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Eulerian finite element method for the numerical modeling of fluid dynamics of natural and pathological aortic valves

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Abstract

We present a finite element methodology tailored for the simulation of pulsatile flow in the full aorta and sinus of Valsalva interacting with highly deformable thin leaflets. We describe an extension of the so-called "Resistive Immersed Surface" method. To circumvent stability issues resulting from the bad conditioning of the linear system, especially when flow and geometry become complex after the inclusion of the aorta, we use a Lagrange multiplier technique that couples the dynamics of valve and flow. A banded level set variant allows to address the singularity of the resulting linear system while featuring, in addition to the parallel implementation, higher accuracy and an affordable computational burden. High-fidelity computational geometries are built and simulations are performed under physiological conditions. Several numerical experiments illustrate the ability of the model to capture the basic fluidic phenomena in both healthy and pathological configurations. We finally examine numerically the flow dynamics in the sinus of Valsalva after Transcatheter Aortic Valve Implantation. We show numerically that flow may be subject to stagnation in the lower part of the sinuses. We highlight the far-reaching consequences of this phenomenon and we hope inciting adequate studies to further investigate this potential clinical consequences.

Keywords: Computational hemodynamics, Finite Element Method, Lagrange multiplier, Damped Newton, Aortic valve, Aorta
2010 MSC: 35Qxx, 65Lxx, 65Nxx, 65Yxx, 76-xx

1. Introduction

The aortic valve, referred to as AV, permits oxygenated blood to circulate from the left ventricle through the systemic circulation. It has three leaflets (or cusps) of very similar size which behave stiff but compliant. They are faced by three corresponding pouches of the aorta called sinus of Valsalva (SV). Leaflets are thin elastic structures (≈0.2-0.4 mm thickness) with complex anatomical features characterized by a non-homogeneous fibrous texture [14]. They synchronize the opening in early systole [11], whereas they are driven to closure in late systole by both the fluid vortices trapped within the sinuses [4, 58] and the deceleration of the aortic flow [24]. Backflow is prevented during diastole in which high transvalvular pressure jump occurs [1]. Valvular pathologies, such as stenosis and regurgitation, can affect the normal functioning of valves leading to the deterioration of the life quality. Advancing the computational understanding of the main processes of the valve function, boosted by the recent advances in mathematics and computer science, is certainly of great potential in the development and improvement of novel therapies. In spite of increasing interest in the modeling of valves and blood flow in the full aorta, this coupled problem remains extremely challenging

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