SIMULATION OF BLOOD FLOW AND DEFORMATIONS OF MECHANICAL HEART VALVES USING BOUNDARY INTEGRAL TECHNIQUES

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INTRODUCTION

Approximately 170,000 individuals worldwide receive prosthetic heart valves every year; 95% of these are mitral and aortic valve replacements, and more that 60% of those are mechanical heart valves. In general, mechanical heart valves tend to last longer than biological prosthetic valves, but they also carry a greater long-term risk of cardiovascular complications. Such complications are thought to be caused by high blood shear stress, turbulence and the overall complexity of hemodynamics in the mechanical heart valves. So far, important advances have been achieved in the implementation of computational fluid dynamics to study cardiovascular physiology using numerical techniques that require domain discretization, such as finite element methods or finite difference techniques. However, these cannot fully represent the moving and deforming boundaries present in an operating valve, an issue that can be approached using the Boundary Element Method (BEM), a numerical technique that has not yet been applied in cardiovascular modeling.

The main goal of this project is to develop a mathematical and numerical model to simulate blood flow through bileaflet prosthetic valves based on the BEM. This technique will be suitable for modeling the flow in these geometrically complex systems which are dominated by moving and deforming boundaries.

METHODS

The flow of blood in the cardiovascular system can be considered incompressible and Newtonian. Therefore, the momentum equations are reduced to the Navier-Stokes equations, a system of partial differential equations that basically describe fluid flow; though fundamental and rigorous, they are nonlinear, non-unique, complex and difficult to solve. They do not have a general solution, and so far only a few particular solutions have been found. These exact solutions are important because basic phenomena described by the mathematical model can be analyzed; also they can be used as standard solutions to compare with the approximate numerical solutions. However, in almost every practical situation, it is necessary to use numerical methods in order to obtain a solution of the Navier-Stokes equations.

Through mathematical manipulation, the governing equations were transformed into boundary integrals, requiring a boundary-only discretization for their solution. This solution scheme of the complex equations, which include moving boundaries, is the BEM.

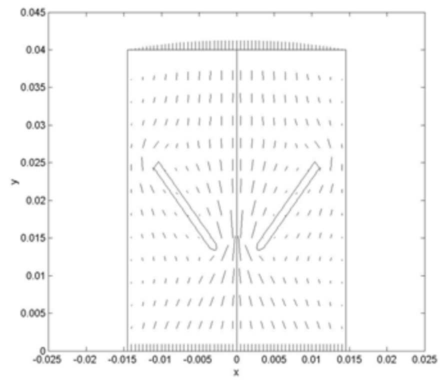

Figure 1: Snapshoot of flow through the valve.

A two-dimensional (2D) model of the mechanical bileaflet valve geometry was developed, which consisted of a cylindrical tube containing a bileaflet valve. Due to the symmetry the simulation was performed to half the domain (see Figure 1). The valve diameter and thickness were 29 mm and 1 mm, respectively; the length of the tube was 40mm. The gap between the leaflet and the tube wall in the closed position was fixed to 0.1 mm. The constant values used for density and viscosity were 1,000 kg/m^3 and 0.004 kg/m-s, respectively. The non-slip boundary condition was used on the tube wall.

RESULTS AND DISCUSSION

Simulations were performed on 10 valve positions between 0° and 70° with respect to the transverse axis of the tube. Figure 1 shows the velocity vectors through an opening valve (55° position). At small opening positions, vortices between the two leaflets were generated due to high flow acceleration in that region. As the valve opens, the flow stabilizes and shows a characteristic parabolic profile downstream.

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