Coupled fluid–structure interaction hemodynamics in a zero-pressure state corrected arterial geometry

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\textbf{Abstract}

Hemodynamic conditions in large arteries are significantly affected by the interaction of the pulsatile blood flow with the distensible arterial wall. A numerical procedure for solving the fluid–structure interaction problem encountered in cardiovascular flows is presented. We consider a patient-specific carotid bifurcation geometry, obtained from 3D reconstruction of \textit{in vivo} acquired tomography images, which yields a geometrical representation of the artery corresponding to its pressurized state. To recover the geometry of the artery in its zero-pressure state which is required for a fluid–structure interaction simulation we utilize inverse finite elastostatics. Time-dependent flow simulations with \textit{in vivo} measured inflow volume flow rate in the 3D undeformed artery are performed through the finite element method. The coupled-momentum method for fluid–structure interaction is adopted to incorporate the influence of wall compliance in the numerical computation of the time varying flow domain. To demonstrate the importance in recovering the zero-pressure state of the artery in hemodynamic simulations we compute the time varying flow field with compliant walls for the original and the zero-pressure state corrected geometric configurations of the carotid bifurcation. The most important resulting effects in the hemodynamic environment are evaluated. Our results show a significant change in the wall shear stress distribution and the spatiotemporal extent of the recirculation regions.

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1. Introduction

Three-dimensional numerical modeling of fluid–structure interaction (FSI) of blood flow/distensible arterial vessel is a challenging task and has received increasing attention in recent years. Various computational techniques have been proposed in order to simulate blood flow in the vasculature. These techniques broadly fall into two main categories, where the wall is assumed rigid (Taylor et al., 1998; Oshima et al., 2001; Cebral et al., 2003; Shojima et al., 2004; Salmon et al., 2003) or compliant (Quarteroni et al., 2000; di Martino et al., 2001; Formaggia et al., 2001; de Hart et al., 2003; Wolters et al., 2005; Torii et al., 2006; Scotti and Finol, 2007; Khanafet et al., 2009).

The rigid wall approximation was primarily adopted due to the difficulty in solving the coupled FSI blood flow/vessel problem. In large healthy arteries, the vessel diameter variation during the cardiac cycle is relatively small (approximately 5–10%) and is further reduced in less compliant diseased vessels (Nichols and O’Rourke, 2005); thus, the rigid wall simplification could be acceptable. However, recent studies including full FSI analysis in vascular conduits indicate that the rigid wall assumption precludes wave propagation phenomena (Formaggia et al., 2001; Vignon-Clementel et al., 2006; Figueroa et al., 2006), which influence the character of the numerical solutions.

FSI modeling of pulsatile blood flow in a compliant artery requires the solution of both the equations describing fluid motion and the elastic wall motion. This can be achieved either by solving the governing equations separately in a staggered iterative manner (Papaharilaou et al., 2007; Jarvinen et al., 2008) or simultaneously in a fully coupled manner (di Martino et al., 2001; le Tallec and Mouro, 2001; Itron and Madlik, 2007). The numerical method most widely used for fully coupled FSI is the arbitrary Lagrangian–Eulerian (ALE) formulation in the finite element method (FEM) framework (Hughes et al., 1981; Donea et al., 1982; Nomura, 1994; Bathe et al., 1995). However, ALE formulations are computationally expensive as they require mesh updating, due to the continuous geometry update of both fluid and solid domains, and introduce errors, when projecting the solution from the old mesh to the updated one. Furthermore, a suitable sub-iteration process must be established to converge to the correct wall velocity that appears in the fluid momentum equations. Alternative FSI formulations are the immersed boundary method (Peskin and McQueen, 1995), transpiration techniques based on linearization principles (Fernandez and le Tallec, 2003),...