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Research Paper

On the necessity of modelling fluid–structure interaction for stented coronary arteries

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ABSTRACT

Although stenting is the most commonly performed procedure for the treatment of coronary atherosclerotic lesions, in-stent restenosis (ISR) remains one of the most serious clinical complications. An important stimulus to ISR is the altered hemodynamics with abnormal shear stresses on endothelial cells generated by the stent presence.

Computational fluid dynamics is a valid tool for studying the local hemodynamics of stented vessels, allowing the calculation of the wall shear stress (WSS), which is otherwise not directly possible to be measured *in vivo*. However, in these numerical simulations the arterial wall and the stent are considered rigid and fixed, an assumption that may influence the WSS and 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 the hemodynamic quantities. Two different materials are considered for the stent: cobalt–chromium (CoCr) and poly-L-lactide (PLLA). The results of the FSI and the corresponding rigid-wall models are compared, focusing in particular on the analysis of the WSS distribution.

Results showed similar trends in terms of instantaneous and time-averaged WSS between compliant and rigid-wall cases. In particular, the difference of percentage area exposed to TAWSS lower than 0.4 Pa between the CoCr FSI and the rigid-wall cases was about 1.5% while between the PLLA cases 1.0%. The results indicate that, for idealized models of a stented coronary artery, the rigid-wall assumption for fluid dynamic simulations appears adequate when the aim of the study is the analysis of near-wall quantities like WSS.

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1. Introduction

Among the percutaneous interventions, stenting is the most commonly performed procedure for the treatment of coronary atherosclerotic lesions; however, serious clinical complications remain such as in-stent restenosis (ISR), which is the reduction in lumen size following the stent implantation (Park et al., 2012). The primary process leading to ISR is neointimal hyperplasia (NH) that consists in an excessive growth of tissue in and around the implanted stent, resulting in a decreased blood flow through the vessel. One of the stimuli to NH is the altered hemodynamics due to the stent presence that causes abnormal shear stresses on the endothelial cells (Wentzel et al., 2008).

To date, numerical models have been established as a valid tool for studying the local hemodynamics of stented vessels, allowing the calculation of the wall shear stress (WSS), which is otherwise difficult to be measured *in vivo*. Many computational fluid dynamic (CFD) studies have been proposed in the literature, considering idealized (Gundert et al., 2013, 2012, Murphy and Boyle, 2010a, Pant et al., 2010) or more complex image-based stented coronary models (Chiastra et al., 2013, Ellwein et al., 2011, Gundert et al., 2011). Despite providing a great deal of information, in these fluid dynamic models the arterial wall and the stent are considered rigid and fixed, an assumption that may influence the WSS and flow pattern results. In the recent past the fluid–structure interaction (FSI) approach has been applied to a wide range of arterial problems including the aorta (Figueroa et al., 2006), abdominal aortic aneurysms (Leung et al., 2006; Scotti et al., 2008; Scotti and Finol, 2007; Tezduyar et al., 2007; Wolters et al., 2005), cerebral aneurysms (Gerbeau et al., 2005; Takizawa et al., 2012, 2011; Tezduyar et al., 2007), carotid artery bifurcations (Filipovic et al., 2013; Gao et al., 2009; Gerbeau et al., 2005; Lee et al., 2012; Perktold and Rappitsch, 1995; Tezduyar et al., 2007), and anastomoses of bypass grafts (Hofer et al., 1996; Leuprecht et al., 2002). The extensive study of Tang and coworkers on human carotid atherosclerotic plaque (Tang et al., 2008, 2004, 2001, 1999, Teng et al., 2010, Yang et al., 2011, 2010) deserves special mentioning. Indeed, they provided structural and hemodynamics markers for the initiation and development of atherosclerosis in carotid arteries using the FSI approach. In a further study Belzacq et al. (2012) investigated the effect of the length, the stiffness, and the severity of an asymmetric carotid atherosclerotic plaque on the mechanical action of the blood flow by developing a parametric FSI model.

FSI simulations of coronary artery models have been performed only in a limited number of studies, without considering the presence of stents. Koshiba et al. (2007) simulated blood flow, arterial wall deformation and filtration flow in the wall of a coronary artery with multiple bends. The results of the FSI simulation were used to analyze the low density lipoproteins transport in the arterial lumen and wall by solving the advection–diffusion–reaction equation. Yang et al. (2009) developed a FSI model of the middle segment of the human right coronary artery (RCA) with atherosclerotic plaques, based on intravascular ultrasound (IVUS) images, in order to quantify the effects of anisotropic vessel properties and cyclic bending of the coronary plaque on flow and plaque stress/strain conditions. A similar study was recently conducted by Asanuma et al. (2013) who investigated the distributions of shear stress and tissue stresses in the proximal segment of a stenotic human left anterior descending coronary artery (LCA). Torii et al. (2009) performed a FSI analysis of a human stenotic RCA using physiological velocity and pressure waveforms to investigate the effects of wall compliance on hemodynamics. A comparison between a FSI and a rigid-wall model was carried out showing noticeable differences in instantaneous WSS profiles. Finally, Malvè et al. (2012) made a comparison between the WSS distribution of a compliant and a rigid-wall model of a human left main coronary artery with its main branches. WSS distributions were substantially affected by the arterial wall compliance, in particular considering the minimum and maximum values of WSS.

The aim of the present work is to perform FSI analyses of a stented coronary artery in order to understand the effects of the wall compliance on hemodynamic quantities. Both a bare-metal (cobalt–chromium – CoCr) and a polymeric (poly-L-lactide – PLLA) stent are considered. The choice of the polymeric stent, with the same design of the metallic one, is done because of the different stiffness of the device, which could produce bigger deformations with a great influence on the fluid dynamics. The results of the FSI and the corresponding rigid-wall models are then compared, focusing in particular on the analysis of the WSS distribution.

2. Materials and methods

2.1. Geometry

A geometrical model of a straight coronary artery and a typical open-cell stent were created using the CAD software RHINOCEROS v.4.0 Evaluation (McNeel & Associates, Indianapolis, IN, USA). The geometry of the artery was created with a length of 20 mm, an internal diameter of 2.7 mm and an arterial wall thickness of 0.9 mm. The stent model is characterized by eight rings with a total length of 8.5 mm, an external diameter of 1.55 mm (uncrimped configuration) and strut thickness of 90 μm.

In order to obtain the geometrical model of a stented artery which is not based only on geometrical assumptions but also takes into account the deformation of the vessel caused by the stent deployment, the device was expanded inside the vessel through a structural analysis reaching the final diameter of 3 mm. The simulation was carried out by means of ABAQUS/Explicit (Dassault Systemes, Simulia Corp., RI, USA) following the method proposed in Gastaldi et al. (2010).

The final geometrical configuration, after the elastic recoil, was exported as a triangulated surface and used to create the fluid and solid domains for the subsequent FSI and CFD analyses (Morlacchi et al., 2011). An extension with a length of four diameters (10.8 mm) was added at both extremities of the arterial model (Fig. 1a) in order to obtain developed flow near the region of the stent and avoid border effects due to