Blood Damage Quantification in Cardiovascular Flows Through Medical Devices Using a Novel Suspension Flow Method

B. Min Yun

Cyrus K. Aidun

Ajit P. Yoganathan

Georgia Institute of Technology and Emory University,
Atlanta, GA

Introduction

Blood damage is a major concern for cardiovascular flows with the presence of implanted medical devices. The use of computational simulations to model flow through medical devices can characterize and analyze flows in ways that experiments cannot. A truly multiphase flow solver can be used to quantify blood damage by modeling suspended particles with finite size and meshed surfaces for tracking shear stresses. The aim of this research is to numerically study blood damage that occurs in medical devices in cardiovascular flows, starting with a baseline case of bileaflet mechanical heart valve (BMHV) flows. The suspension flow method combines lattice-Boltzmann (LBM) fluid modeling [1] with the external boundary force method [2]. The fluid-solid coupling will employ the novel external boundary force (EBF) method, which is validated as 2nd order accurate. In the future, this methodology can be used to evaluate newer medical devices with accurate flow modeling, blood damage quantification, and parallel computing.

Methods

The lattice-Boltzmann method (LBM) is a fluid flow solver whose solution converges to the solution of the Navier–Stokes equations. The Entropic lattice-Boltzmann (ELB) method allows for high Reynolds number flow modeling by eliminating numerical instabilities. Solid suspended particles use Lagrangian frames that move through the Eulerian fluid domain, which allows for the exact position of the solid boundary surface to be determined within the fluid grid. The external boundary force [2] is the fluid-solid interaction force required to impose the no-slip boundary condition at the fluid–solid interface. Motion and orientation of solid particles are solved using Newtonian dynamics. A simple linear shear stress-exposure time damage accumulation blood damage index (BDI) model was selected for calculating platelet damage with LBM-EBF [3]. The LBM-EBF method models small particles such as platelets without the need for a fluid grid with the same resolution, modeling particles with meshed surfaces and finite volume. Simulations are performed of pulsatile suspension flow through a St. Jude Medical (SJM) BMHV in the aortic position. Thousands of platelets are released, tracking accumulated damage.

Results

Simulations performed at high spatiotemporal resolution are able to capture small turbulent eddies in systolic flow. These occur from vortex shedding past the leaflets or in the sinus aortic expansion (Fig. 1).

5400 platelets are released, with 300 platelets released every 20 ms during systole. Platelets are released upstream of the valve at the same axial position but with random cross-sectional positions and orientations. For a Lagrangian view, platelets with highest accumulated

Fig. 1 Vorticity plot - peak flow ($Re = 5800$)

Fig. 2 Platelet pathline

Fig. 3 BDI contour plot

damage are isolated and pathlines are mapped in Fig. 2. Highest damaged platelets are found residing in the valve and sinus regions, despite 64% of platelets advecting beyond the sinus region by the end of the simulation. The highest damaged platelets are found near the leaflet surfaces, valve walls, and near the walls of the sinus expansion.

For Eulerian views (Fig. 3), a platelet damage contour plot is created showing the evolution of platelet damage in space, over time. The largest number of high damage regions is found in the sinus expansion near the walls. The flow in the sinus expansion is characterized by strong vortices and recirculation regions. This is particularly dangerous as increased platelet residence time in the recirculation region could lead to platelet activation, consistent with previous results based on a model geometry [3].

Discussion

This baseline case of a SJM valve has demonstrated the capabilities of LBM-EBF as a numerical tool to evaluate blood damage performance of medical devices. BMHVs are a suitable initial case due to the simplified geometry and flow, and extensive previous data available for comparison. The numerical tool can be used as an accurate and valuable methodology for a wide variety of new medical devices and cardiovascular flows.

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References

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