BLOOD–ARTERY INTERACTION AND SIMULATION-BASED ANALYSIS OF AORTIC ANEURYSM

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EXECUTIVE SUMMARY

Fluid–Structure Interaction (FSI) techniques in biofluid dynamics integrate blood-flow and tissue models in a unified manner and provide a tool for comprehensive analysis of arterial diseases. High-fidelity simulations can enhance our understanding of the underlying biomechanical processes involved in the progression of the disease and also help with cardiac surgical planning. In this work, we have advanced our numerical methods and coupled, finitely deforming, nonlinear viscoelastic tissue models for the artery with non-Newtonian models for blood. The method is applied to a patient-specific geometry with progressive abdominal aortic aneurysm. The algorithm and code are optimized for XE nodes of Blue Waters.

RESEARCH CHALLENGE

Aortic aneurysm is an arterial disease that involves abnormal bulging of the walls of the aortic vessels. Aneurysm is characterized by a low stiffness of the artery walls, which leads to local ballooning effects that give rise to a localized swirling flow of blood. The challenges in numerical simulations of this physiological phenomenon include the complexity of constitutive models of blood as well as the large motion of the confining arterial walls. Our research has focused on developing scalable algorithms for computational Fluid–Structure Interaction regarding the cardiovascular system.

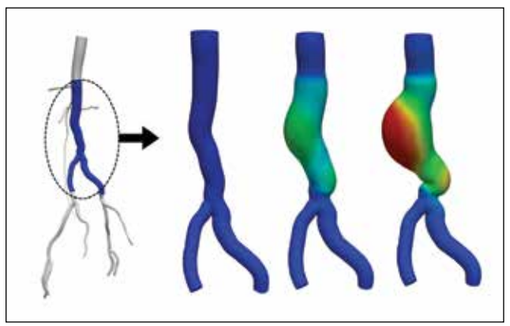

Figure 1: Growth of the abdominal aortic aneurysm (colored by the deformation of the artery wall).

METHODS & CODES

The scope of the research ranges from building a patient-specific model to developing the FSI formulation, a scalable algorithm, and a computer code.

Developing a Patient-Specific Model from CT-Scan Images: We obtained Computerized Tomography (CT) scan images from our collaborative institution, the Carle Foundation. The patient-specific geometric model of the aortic and femoral arteries was constructed from the CT images. A computational grid was constructed using 10-node tetrahedral elements while accounting for the thickness of the arterial walls, with two tetrahedral elements through the thickness of the wall.

Computational Fluid–Structure Interaction: The coupled FIS problem was solved on XE nodes of Blue Waters. Blood was modeled as a non-Newtonian fluid, while the deforming artery was modeled as a hyperelastic solid with fiber reinforcement in the circumferential direction. A key component in FSI methods is embedding of the kinematic and kinetic coupling between fluid and solid to the framework. The FSI techniques we developed enable the simulation of swelling behavior of the artery walls, or aneurysm, due to the blood pressure.

Parallel Implementation: The code was parallelized for distributed memory computations, adapting the ghost node approach and using the standard Message-Passing Interface (MPI). Various linear system solvers available in the PETSc [1] libraries were employed for the iterative solution in the Newton method.

RESULTS & IMPACT

We have simulated the evolution of the aneurysm, as shown in Fig. 1. The first few cycles correspond to the progression of the disease, which occurs over months or years. This is shown via the second and third image in Fig. 2, which show instantaneous snapshots of the system. The last three cycles correspond to flow through the progressed aneurysm, and the last image in Fig. 2 presents an instantaneous snapshot of the deformed geometry at the peak of systole. We have attempted to show via this test case that numerical simulations can be employed for accelerated modeling of disease progression, and at the same time they can be used to decipher the physiological features of the advanced stage of the disease. The computed results in Fig. 2 show the instantaneous snapshot of the velocity field of blood projected on the instantaneous displacement fields of the blood vessel. Also

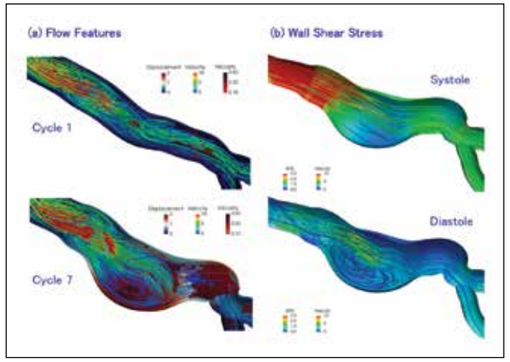

Figure 2: Numerical results of the blood–artery interaction: (a) velocity stream lines and viscosity contour in blood projected onto an instantaneous snapshot of deformation of the artery wall; (b) wall shear stress on the inner surface of the wall that constitutes the interface between blood and artery.

projected is the isosurface of blood viscosity, which is an internal parameter in these calculations.

This test case enables us to identify the high-viscosity regions where blood coagulation can potentially take place. We have also projected the arterial Wall Shear Stress (WSS) on the arterial walls. It is important to note that WSS is one of the most significant factors for the progression of arterial disease. We further want to note that WSS data is very difficult to obtain via *in vivo* experiments.

To summarize, we have shown that advanced FSI simulations that can provide important data for the diagnosis and treatment of arterial diseases (such as an aneurysm) are critical in planning and developing strategies to cure these diseases.

WHY BLUE WATERS

The algorithms that we have developed for coupled FSI analysis are amenable to efficient parallelization because major portions of the computations are carried out at the local-element level. These algorithms are well-suited for distributed memory parallelism, and Blue Waters provides an ideal platform for implementation of such algorithms.

PUBLICATIONS & DATA SETS

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