COMPARISON BETWEEN FLUID-STRUCTURE INTERACTION AND FLUID DYNAMIC SIMULATIONS OF STENTED CORONARY ARTERIES

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Summary In-stent restenosis is the main clinical complication after stent implantation in atherosclerotic coronary arteries. Computational fluid dynamics (CFD) analyses are considered a valid tool to study blood flow through stented vessels. However, in this kind of simulations arterial walls and stent are assumed to be rigid and fixed, probably resulting in altered flow patterns. Therefore, the aim of this work is to perform Fluid-Structure Interaction (FSI) analyses of a stented coronary artery in order to understand the effects of the wall compliance on hemodynamic quantities.
Comparative transient CFD and FSI simulations were performed on a single repeating unit of a common open-cell stent using ADINA (Adina R&D Inc., MA, USA). Results showed that the wall compliance can have an influence on wall shear stress. The proposed FSI model may be also useful to assess variables (wall stresses and strains) which are normally not possible to get through rigid wall computations.

INTRODUCTION

Although the use of stent in coronary arteries for the treatment of atherosclerotic lesions has been promising, local reduction in lumen size as a result of neointimal hyperplasia, known as in-stent restenosis (ISR), remains the main clinical complication. ISR mechanism and causes are still not fully understood even if different phenomena are associated with it [1]. In particular, wall shear stresses (WSS) induced by the flow to endothelial cells seems to be predominantly significant. This was demonstrated by a series of in vivo and in vitro studies which showed that low and oscillating WSS leads endothelium into a highly proliferative state [2].
Computational Fluid Dynamics (CFD) provides a valid tool for studying macro and micro aspects of blood flow through stented vessels, including WSS distribution, and their influence on ISR. Several CFD research studies have been proposed in the literature, considering non-bifurcated or bifurcated vessels [3, 4]. Despite providing a great deal of information, in these simulations the arterial wall and the stent are assumed to be rigid and fixed, probably influencing the WSS and flow patterns. Therefore, the aim of the present work is to perform Fluid-Structure Interaction (FSI) analyses of a stented coronary artery in order to understand the effects of the wall compliance on hemodynamic quantities. Both a standard stainless steel stent and a polymeric (poly-L-lactide - PLLA) stent are considered. The results of the FSI simulations are compared to a CFD simulation which was carried out using the same initial model.

MATERIALS AND METHODS

Creation of geometry and mesh

A straight coronary artery with a single repeating unit of a common open-cell stent was considered (Fig. 1a, top). The geometry of the artery was created with realistic dimensions using a CAD software. The single stent repeating unit was expanded inside the vessel through a structural simulation performed in ABAQUS/Standard (Dassault Systemes, Simulia Corp., RI, USA) [5]. The final geometrical configurations after the elastic recoil were exported as triangulated surfaces in the meshing software ANSYS ICEM CFD (Ansys Inc., PA, USA) to discretize the model [4]. A mixed tetra and prism mesh of about 220,000 elements was used for the arterial wall while the stent was meshed with 103,000 tetrahedral elements. Finally the fluid flow grid, which considers a refinement around the device, was composed by 700,000 tetrahedral elements.

FSI simulation: solid model

The arterial wall was modeled as a hyperelastic incompressible isotropic and homogeneous material. The viscoelasticity, the active behavior of muscle fibers of the artery, and the intrinsic anisotropy, due to the preferential directions of collagen and muscle fibers, were not considered. The arterial wall was then characterized by the following strain energy function $W=A\,[\exp(B(\bar{I}_1-3))-1] + U(J)$ [6], where $\bar{I}_1$ is the first invariant of the deviatoric right Cauchy-Green tensor $\hat{\mathbf{C}} = J^{-2/3}\,\mathbf{F}^T\mathbf{F}$, $J = \det(\mathbf{F})$ is the Jacobian, $\mathbf{F}$ is the standard deformation gradient, U is the volumetric energy function and A, B are material constants. In particular, the constants value were set to A=3.71 Pa and B=140.2. This strain energy density function was firstly proposed by Demiray et al. [7]. The function parameters were fitted using the experimental tests of human coronary arteries obtained by Carmines et al. [8].
The stent was given the following mechanical properties: E = 2.1 GPa and $\nu = 0.3$ (stainless steel case), E = 900 MPa and $\nu = 0.35$ (polymeric case). The geometries of the two stents were considered identical.

