Computers in Biology and Medicine 64 (2015) 117–126

Contents lists available at ScienceDirect

Computers in Biology and Medicine

journal homepage: www.elsevier.com/locate/cbm

Hemodynamic characterization of transient blood flow in right coronary arteries with varying curvature and side-branch bifurcation angles

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ARTICLE INFO

Article history:
Received 7 March 2015
Accepted 11 June 2015

Keywords:
Computational simulation
Parametric analysis
Right coronary artery
Side-branch bifurcation
Wall shear stress
Wall pressure gradient

ABSTRACT

Hemodynamics plays a critical role in the development and progression of plaques that are prone to sites of arterial curvatures and branch bifurcations. The occurrence of atherosclerosis at curvatures of coronary arteries and at the bifurcation sites of their branches are of medical importance. In this study, we have employed computer simulation coupled with a parametric analysis to rigorously quantify the transient wall shear stress (*WSS*) and wall pressure gradient (*WPG*) in idealized and image-based right coronary artery (RCA) models with side-branches, in order to explore the effects of curvature and bifurcation on blood flow characteristics and its hemodynamic variables. Upon establishing and implementing this parametric analysis framework, it is found that the relatively lower wall shear stress and *WPG* regions at the curvature and branch bifurcation sites of arteries coincide with the plaques prone points of the three investigated image-based arteries, to thereby confirm the correlation of the fluid mechanical properties with the arterial geometry variation in consistence with the data from existing literatures. Moreover, the average *WSS* and Pressure drop (from inlet to outlet) are significantly increased with the more complex geometry of realistic arteries in comparison with idealized arterial models. It can hence be concluded that the geometry of curvature and angulation of the side branches has a significant effect on the *WSS* and *WPG* in hemodynamics analysis of RCAs and its correlation with atherosclerotic lesions.

1. Introduction

The distribution of wall shear stress (*WSS*) in coronary arteries is a significant contributory factor for the onset of coronary disease. Recently, there have been some debates as to what degree of *WSS* or large *WSS* gradients is contributory to the onset of plaque formation and rupture at the same time. Various studies have gone into explaining how regions are differentiated into varying degrees of *WSS* and link their implications to vessel narrowing [3,32,14,36]. It is widely available in these literatures that atherosclerotic plaques are located at low *WSS* and wall pressure gradient (*WPG*) regions, and it is accepted that local hemodynamic forces play an important role in the formation and rupture of atherosclerotic plaques. Dynamic curvilinear arterial geometries have been demonstrated to strongly affect *WSS* based on coronary artery bifurcation models [41,13,28]. However, a detailed quantification of the *WSS* variations with this arterial curvature has not been studied with sufficient analytical and computational sophistication.

The purpose of our study is hence to computationally analyze the *WSS* and *WPG* variations in idealized and realistic right coronary artery (RCA) models, and focus on: (a) determining the distribution map of *WSS* and *WPG* in RCAs, by taking into account their curvatures and bifurcations; (b) evaluating the variations of average *WSS* (defined as $\overline{\boldsymbol{WSS}}$) on the vessel wall and pressure drop (ΔP) across the arterial inlet and outlet. Despite the well-known relationship of arterial curvature with *WSS* and ΔP, an elaborate and concise parametric study of ‘how the geometrical variation of the curvilinear arteries and its branches affects the

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http://dx.doi.org/10.1016/j.compbiomed.2015.06.009
0010-4825/

blood flow and hemodynamic properties' has not be performed previously to the best of our knowledge. Quantitative hemodynamic analysis and the flow properties of specifically-defined regions, such as the inner and outer walls of the trunk, are presented herein to enable a detailed understanding of the relationship between (i) arterial trunk curvature, angle of branching, as well as curvature of the branches, and (ii) the fluid mechanics of blood through it.

Computational fluid dynamics (CFD) is now widely employed in the hemodynamic analysis of aorta, carotid and coronary arteries under simulated physiological and pathological conditions [37,39]. In our study, we have (i) demonstrated that there are significant differences in the magnitudes of *WSS* and *WPG* in arteries with different curvature and angulation, and (ii) determined these hemodynamic properties in right coronary arteries sites of high curvature and branch bifurcation locations associated with occurrence of atherosclerotic plaques. These results reveal that curvature and branch flows have a big influence on the distributions of *WSS* and *WPG* in the coronary arterial trunk. After this study, we intend to utilize these findings and adopt a methodology for carrying out pre-surgical analysis of plaque-occluded arteries. It allows us to plan the surgical designs of coronary arterial bypass grafts (CABGs) so as to minimize the adverse hemodynamic flow patterns and the values of the hemodynamic parameters in their distal anastomoses with the occluded arteries (in terms of anastomosis sites and angle of anastomosis). This is undoubtedly a complex study which will bring significant clinical benefits. Hence our findings in this study will contribute to an over-all project of hemodynamics of coronary arteries and models of CABGs (for customized optimal surgical CABG designs for maximal CABG patency).

