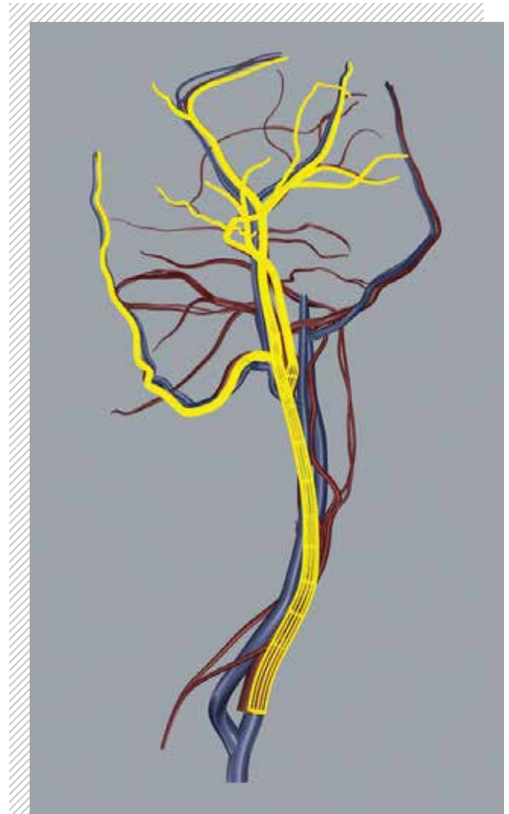
Significant results from these studies are: (i) A correlation is found between high G forces and local reduction of pressure and flow rate to the **brain**, an issue of considerable concern in high speed roller coasters as well as in gravity-induced loss of consciousness (G-LOC) which is a major threat to high-performance aircraft pilots and astronauts. (ii) Standing waves are found in continuous flow ventricular assist devices (VADS), where pulsatility gets minimized, and consequently, the risk factor for blood coagulation and therefore of stroke increases.

INTRODUCTION

We have developed **novel** numerical methods that are integrated with non-Newtonian constitutive models to simulate and analyze blood-artery interaction in patient-specific geometries in the cardiovascular system (Figs 1, 2). Since blood artery interaction models are mathematically involved and computationally expensive, Blue Waters was employed to explore the mathematical attributes of our new coupling scheme. Our target problem was predicting the probability of stoke in patients who have received surgical treatments for VAD insertion. One risk factor is the hemodynamic conditions, and reduced pulsatility is considered to be a major contributor to it. Local states of flow in the arterial system are also important. For example, an aneurysm in the carotid artery can provide a local spot for blood to flow slow, increasing the risk for coagulation. Consequently, accurate representation of the geometry is important, and any information related to local changes in artery diameters needs to be accounted for. Another allied investigation led us to investigate the effect of high G forces on reduced perfusion of the brain and potential loss of consciousness.

Using our codes, we investigated the effects of the stiffening of arterial walls that can occur as a function of age on the progression of hypertension or high blood pressure—a problem of great relevance as uncontrolled high blood pressure increases the risk of heart attack and stroke. We were able to carry out a set of parametric studies with larger arterial systems as shown in Figures 1 and 2. These studies helped us identify standing waves in continuous flow VADS, and we found optimal pulsatility that can disrupt the standing wave without inducing heavy mechanical beating on the flow pump. Also, to develop methods that can focus on smaller subsections of the arterial model, outflow boundary conditions for non-Newtonian models for blood were developed. This development required numerous high fidelity computations and comparison with clinical data. A third allied investigation led us to the modeling of

FIGURE 1: Side view of the patient-specific geometric model of arterial system in the brain. Also shown is one of the cruder meshes that were employed in the numerical simulations.



METHODS & RESULTS

Our previous work on Blue Waters allowed us to extend and verify our non-Newtonian models for blood that account for shear-rate response in patient-specific geometries. We developed hierarchical multiscale finite-element methods with local and global (coarse and fine) description of the variational formulations that result in telescopic depth in scales. The telescopic depth in scale leads to two coupled nonlinear systems, namely, the coarse-scale and the fine-scale subsystems. Fine-scale models that were extracted from the residual-driven fine-scale sub-problems were then variationally embedded in the coarse-scale description of the problem, and led to the class of hierarchical multiscale methods for non-Newtonian fluids with enhanced stabilization properties.

Our newly developed methods employed here led to substantially reduced global communications in favor of increased local computing. With a five percent increase in the cost of computation of the stiffness matrix and the residual force vector, we were able to reduce the mesh size to less than half the nodes that would otherwise be needed for equivalent engineering accuracy, thereby substantially reducing the overall cost of computation of the problem. This unique feature of our method is of tremendous benefit in massively parallel computing as it reduces communication costs across the partitioned subdomains.