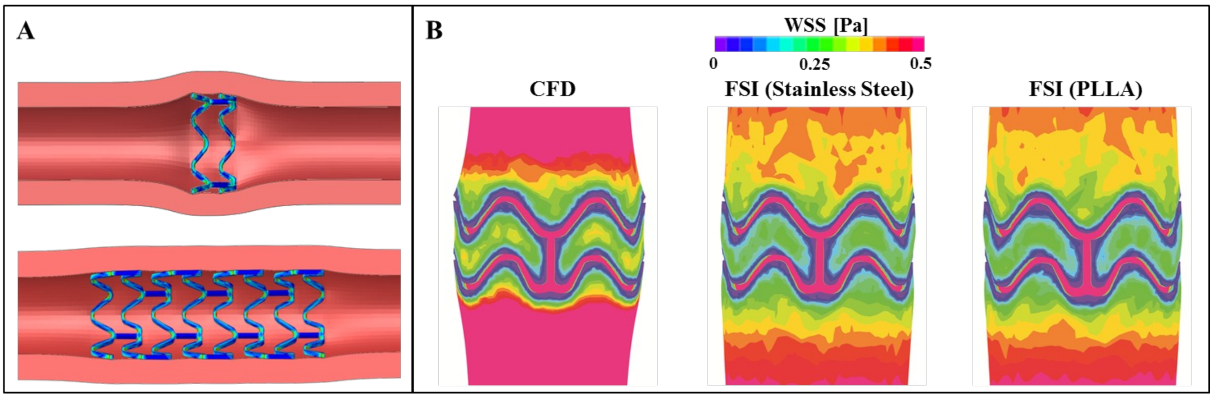

Figure 1 – A) 3D model of a straight coronary artery characterized by the presence of a single repeating stent unit (top) and a full stent (bottom). B) WSS contours at the peak of pressure cycle for the three considered cases.

FSI simulation: fluid model
The blood rheology was assumed as Newtonian, with a density of 1050 kg/m^3 and a viscosity of 0.003528 Pa s. Based on the Reynolds number of Re=150, the blood flow was assumed laminar and incompressible under unsteady flow conditions. As boundary conditions, the physiological curves of flow and pressure measured in vivo by Davies et al. [9] were imposed at the inlet and at the outlet of the model, respectively.

Simulations
Two transient FSI simulations (considering the stainless steel and polymeric stent) and one transient CFD simulation were carried out using ADINA (Adina R&D Inc., MA, USA).

RESULTS AND DISCUSSION

The present work shows the feasibility of making FSI simulations of a stented coronary artery. FSI results are compared to a CFD simulation to investigate the influence of the vessel compliance on hemodynamic quantities. For example, in Fig. 1B WSS contours for the three examined cases are depicted at the peak of pressure cycle, which corresponds to the maximum deformation of the artery. WSS lower than 0.5 Pa (values considered dangerous for restenosis) are located in correspondence of the stent struts. In particular, FSI models are characterized by a wider area with low WSS in comparison to the CFD case. This is due to the enlargement of the artery in the regions around the stent provoked by vessel deformation during the FSI analyses. CFD simulations do not take into account the effects of the pulse pressure on the wall and this results in a smaller vessel lumen area. In future works the effects of the deformation caused to the arterial wall by the pressure should be considered in the CFD simulations to obtain more realistic results.
Minimal differences on WSS are present comparing the stainless and the polymeric stent in the FSI analyses.

CONCLUSIONS

To our knowledge there are not FSI studies on stented coronary arteries in the literature. The proposed FSI simulations showed that the vessel compliance can influence the WSS distribution in comparison to the CFD simulation. These analyses may be also useful to assess variables (wall stresses and strains) which are normally not possible to obtain through rigid wall computations. Finally, a future FSI simulation of a straight coronary artery with a full stent deployed (Fig. 1A, bottom) will be performed to support the obtained results.

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