FLUID–STRUCTURE INTERACTION MODELING FOR EVALUATING SENSOR-BASED TRANSCATHETER HEART VALVES

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Introduction

The function of human heart valves is to direct blood flow unidirectionally through the chambers, utilizing a tandem operating mode, towards other organs. Finite-element analysis, computational fluid dynamics (CFD) models and fluid-structure interaction (FSI) models were mostly employed to represent aortic valve hemodynamic and structural mechanics [1]. The complexity of the interaction between blood flow and the relevant anatomical and/or device configurations presents technical challenges requiring the utilize of FSI models [2]. Moreover, different technologies and devices have been studied in literature which allow to obtain in-situ blood pressure measurement for the corresponding monitoring and control [3].
The aim of the study is to carry out a computational framework for the FSI simulation of prosthetic valve with the goal to virtually model the presence of sensors embedded in the valve to measure velocity, blood pressure and vessel deformation for monitoring the deterioration of prosthetic valve leaflets.

Materials and methods

The CAD tool Rhinoceros (Rhinoceros v.7, McNeel & associates, USA) was used to generate an idealized geometrical model of the aortic root, including the ascending aorta, left ventricular outflow tract and valve leaflets.
The FSI simulation was solved by a partitioned approach with a two-way coupling utilizing the XFlow2022 and Abaqus2021 (Dassault Systemes, Simulia Corp., Providence, RI) solvers for the fluid and structure, respectively. SIMULIA Co-Simulation Engine (Dassault Systemes, Simulia Corp., Providence, RI) managed the data transfer between the solvers. The flow field was discretized with ~1M unity D3Q27 lattices (84×84×155) with high number of degrees of freedom per discrete element of fourth-order spatial discretization. Time-dependent physiological pressure amplitude boundary conditions were imposed on both sides of the domain as outlets pressure boundary conditions. The wall boundary conditions were applied to all other surfaces inside the fluid domain. In addition, following streaming, the bounce-back technique was utilized to impose a no-slip condition close to the walls. For the structural solver, the aortic wall is modeled using an hyperelastic, fiber-reinforced constitutive models, with the distal and proximal ends fixed in the longitudinal direction. For the evaluation of pressure and velocity, two points placed proximally and distally the aortic valve were used to monitor the fluid flow field.

Results

The flow velocity field evolution using FSI analysis at representative time instants for aortic valve (AV) confirm the ability of FSI model to predict the flow and structural properties of AV.
At the beginning of systole (50 ms), the flow field begins to develop and reaches its peak in the systole peak phase (100 ms), where the flow is characterized as a symmetric central jet flow with a maximum jet velocity of 1.00 m/s. Toward the end of systole (267 ms), a backward flow due to the pressure drop leads to partial to complete closure of the leaflets at the end of systole (300 ms). As the fluid is forced to change direction or stop abruptly, a pressure surge propagates through the valve during this period, and velocity variations are observed. In the diastolic phase of the cardiac cycle (300-870 ms), the velocity decreases toward zero due to decaying small flow fluctuations, especially in mid-diastole (500 ms).

Discussion

The proposed FSI framework is presented and used for the analysis of transcatheter heart valve. The coupled FSI analysis is very effective and provides good correlations with existing resolved results reported in the literature. We have shown that the FSI model can predict the flow of the transcatheter heart valve.
In future research it would be extremely useful to develop and validate an in-silico simulation that reproduces principle of sensing applied to different valve models for instance simulating electric field in XFlow software. This may help to further optimize the sensor size, shape and positioning according to different prosthesis models, as well as to simulate various altered working conditions for the leaflet.

References

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