Fluid-Structure Interaction Simulation of Mitral Valve Structures in Patient-Specific Left Ventricle Model

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Summary

Simulations of blood flow in the heart show promise to improve treatment of heart disease by predicting the effects of surgical procedures. Here, we present a patient-specific model of the left ventricle (LV), combined with a novel idealized fluid-structure interaction (FSI) model of the mitral valve (MV). The detailed model of the MV enables accurate localization of elevated shear levels within the LV, which could indicate risk for damage to blood cells post surgery.

The triple decomposition of the velocity gradient tensor was used to compute the shear levels. Additionally, we examined the E-wave propagation index to estimate the risk for blood stasis in the apical LV region.

Shear levels were found to be below risk thresholds, with the highest values found along the posterior leaflet surface. The EPI value was ≥ 1, indicating that simulations of this healthy LV results in line with expectations.

Introduction

Simulations of blood flow in the human heart is a rapidly growing field which may come to revolutionize decision making in treatment of heart disease. One aspect they may predict is whether a procedure may lead to adverse effects, such as elevated shear rates which can lead to hemolysis or platelet activation, or occurrence of static regions.

Substantial research has been done on patient-specific ventricle models, or on detailed models of the heart valves. Combining both of them in the same model, however, introduces significant challenges. The MV has a complex structure, including leaflets, papillary muscles (PMs), and chordae tendineae that are difficult to capture in imaging. These structures also move during the heartbeat cycle, which increases demands on models.

Here we present the results of a recent study[1], where we combine an FSI MV model with a patient-specific LV, which successfully simulates the blood flow in the LV and the resulting movement of the MV leaflets during the diastolic phase of one heartbeat.

Methods

The patient-specific LV model was created from transthoracic echocardiography (TTE) images, taken at snapshots throughout the heartbeat cycle at different angles as described by Larsson et al.[2] to give a full 3D volume. To add the MV structures, an idealized geometry by Votta et al.[3] was used. The chordae tendineae were simulated as a porous region between the leaflet tips and the PMs, to partially block the flow.

To solve the FSI problem, a monolithic approach was applied, with fluid and solid equations included in a single equation system. This removes the need for mapping solutions between separate systems, and eliminates risk for errors being introduced. Additionally, an arbitrary Lagrangian-Eulerian method was used to let the mesh deform with the geometry. This was done with no remeshing during runtime, eliminating another possible source of errors.

To analyze the shear levels in the blood flow, the triple decomposition of the velocity gradient tensor was applied[4]. This separates the flow into components of straining flow, rigid body rotation, and shear flow. The shear levels were compared to a threshold value of 6 N/m^2, taken from Chesnutt and Han,[5] that indicates an elevated risk for platelet activation and subsequent thrombosis formation.

The E-wave propagation index was also applied[6], to evaluate the risk of blood stasis in the apical region of the LV. This method effectively measures the length of the E-wave jet relative to the LV length. An EPI of ≥ 1 means that the E-wave reaches all the way to the apex, which indicates low risk for stasis.

Results and Discussion

Shear levels within the LV were found to be < 6 N/m^2 in 99.97% of the ventricle volume during the whole diastolic phase. The highest values were observed along the surface of the posterior leaflet during the E-wave peak.

The computed EPI value of the simulation was 1.21. The value being ≥ 1 means that the E-wave reaches the apical region of the LV, which indicates proper apical washout. In a study by Harfi et al.[6] a mean value of 1.7 was found for healthy individuals. Our slightly lower value is likely due to the MV model starting in a fully open configuration at the start of diastole.

Since the LV model is from a healthy heart, the shear levels and EPI value were expected to be within a healthy range, which is as observed. This study thus serves as a promising proof of concept.

Conclusions

Simulations results indicate shear levels almost exclusively below risk thresholds, and an EPI level ≥ 1, albeit slightly lower than normal. These results are as expected, and indicate that the LV model with the FSI MV may be useful for improving patient-specific blood flow simulations.

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