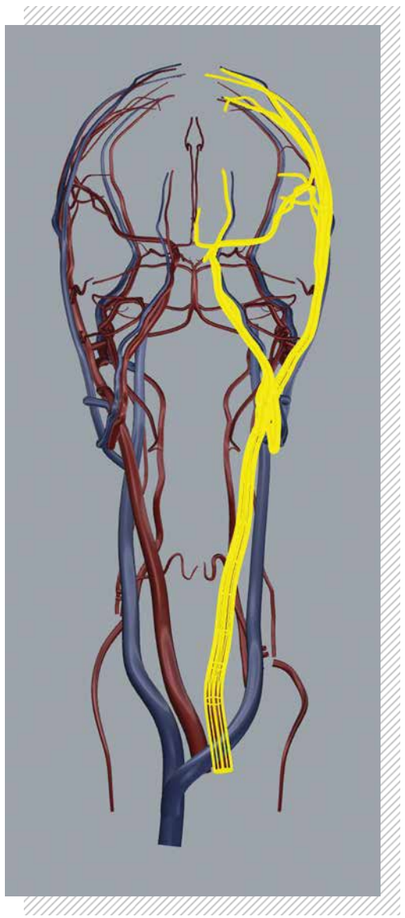


FIGURE 2: Frontal view of the patient specific geometric model of arterial system in the brain along with the superposed computational grid.

the high G forces on reduced perfusion of the brain and potential G-LOC. To summarize, following are the significant findings of our work:

1. We show that the Newtonian model for blood underestimates the wall shear-stress (WSS) by 16% in diastole, which is a non-conservative estimate from patient care perspective.

2. We show viscosity build-up in aneurisms in arteries where local ballooning effect causes a recirculation region, and viscosity build-up is significant at the end of diastole which can lead to clot formation that is caused by local stagnation.

3. We show that constant flow VADS with minimal pulsatility lead to standing waves that cause viscosity build-up which can increase the risk factor for stroke in the patients. This aspect of simulation can be used to introduce minimal pulsatility in the VAD device, thus optimizing the device for the patient, giving rise to patient-specific treatments.

4. We can calculate increased pressure fields in stiffened arteries, even when other geometric and flow conditions are held constant, thus providing insight into the effects of mechanical and rheological factors on hypertension.

5. High-performance aircraft pilots are routinely exposed to high levels of +Gz (head-to-foot) accelerations. G-LOC is a major threat to high performance aircraft pilots and astronauts. With recent advances in MRI technology and computing power, cerebral hemodynamic simulations can now be run using individual arterial geometries, and these can open the door to understanding G-LOC from an intracranial perspective.

WHY BLUE WATERS

This work relies on having many long simulations to achieve rigorous sampling of the variability in biological systems. Blue Waters was critical for both the development of **cutting-edge** software and the application of this software to perform large-scale biomechanics simulations. We found Blue Waters to be an extremely powerful and versatile computational resource that, in addition to powerful CPU and GPU hardware, provided fast interconnects that allowed us to do types of calculations that we could not have done on other platforms. Specifically, the large local memory of Blue Waters is ideally suited for our methods as we can exploit the resident memory on the processing nodes to make the macro elements "smart," reducing the size of the global problem and minimizing data communication. The Blue Waters project staff provided in-depth technical information and timely advice on the optimal deployment and performance tuning of our software.

NEXT GENERATION WORK

In the next Track-1 system we plan to extend and embed the method in a probabilistic framework for blood flow simulation in patient-specific arterial geometries, with the objective of optimization of VADs for patient-specific needs.

PUBLICATIONS AND DATA SETS

Weddell, J.C, J. Kwack, P.I. Imoukhuede, and A. Masud, Hemodynamic analysis in an idealized artery tree: Differences in wall shear stress between Newtonian and non-Newtonian blood models. *PLoS ONE*, 10(4): e0124575, 2015.

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Kwack, J., A. Masud and K.R. Rajagopal, Stabilized Mixed Three-field Formulation for a Generalized Incompressible Oldroyd-B Models, *Int. J. Num. Meth. Fl.*, (2016), doi: 10.1002/fld.4287

IMPROVING THE RESOLUTION OF BRAIN BLOOD FLOW IMAGING WITH ADVANCED MRI ACQUISITIONS AND COMPUTATION

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EXECUTIVE SUMMARY

Adequate blood flow in the brain is critical for supporting healthy brain function into old age. Imaging of the brain's blood flow and obtaining information about the age-related changes in the structure of blood vessels, noninvasively using magnetic resonance (MR) imaging, requires advanced approaches for measuring this small signal. The small volume fraction of blood in the brain allows for physics-based image reconstruction models to be used to improve quality and usefulness of the images. These reconstruction models can be computationally demanding, and hundreds of images may need to be acquired to estimate information about the blood flow and vessels. As part of this project, PowerGrid, a toolkit for accelerating MR image reconstructions using graphics processing units (GPUs) and distributed computing, was created in C++ and OpenACC, while also leveraging message passing interface (MPI) to distribute across multiple GPUs. Using PowerGrid, we can reconstruct full datasets of images from a patient in a time frame similar to the acquisition of the images.

INTRODUCTION

Sufficient and reactive blood flow in the brain is a critical component for the health of neurons and their supporting cells. However, advanced aging is accompanied by critical changes to the vasculature [1], including the microvasculature that is involved in exchanging nutrients and waste with tissues. Measuring changes and degradations in the microvascular architecture of the human brain is