Simulation of 3-D Blood Flow in the Full Systemic Arterial Tree and Computational Frameworks for Efficient Parameter Estimation

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Computational methods for simulating blood flow have become powerful tools to gain insight into the physical behavior of the cardiovascular system in health and disease. An area of cardiovascular disease research that has received relatively little attention from a computational perspective is the investigation of arterial stiffening with age and disease and its relationship to the underlying hemodynamics. Because of the strong interactions between the evolving arterial wall properties and the associated hemodynamics, there is a specific need to understand how local changes in arterial stiffness are reflected in the local and global hemodynamics, and conversely, how disruptions in normal hemodynamic patterns may initiate disease progression. Due to the complex geometry and material properties of the central arteries, and the hemodynamics therein, large-scale three-dimensional computational models of arterial mechanics can improve our ability to interpret current clinical hemodynamic metrics and to advance our fundamental understanding of the mechanisms of disease progression.

In this work, we focus on developing computational models of fully three-dimensional and unsteady hemodynamics within the primary large arteries in the human systemic circulation from head to legs. We demonstrate that this virtual full body systemic arterial tree is able to reproduce many of the key physiological features of the human arterial circulation and is a promising first step toward further computational analyses of the relationship between blood flow and arterial stiffening. As part of this work, we have tested and implemented an important boundary condition for the arterial fluid-solid interaction problem that mimics the tethering effect of the external tissues and stabilizes simulations in large networks of vessels.

The task of efficiently fitting large-scale 3-D models to patient-specific measurements is challenging due to the large computational effort required for a single forward simulation. We implemented and tested two different computational frameworks for parameter estimation: the first is based on computationally inexpensive one-dimensional analogues of the full 3-D system. The second method is based on sequential data-assimilation techniques, specifically, non-linear Kalman filtering. We demonstrate that these frameworks may be used to rapidly estimate the parameters of large-scale 3-D models based on clinical measurements of blood flow, pressure, and vessel wall distensibility.