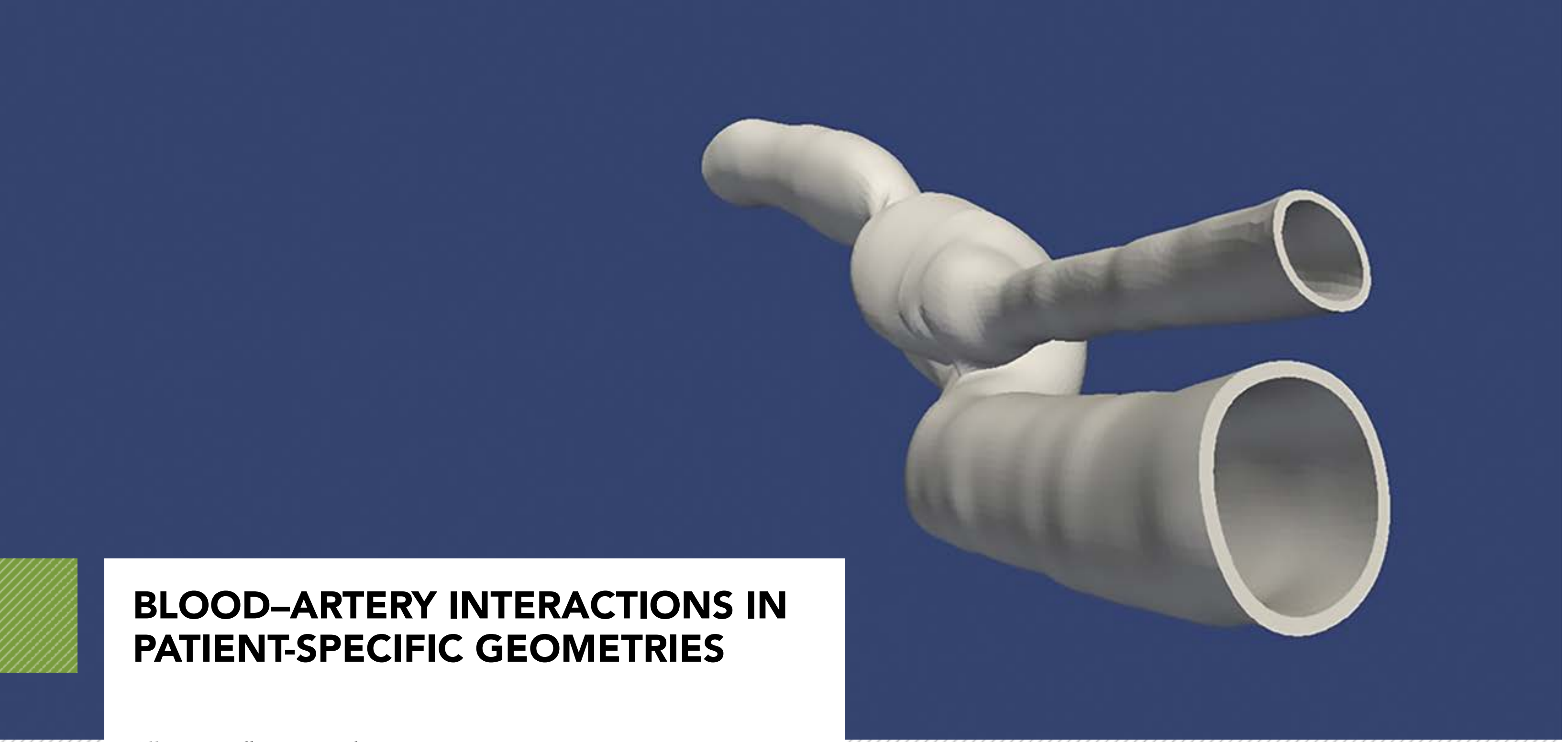

BLOOD–ARTERY INTERACTIONS IN PATIENT-SPECIFIC GEOMETRIES

Allocation: Illinois/42 Knh
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EXECUTIVE SUMMARY:

We developed highly stable and accurate blood–artery interaction models that are based on our earlier works on fluid–structure interaction (FSI) methods. In this work, 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.

Since both blood and artery walls are modeled via our newly developed multiscale finite-element methodology, the new FSI method provides a unified platform for developing advanced coupled-solution algorithms with enhanced stability properties that play a crucial role in carrying out highly transient flow simulations. Extracted flow physics highlights the effects of stiffening of the arterial walls on the progression of hypertension in patient-specific models of the carotid artery.

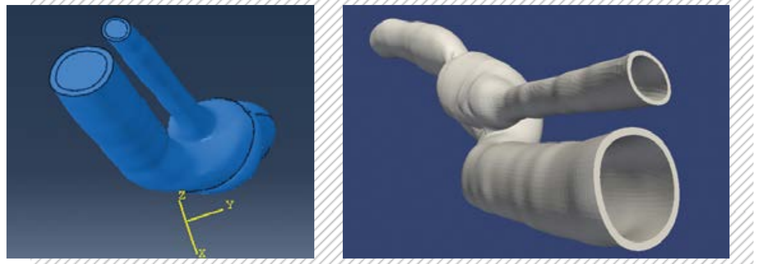

FIGURE 1: Geometry of patient-specific artery: (a) arterial subdomain, (b) full model.

