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Computational Modeling of the Effect of Mitral-Valve Leaflet Dynamics on Intraventricular Flow

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In this study, we investigate the fluid structure interaction (FSI) between the mitral valve leaflets (MVL) and blood flow in the left ventricle (LV) to elucidate its effect on the intraventricular hemodynamics. Analysis of blood flow in the ventricle can possibly be used for the diagnosis of ventricular dysfunction, since the intraventricular flow patterns are known to be very sensitive to the condition of the heart. Computational fluid dynamics (CFD) based analysis can provide high resolution flow field information along with key quantities such as pressure and shear stresses. One major limitation in most LV flow simulations to date is the accurate modeling of MVL dynamics and associated effects on flow. Recent echo-PIV studies have shown that the mitral valve configuration could totally change the LV flow patterns[1,2], and thus the proper modeling of MVL is essential to the accurate simulation of LV hemodynamics. While MVL structural dynamics[3] and flow structure interaction have been studied in idealized flows[4], the modeling of whole system by coupling non-linear MVL structural dynamics and realistic LV flows is still a challenging proposition.

In the present work, we perform computational studies of the FSI of MVL in a realistic LV flow model using the immersed boundary method (IBM)[5]. The LV model is constructed based on the high-resolution contrast CT-scan data for the normal human heart and the MVL geometrical model is generated from the physiological morphology. The intraventricular flows are simulated by solving the incompressible Navier-Stokes equations on the non-body conformal Cartesian volume grid using the IBM, and the mitral valve is considered as a nonlinear hyperelastic membrane with zero thickness and numerically modeled with a subdivision-surface finite element method. The effects of major embedded fibers inside the mitral valve are modeled using inextensible nonlinear fiber with small bending stiffness, while the effects of secondary fibers are considered in the material model used for the valve membrane. In order to delineate the effect of mitral valve on the ventricular hemodynamics, we have performed the series of simulations for: 1) no MVL, 2) MVL with prescribed motion, and 3) full FSI MVL, and the results are analyzed in detail.

Figure 1 shows the three-dimensional vortical strcutures for the intraventricualr flows during early filling stage without MVL (Fig. 1A) and with prescribed motion MVL (Fig. 1B). The figure shows how vortical strictures are affected by the presence of MVL. Without the mitral valve, the vortex ring starts to roll-up at the mitral annulus and remains symmetric until it breaks off. With the mitral valve, however, a clear vortex ring structure is observed during deceleration phase at the downstream of MVL tips. This vortex ring developes asymmetrically and the septal wall side (left hand side) structure becomes dominant at the center of the ventricle. We have found that this asymetric vortical flow enhances circulatory flow in the LV and affects the endocardial wall shear stress and local blood washout phenomena. The result of full FSI MVL, the effect on the ventricualr hemodynamics, and its clinical implication will be presented in detail.

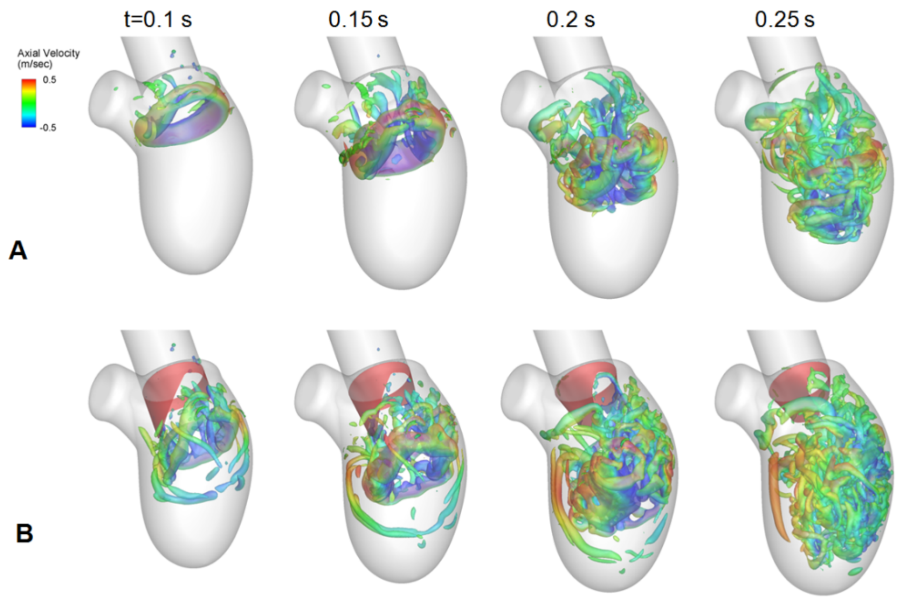

Figure 1. Three-dimensional vortical structure during diastole (filling) stage. Iso-surface of Q-criteria colored by axial velocity. A) without mitral valve model, B) with prescribed motion mitral valve model (red-surface represents mitral valve leaflet).

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