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Uncertainty quantification in coronary blood flow simulations: impact of geometry, boundary conditions and blood viscosity

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Abstract

Computational fluid dynamic methods are currently being used clinically to simulate blood flow and pressure and predict the functional significance of atherosclerotic lesions in patient-specific models of the coronary arteries extracted from noninvasive coronary computed tomography angiography (cCTA) data. One such technology, $\mathrm{FFR_{CT}}$, or noninvasive fractional flow reserve derived from CT data, has demonstrated high diagnostic accuracy as compared to invasively measured fractional flow reserve (FFR) obtained with a pressure wire inserted in the coronary arteries during diagnostic cardiac catheterization. However, uncertainties in modeling as well as measurement results in differences between these predicted and measured hemodynamic indices. Uncertainty in modeling can manifest in two forms - anatomic uncertainty resulting in error of the reconstructed 3D model and physiologic uncertainty resulting in errors in boundary conditions or blood viscosity. We present a data-driven framework for modeling these uncertainties and study their impact on blood flow simulations. The incompressible Navier-Stokes equations are used to model blood flow and an adaptive stochastic collocation method is used to model uncertainty propagation in the Navier-Stokes equations. We perform uncertainty quantification in two geometries, an idealized stenosis model and a patient specific model. We show that uncertainty in minimum lumen diameter (MLD) has the largest impact on hemodynamic simulations, followed by boundary resistance, viscosity and lesion length. We show that near the diagnostic cutoff ($\mathrm{FFR_{CT}} = 0.8$), the uncertainty due to the latter three variables are lower than measurement uncertainty, while the uncertainty due to MLD is only slightly higher than measurement uncertainty. We also show that uncertainties are not additive but only slightly higher than the highest single parameter uncertainty. The method presented here can be used to output interval estimates of hemodynamic indices and visualize patient-specific maps of sensitivities.

Keywords: uncertainty quantification; coronary simulations; blood flow; fractional flow reserve