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. Since blood–artery interaction models are mathematically involved and computationally expensive, Blue Waters resources were employed to further explore the mathematical attributes of our new coupling scheme. This study also helped investigate 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. It is a problem of great medical relevance as uncontrolled high blood pressure increases the risk of serious health problems, including heart attack and stroke.

METHODS & RESULTS

Based on our previous Blue Waters allocations we were able to extend and verify our non-Newtonian models for blood that account for its 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. This scale split leads to two coupled nonlinear systems, 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 it led to the class of hierarchical multiscale methods for non-Newtonian fluids with enhanced stabilization properties.

During the last year, we developed the arterial model as shown in fig. 1a, which is a patient-specific model of a carotid artery that suffers from stenosis and aneurysm. Fig. 1b shows the coupled model where the blood and artery subdomains can be seen. A coupled response of the system is shown in fig. 2, where velocity magnitude is projected on various cross sections along the length of the artery. A set of parametric studies with different relaxation times were carried out for the arterial walls and pressure parameters computed, which provided insights into the effects of mechanical material parameters on an increase in blood pressure.

From a computational and algorithmic perspective the newly developed coupled hierarchical multiscale 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 fewer 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 is of tremendous benefit in massively parallel computing as it reduces communication costs across the partitioned subdomains.

WHY BLUE WATERS?

Blue Waters' architecture, with large local memory, is ideal for our methods as we are able to exploit the local memory on the processing nodes to make the macro elements "smart," thereby reducing the size of the global problem and minimizing data communication. Ready access to Blue Waters for large-scale computing and to project staff to discuss various technical points arising in code development were key in making these major strides. Using the next Track-1 system, we plan to extend and embed our method in a probabilistic framework for blood flow simulation in patient-specific arterial geometries, with the objective of optimization of ventricular assist devices (VADs) for patient-specific needs.

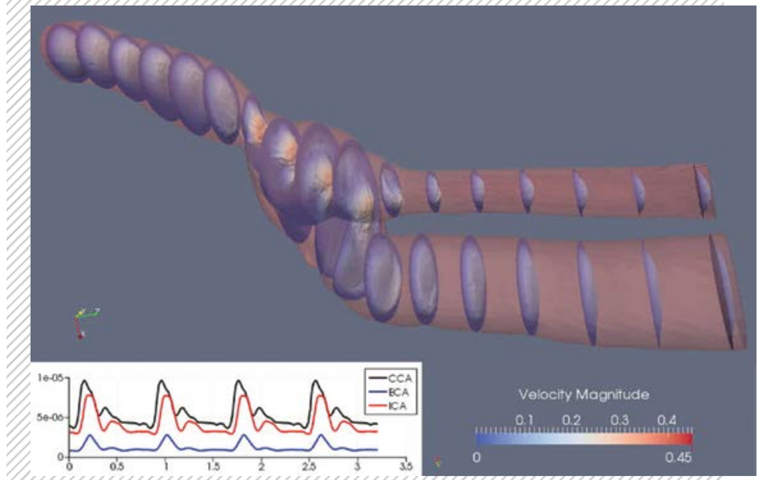

FIGURE 2A: Stiff and moderate viscoelastic carotid artery wall. Velocity profiles at various cross sections.

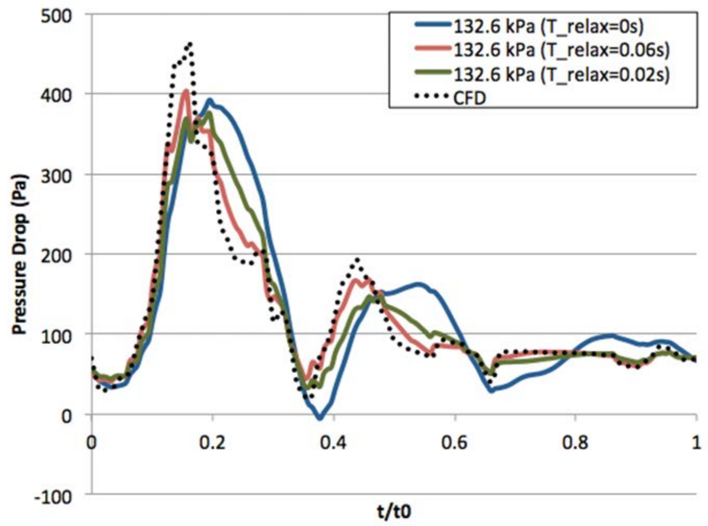

FIGURE 2B: Pressure drops between inlet and outlets.