Commun. Comput. Phys.
doi: 10.4208/cicp.scpde14.20s

Vol. **19**, No. 5, pp. 1167-1190
May 2016

3D Simulations of Blood Flow Dynamics in Compliant Vessels: Normal, Aneurysmal, and Stenotic Arteries

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Received 17 February 2015; Accepted (in revised version) 30 December 2015

Abstract. Arterial diseases such as aneurysm and stenosis may result from the mechanical and/or morphological change of an arterial wall structure and correspondingly altered hemodynamics. The development of a 3D computational model of blood flow can be useful to study the hemodynamics in major blood vessels and may provide an insight into the noninvasive technique to detect arterial diseases in early stage. In this paper, we present a three-dimensional model of blood flow in the aorta, which is based on the immersed boundary method to describe the interaction of blood flow with the aortic wall. Our simulation results show that the hysteresis loop is evident in the pressure-diameter relationship of the normal aorta when the arterial wall is considered to be viscoelastic. In addition, it is shown that flow patterns and pressure distributions are altered in response to the change of aortic morphology.

AMS subject classifications: 76D05, 66Z05, 92C35

Key words: Blood flow, immersed boundary method, compliant vessel, aortic aneurysm, aortic stenosis.

1 Introduction

The aorta is the largest artery that carries oxygen-rich blood from the left ventricle of the heart and runs down to the abdomen [39]. In healthy human individuals, the aorta normally takes the shape of a candy cane, and the primary constituents of the aortic wall are known as elastin, collagen, smooth muscle, and ground substance [9,55]. Note in general that collagen is stiffer than elastin. The close association of those components determines

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the mechanical properties of the aorta, in particular, its viscoelasticity that accounts for many mechanical features of the aorta. The aortic wall expands during systole (contraction of the heart muscle) and contracts during diastole (relaxation of the heart muscle). The motion of the aortic wall is closely related to the aortic pressure as a result of the nonlinear elasticity of the arterial wall [1,2,4,9,10]. Variations in both the elastic properties of the artery and the blood pressure inside the artery are crucial factors in early stage of the development of potential cardiovascular diseases [10,36,37].

There have been various approaches to explore the interaction between the blood flow and the arterial wall, in which models with different spatial dimensions are used for such exploration. One-dimensional (1D) models have been proposed by averaging the fluid properties over the cross-section of the vessel [7,8,18,45,48]. Two-dimensional (2D) models have been used to address the interaction between the incompressible viscous fluid and the deformable viscoelastic wall, where the blood vessel is assumed to be axially symmetric [10,11,23]. Another approach is to use three-dimensional (3D) models for the blood inside the compliant wall where the displacement of the wall is described by an appropriate boundary condition [5, 12, 13, 31, 33, 40, 47, 53]. There are also multi-scale models that couple 3D models with 1D models associated with appropriate coupling conditions [17,19,38].

In this paper we present a mathematical model which can predict the flow velocity and pressure of blood in the aorta in relation to the mechanical and geometrical properties of the arterial wall. We have previously applied the immersed boundary (IB) method to a 2D model of blood flow in a compliant vessel [29] and have shown that the method is well suited for the interaction between the blood and a moving vessel wall. However, the results in [29] and generally in 2D simulations are inherently artificial. In fact, it is difficult in 2D simulations to evaluate the wall properties in a realistic way and to investigate the relation between the elastic properties of the vessel wall and the blood flow, which is the main purpose of this research. Here we extend and generalize the IB method used in [29] to a full three-dimensional model of the fluid-structure interaction. In the IB formulation, since the action of the deformable elastic vessel wall appears as a localized body force acting on the blood flow, the Navier-Stokes solver does not need to know anything about the complicated time-dependent geometry of the elastic vessel, and therefore we can avoid the difficulties caused by the fluid-structure interaction.

One of the main features of the IB method [42, 44] is that the method enables us to model the structure of the arterial wall by imitating closely its anatomy. In our model, the aortic wall is composed of several layers, each of which is then made up of elastic fibers. This fiber structure is observed in the actual arterial wall [1] and has been shown to be an optimal one for a blood vessel [4]. A source and a sink are used to prescribe the flow rate at the inlet and the blood pressure at the outlet, respectively, based on the experimental data measured in healthy human subjects [29,39].

Hysteresis behavior, in general, is a property of physical systems, in which the system reacts to the applied force with a time delay. This hysteresis phenomenon is apparently observed in the relationship between the blood pressure and the vessel diameter [9]. The