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MULTI-SCALE MODELING OF BLOOD VESSELS USING A FLUID-SOLID GROWTH FRAMEWORK

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ABSTRACT

Introduction: Blood vessels adapt and remodel in response to changes in their biomechanical and biochemical environment during development and aging, and with diseases including atherosclerosis, aneurysms, and hypertension to name a few examples. While computational methods have been utilized separately to quantify hemodynamic conditions and to simulate growth and remodeling processes, there is a pressing need for a unified approach to model vascular adaptation and disease progression in response to biomechanical and biochemical stimuli. This class of *Fluid-Solid Growth* (FSG) problems is inherently multi-scale in time since the biomechanical forces due to the heart beat change over seconds whereas vascular adaptation can occur over days to weeks and diseases progress over months to years. In addition, FSG problems are multi-scale in space since biomechanical forces and biochemical stimuli, sensed at a molecular and cellular scale, elicit adaptive and maladaptive responses from molecular (nm) to organ (cm) scales. We describe herein a novel computational method to model fluid-solid growth problems and illustrate this method by applying it to simulate the enlargement of a cerebral aneurysm in response to shear and tensile stress.

Methods: We have developed a computational framework to simulate FSG mechanics in the vasculature [1] that incorporates some of the key multi-scale temporal and spatial processes that play a role in arterial adaptation. This unified framework couples modules that represent Growth and Remodeling (G&R) [2] and Fluid-Structure Interaction (FSI) [4] by exploiting a theory of small on large [5] to resolve differences in temporal and spatial scales. The G&R module uses a constrained mixture theory [3] to model the turnover of individual structurally significant constituents of the vascular wall, including changes in the production and removal of separate families of collagen fibers and changes in the vasoactive behavior of smooth muscle cells in response to deviations from a homeostatic state. The G&R module incorporates biochemical and biomechanical processes from molecular to tissue scales, but these phenomena occur over long time scales. The FSI module utilizes the Coupled Momentum Method for Fluid-Solid Interaction (CMM-FSI) to quantify shear and tensile forces acting on the vascular wall in geometrically accurate patient-specific models [4]. The FSI module

resolves biomechanical forces at the tissue spatial scale, but these phenomena occur over short time scales.

Results: The FSG framework was employed to model the evolution of an idealized fusiform basilar artery aneurysm. Figure 1 depicts the evolution of the aneurysm without (top) and with (bottom) the influence of a shear-stress mediated response.

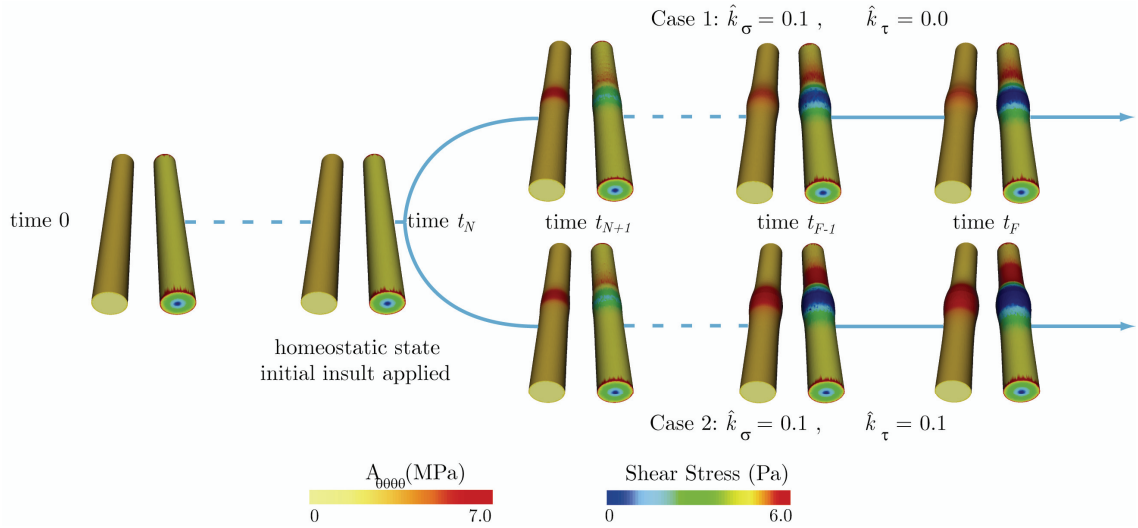

Figure 1. Schematic representation of the FSG for an idealized model of a fusiform basilar artery aneurysm. A homeostatic state for the artery is computed followed by two different simulations of stress-mediated growth and remodeling.

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