2. Literature review

Atherosclerosis is the main disease of the large and medium arteries (e.g. carotid, aorta, and other proximal arteries) and tends to be localized in regions of curvature and branching in arteries. Right coronary arteries (RCAs) display localized atherosclerotic plaques throughout their length. These atherosclerotic plaques develop more frequently on the myocardial side of the vessel wall and on the proximal part which is shown to be predisposed to eccentric intimal thickening in autopsy and histological studies [5,4,22,26], and imaging studies [15,12,16,11] of Intravascular Ultrasound and multidetector CT angiography.

Using numerical simulation, researchers have confirmed that there are more complex hemodynamic changes in S-shaped curved arteries, in terms of the large changes of pressure and *WSS* [29]. It has been found that atherosclerotic plaques and wall thickenings in left and right coronary arteries are localized almost exclusively on (i) the outer wall of one or both daughter vessels at major bifurcations and T-junctions, and (ii) along the inner wall of curved segments, where *WSS* is low [1,24,34]. It has been demonstrated that *WSS* is clearly different in the case of small bifurcation angle in comparison to the large bifurcation angle, due to the complex hemodynamic flow effect of the bifurcation angle variation [27,2]. Further it has been discovered that high *WSS* also induce plaque growth and rupture; moreover, high *WSS* can induce plaque growth at bifurcations by producing endothelial injury and disruption [30,7,40,31,6]. Also, large *WSS* gradients can induce morphological and functional changes in the endothelium in regions of disturbed flow, and promote the occurrence of plaque [36,19].

In addition to these atherosclerotic factors, the stress development within the arterial wall has a direct effect on the induced pressure in the flow field. Works on the wall pressure distribution and associated atherosclerosis report that low *WPG* is strongly correlated to atherosclerosis [9,10]. The locations of low and high *WPG* at high curvature and branch points are consistent with that of low and high *WSS*; hence, low and high *WPG* could be another 'Evaluation Index' for predicting plaque prone sites.

In conclusion, it is widely available in literature that plaques locate at less intensified *WSS* and *WPG* regions, and are closely associated with the local wall shear stresses. These researches have led to the hypothesis that disturbed flow patterns are associated with the deposition and orientation of localized coronary artery disease; further, there appears to be a strong relationship between regions of atheromas and anatomical features of RCAs. However, it is unclear from literature as to the precise quantitative effects of different curvatures and angulations on *WSS* and *WPG*; To the best of our knowledge, no one has quantitatively analyzed the relationship between these hemodynamic parameters and the geometry variations in RCAs with side-branches and hemodynamics. In order to address if (i) low or high *WSS* are sites of atherosclerotic plaques, (ii) low or high *WPG* are sites of atherosclerotic plaques, (iii) low or high *WSS* gradients and *WPG* contribute to the development of plaque, we will determine the locations of low and high *WSS* and *WPG* regions, and thereby state the possible locations of plaques.

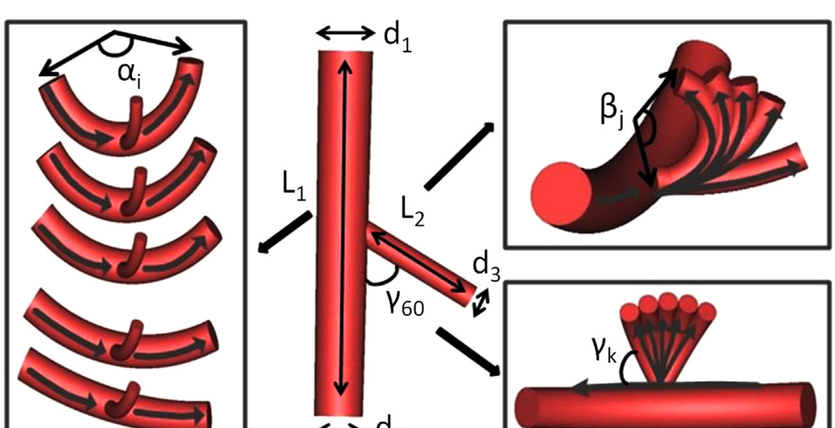

Fig. 1. Geometry of the simulated models, illustrating the geometrical configurations of the main trunk and its side branch (based on the angles α, β and γ). Variable α_i (α_{30}, α_{60}, α_{90}, α_{120} and $\alpha_{150}$from bottom to top),variable β_j (β_{30}, β_{60}, β_{90}, β_{120} and β_{150} from right to left) and variable γ_k (γ_{60}, γ_{75}, γ_{90}, γ_{105}, and γ_{120} from left to right). Unidirectional arrows indicate the direction of blood flow. A reference model may be depicted as $\boldsymbol{\alpha}_0\boldsymbol{\beta}_0\boldsymbol{\gamma}_{60}$.