

Wall Shear Stress Distribution in Patient Specific Coronary Artery Bifurcation

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Abstract: Problem statement: Atherogenesis is affected by hemodynamic parameters, such as wall shear stress and wall shear stress spatial gradient. These parameters are largely dependent on the geometry of arterial tree. Arterial bifurcations contain significant flow disturbances. **Approach:** The effects of branch angle and vessel diameter ratio at the bifurcations on the wall shear stress distribution in the coronary arterial tree based on CT images were studied. CT images were digitally processed to extract geometrical contours representing the coronary vessel walls. The lumen of the coronary arteries of the patients was segmented using the open source software package (VMTK). The resulting lumens of coronary arteries were fed into a commercial mesh generator (GAMBIT, Fluent Inc.) to generate a volume that was filled with tetrahedral elements. The FIDAP software (Fluent Corp.) was used to carry out the simulation by solving Navier-Stokes equations. The FIELDVIEW software (Version 10.0, Intelligent Light, Lyndhurst, NJ) was used for the visualization of flow patterns and the quantification of wall shear stress. Post processing was done with VMTK and MATLAB. A parabolic velocity profile was prescribed at the inlets and outlets, except for 1. Stress free outlet was assigned to the remaining outlet. **Results:** The results show that for angle lower than 90°, low shear stress regions are observed at the non-flow divider and the apex. For angle larger than 90°, low shear stress regions only at the non-flow divider. By increasing of diameter of side branch ratio, low shear stress regions in the side branch appear at the non-flow divider. **Conclusion:** It is concluded that not only angle and diameter are important, but also the overall 3D shape of the artery. More research is required to further quantify the effects angle and diameter on shear stress patterns in coronaries.

Key words: Wall shear stress, bifurcations, coronary artery, computational fluid dynamics

INTRODUCTION

Atherogenesis is affected by hemodynamic parameters, such as Wall Shear Stress (WSS), Wall Shear Stress Spatial Gradient (WSSG) and Oscillatory Shear Index (OSI) (Mohammad *et al.*, 2010; Soulis *et al.*, 2006; 2007; Huo *et al.*, 2007; 2009). These parameters are strongly influenced by flow disturbances, which are largely dependent on the geometry of arterial tree (Prosi *et al.*, 2004). The locations with low WSS and high OSI have been thought to be atherosclerotic-prone (Gijsen *et al.*, 2008; Chen *et al.*, 2006; Naderi *et al.*, 2009). The coronary arterial system is an important clinical site of atherosclerosis. The changes in geometry of blood vessels during branching can lead to significant flow disturbances (e.g., flow separation, secondary flow,

stagnation point flow, reversed flow and/or turbulence) due to convective inertia (Chen and Lu, 2006).

The Computational Fluid Dynamic (CFD) model has been used to describe the flow patterns in different anatomical geometries. The pulsatile flow field in an anatomically realistic model of the bifurcation of the left anterior Descending Coronary Artery (LAD) and its first Diagonal branch (D1) was simulated numerically and measured by laser Doppler anemometry (Perkthold *et al.*, 1998). The flows in these models exhibited many of the features seen in simpler models, but they also showed that there is considerable individual variability in the flow field in specific regions of the tree and perhaps more important, that there were qualitative differences in some cases between the flow field in idealized and in highly realistic geometries.

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The relationship of vascular geometry and pathophysiology has been the subject of a number of investigations (Caroline *et al.*, 2007; Cheng *et al.*, 2006). These investigations suggest that there are significant relationships between coronary arterial geometry and histomorphometry. Each geometric variable affected the morphometrics differently. With respect to the effect of branch angle, this research has been shown that large angles are associated with intimal thickening and are presumably adverse. Thus, the relation between branch angle and intimal thickness seen here is plausible. The shear stress distribution distal to a branch is not circularly symmetric and it may be significant that the mean intimal thickness of the thickest quadrant of the vessel cross-section correlated with angle more strongly than did the mean intimal thickness of the entire cross-section.

Branch area ratio was primarily correlated with medial variables. The effect of area ratio on medial dimensions decays rapidly, indicating that the medial thickening of the LAD associated with the presence of a branch is localized to its immediate neighborhood.

