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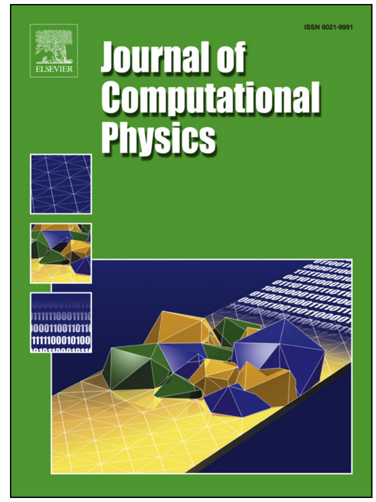

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A Method for the Computational Modeling of the Physics of Heart Murmurs

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A computational method for direct simulation of the generation and propagation of blood flow induced sounds is proposed. This computational hemoacoustic method is based on the immersed boundary approach and employs high-order finite difference methods to resolve wave propagation and scattering accurately. The current method employs a two-step, one-way coupled approach for the sound generation and its propagation through the tissue. The blood flow is simulated by solving the incompressible Navier-Stokes equations using the sharp-interface immersed boundary method, and the equations corresponding to the generation and propagation of the three-dimensional elastic wave corresponding to the murmur are resolved with a high-order, immersed boundary based, finite-difference methods in the time-domain. The proposed method is applied to a model problem of aortic stenosis murmur and the simulation results are verified and validated by comparing with known solutions as well as experimental measurements. The murmur propagation in a realistic model of a human thorax is also simulated by using the computational method. The roles of hemodynamics and elastic wave propagation on the murmur are discussed based on the simulation results.

Keywords: Heart sound; Cardiovascular flow; Immersed boundary method; Hemodynamics; Elastic waves; Systolic murmur.

1. Introduction

Blood flows associated with many abnormal cardiovascular conditions generate characteristic sounds called "murmurs" or "bruits", and these sounds can be measured on the skin surface using a stethoscope [1-3]. This technique of "auscultation" [4, 5][6, 7] has been used for over a hundred years to diagnose cardiovascular diseases, but the physical mechanisms that generate these sounds, as well as the physics of sound transmission through the body, are still not well understood. It has long been accepted that the source of most murmurs are disturbances in blood flow caused by obstruction in the vessels, and there have been many previous studies on the dynamics of flows through stenosed or partially obstructed vessels[8-13]. Several previous studies [3, 14-16] have also shown that the murmur is actually related to the pressure fluctuations on the arterial wall or lumen. A complication with understanding the mechanism of murmur however is that the sound is sensed on the skin surface, and thus, the elastic wave that originates from the blood vessel has to propagate through the various tissues and organs of the

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