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On the pulsatile flow through a coronary bifurcation with stent

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ABSTRACT

The present study investigates pulsatile flow through models of junctions corresponding to geometries most usually observed in the major coronary artery, with and without stent. A transparent experimental device is used to obtain PIV measurements of the instantaneous flow fields with respect to both meridian and cross sections. They clearly show the persistence of a strong secondary flow, even when a stent is implanted. A numerical analysis is then performed from the experimental data to deduce the circulation of the cross velocity field. The balance of the circulation within the three measurement sections can be interpreted as a factor measuring the Wall Shear Stress (WSS). It is a relatively simple way to estimate the total WSS caused by changing flow due to the presence of a stent.

1. Introduction

Endovascular stents are commonly used to reduce atherosclerotic lesions and minimize the incidence of restenosis. Despite the success of the technique, as the number of the coronary stenting implantations achieved each year shows, the restenosis rate remains high and it is even worse in the case of bifurcation lesions [1,2]. Stent implantation effectively restores circulation, but may modify local blood flow and mismatch the vessel compliance. The wall shear stress (WSS) is altered, thereby rendering specific areas of the vessel wall more susceptible to neointima hyperplasia[1] and restenosis [3,4, e.g.]. Although the use of recent drug-eluting stents (DES) has reduced restenosis rates, long-term outcomes are tempered by an increased risk of late thrombosis [5,1]. The persistence of clinical complications, even in the presence of DES [6,7], emphasizes the need for a better understanding of factors contributing to restenosis. It seems that increased risk of late thrombosis associated to DES implantation may be exacerbated at bifurcation sites, perhaps due to stent-induced flow disturbances in combination with locally eluted drugs [8]. A review of the state of the art in relation to coronary stents may be found in the papers of [9,10].

The arteries where atherosclerosis seems to be more frequently observed are rich of curvatures and bifurcations (see, for example, [1]). From their origin in the aorta, coronary arteries divide into many smaller and smaller vessels and the streamlines of the flow describe curves more or less pronounced. Thus, the onset of a secondary flow perpendicular to the direction of the main flow can be expected. This has been extensively studied and affirmed since the early work of [11]. It is known that in pipes, even a slight curvature generates a centrifugal force which induces a pressure gradient in the fluid and therefore a secondary flow taking the form of a pair of counter-rotating vortices when viewed in cross section. The flow in a curved pipe is even more complex when it is driven by an oscillatory motion. [12] was the first to highlight the dynamics of such a flow. There are many practical applications, especially in relation to physiological fluid flows, for pulsating flow in bifurcated and curved pipes. A large number of studies have been carried out in this area and a description of the current knowledge of these flows may be found in the works of [13–15]. These authors adopt a theoretical and numerical approach while [16,17] present experimental studies.

Among the studies of fluid dynamics induced by the presence of a stent in a coronary artery, one can cite the main works of [18]. They reported the existence of zones of separation and

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[1] The neointima hyperplasia is an increase in the thickness of the lining of a blood vessel. It is characterized by the migration of smooth muscle cells into the graft, followed by the release of cytokines that damage the vessel wall and contribute to its degradation by inflammation.

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recirculation with a significant effect on local hemodynamics and [19], whose simulations have shown the relationship between the WSS and the neointimal thickness. [20] were probably among the first to use Particle Image Velocimetry (PIV) to characterize the flow inside, but their model of stent was too far from reality to deduce reliable information. [21] has shown for the first time an in vitro measurement of the flow within stented compliant arteries on a 1:1 scale under physiologically realistic flow conditions. They used PIV with a very high spatial and temporal resolution to observe very small fields of the stented region. Comparisons between four different drug-eluting stents and a matching bare metal stent suggest the importance of stent design on WSS experienced by endothelial cells in arteries. Even more recently, [22] compared flow patterns within stented and non-stented coronary bifurcation models using PIV and numerical methods. The study is limited to steady flow conditions and measurements as well as velocity computations are restricted to the meridian plane of the vessel. A precise methodology and a very careful analysis for PIV allowing comparison between numerical and experimental results. Both methodologies display highly disturbed velocity fields in cases of wider angles and double-stenting procedures. Several intrinsic fundamental differences between the two methodologies including stent placement, vessel length, and modeling approximations have been discussed and provide rationale for the observed discrepancies. These differences currently prevent the straightforward quantitative comparison necessary for complete validation of CFD with PIV measurements. However, the results underline how both analyses are able to capture the main trends of the fluid flows within the stented and nonstented cases, increasing the reliability of both methods. These findings suggest that the role of hemodynamics before and after stenting procedures might be assessed with both strategies. This interesting work needs to be extended to physiologically realistic flow conditions.

Three-dimensional computational fluid dynamics is implemented by [23,3] to model the coronary wall shear stress produced by stent implantation. They confirm the hypothesis that WSS disturbances produced by a stent may play a subsequent role in intimal hyperplasia and restenosis. These investigations were extended to a stented coronary bifurcation by [24]. They point out that the plastic mechanical deformation of such located stents is unpredictable, because it is directly linked to the initial placement of the cell of the stent within the collateral branch lumen: each dilation can lead to a specific 3D stent deformation. They simulate five possible double stent post implantation configurations that are more or less realistic, in particular for the flow repartition between the Left Main coronary Artery (LMA) and the Left Anterior Descending artery (LAD). Flow features in the bifurcation changed from one model to another and these changes could lead to the occurrence of flow stasis, together with recirculation areas, depending on the way the strut was opened. The stent struts protruding into the lumen of the collateral branch induced high values of shear stress at the stent wall which could stimulate platelet activation. In addition, these areas of high shear stress values were concomitant with areas of low shear stress. These regions could be prone to platelet adhesion and so to thrombo-embolic complications. However, these conclusions would be more convincing if the simulations could be compared with experimental results. The importance of the bifurcation angle has been pointed out by [25]. They concluded that a bifurcation angle $\geq 50^\circ$ is an independent predictor of major adverse cardiac events for patients with coronary bifurcation lesions treated by crush stenting techniques. More recently, [26] proposed a computational method for assessing the influence of current and next-generation stents on local hemodynamics and vascular biomechanics. They analyzed the hemodynamic difference between closed-cell and open-cell stent geometries and demonstrated the usefulness of the method in investigating stent performance in complex vascular beds for a variety of stenting procedures. However, here again, the computational model lacks experimental support and is consequently not fully convincing. Experimental studies of the flow dynamics for implanted stents, using realistic models involving bifurcations, appear necessary to fully validate this rapid and attractive method.

The dynamics of the flows pulsated through junctions is very rich but relatively few experimental studies have been devoted to this topic. There exist even fewer results concerning the influence of one stent positioned in a modeled junction representative of the human arterial system. The present study is devoted to pulsated flow, representing the human hemodynamic system. Junction models are used, these corresponding to the geometries most usually observed in the left coronary arteries, with and without stent. The particle image velocimetry (PIV) method is used to measure instantaneous flow both in meridian and cross section, and the last for the first time, as far as the authors know. Then, an analysis based on experimental velocity fields measures the dissipation of vorticity by stents according to the presence of a distal or proximal aperture. This approach can be implemented to compare the influence of different stent design on WSS. It does not require so high accuracy PIV treatments as some authors had recently developed [21,22].

2. Methods

2.1. Models

The LMA usually originates in the left coronary sinus and bifurcates into LAD and the Left CircumfleX artery (LCX). For the purpose of the present study, models of bifurcations were made of Polymethyl Methacrylate (PMMA) with the geometry most commonly observed in the left coronary arteries (cf. Figs. 3 and 5). The artery was assumed to be a circular duct of internal diameters $d_{LMA} = 4.4$, $d_{LCX} = 3.3$ and $d_{LAD} = 3.5$ mm for the LMA, LCX and LAD respectively. The fabrication accuracy can be estimated between 10 and 50 μm. The length of the LMA was 5 mm (size usually varying between 1 and 20 mm). Two angles (30° and 90°) between the LCX and LMA were examined while the angle between the LMA and LAD is set at 150° (cf. Fig. 8).

Many studies have focused on analyzing the effect of the elasticity of the vessels on the overall flow structure. The comparison of the results with comparable rigid pipe flows shows variations in the velocity profile amplitude of few percent depending on the phase angle and WSS reduction for the compliant vessels [27,28]. The flow studied here occurs in a vessel that has lost compliance due to stent implantation and can be well modelized by a rigid pipe. In addition, even in a case a flexible radially compliant stent, it is shown [29] that the potential advantages provided are lost within a relatively short time after implantation.

Blood is not Newtonian but in relatively large vessels it can be suitably modeled by a mixture of glycerol (40% by volume) and water to imitate the properties of blood ($\rho = 1050$ g/l and $\nu = 3.5\ 10^{-6}$ m^2/s) [30–32].

2.2. Experimental setup

The mean flow has its source in a tank set at constant height, the oscillatory flow is driven by a piston pump (Model SPS 3891, Vivitro Systems, Canada) as shown in Fig. 1. The oscillatory flow is generated by input of the appropriate wave form to the power amplifier of the pump with a servo feedback control. The flow conditions are similar to those used in the study of [21]. The wave form is derived from clinical measurements (resting condition),