The identification of relationships between geometric variables and hemodynamic patterns can be used to infer which mechanical factors are more likely to be involved in the localization of disease (Dehlaghi *et al.*, 2007; 2008a; 2008b; Wellnhofer *et al.*, 2009).

Computational Fluid Dynamics (CFD) methods based on *in vivo* three-dimensional vessel reconstructions have recently been shown to provide prognostically relevant hemodynamic data. With the development of Computed Tomography (CT), MRI angiography and rotational angiography, patient-specific 3D geometries of coronary arteries are readily available for studies of hemodynamics and resulted in a number of recently published researches (Ramcharitar *et al.*, 2008; Gijssen *et al.*, 2008; van der Giessen *et al.*, 2009; Goubergrits *et al.*, 2009; 2008).

A new imaging technique was applied to generate a 3-D reconstruction of a human coronary artery bifurcation *in vivo* (Gijssen *et al.*, 2007). The observed relationship between SS, WT and remodeling in this specific patient illustrates the spatial heterogeneity of the atherosclerosis in the vicinity of arterial bifurcations. The main geometrical parameters are the angle between the two branches and the surface ratio of the two daughter branches. Some limitations in the current study should be mentioned. The example used in this study was the bifurcation of the LAD with the 2nd diagonal. The angle between the two daughter branches, although being representative for bifurcation angles in the coronary tree, is relatively small. The bifurcation between the LAD and the LCX would pose

additional challenges since the lumen of the LCX will disappear more quickly from the IVUS images due to the larger bifurcation angle. The flow division between the LADdist and the 2nd diagonal is controlled by combining stress free outlet boundary conditions with adjustment of the length of the 2nd diagonal to create identical average SS in the proximal part of the two daughter branches. Whether the assumption of equal average SS is valid for mildly diseased coronary arteries is not studied in detail yet.

This investigation presents the effect of branch angle and vessel diameter ratio at the bifurcations on the wall shear stress distribution in the coronary arterial tree.

MATERIALS AND METHODS

We studied 9 coronary arteries (3 RCA, 2 LCX, 3 LAD and 1 LM). CT images were digitally processed to extract geometrical contours representing the coronary vessel walls. The lumen of the coronary arteries of the patients was segmented using the open source software package VMTK. With VMTK, we selected trash-holds and combine with marching cube techniques to extract lumen of the artery (Fig. 1).

Filtering was applied to smooth the surface (Fig. 2) and clipping of the inlet and outlets was required. The inlet and outlets were extended by straight tubes for easy implementation of the boundary conditions (Fig. 3).

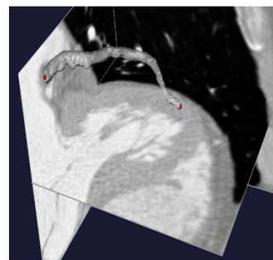


Fig. 1: Extraction of lumen of the artery with VMTK techniques



Fig. 2: Smoothing the surface of the artery with VMTK techniques

The resulting lumens of coronary arteries were fed into a commercial mesh generator (GAMBIT, Fluent Inc.) to generate a volume that was filled with tetrahedral elements. Grid sensitivity tests showed a variation of less than 1% in the solution of the parameters of interest when the size of volumes decreased 10%. The FIDAP software (Fluent Corp.) was used to carry out the simulation by solving Navier-Stokes equations. The blood flow was modeled as an incompressible Newtonian viscous fluid governed by Navier-Stokes equations. Taking into account the previously mentioned assumptions, the governing equations are:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0 \quad (1)$$

$$\rho \frac{DU}{Dt} = \rho \cdot g - \nabla P + \mu \nabla^2 U \quad (2)$$

Where:

- ρ = Fluid density (kg m^{-3})
- U = Velocity vector (m sec^{-1})
- P = Pressure (Pa)
- G = Gravity acceleration (m sec^{-2})
- μ = Fluid viscosity (Pa.s)

A parabolic velocity profile was prescribed at the inlets and outlets, except for 1. Stress free outlet was assigned to the remaining outlet. The dynamic viscosity of blood and its density were assumed to be 3.5×10^{-3} Pa.s and 1050 kg m^{-3} , respectively (Goubergrits *et al.*, 2009; 2008; Gijsen *et al.*, 2007). No-slip condition was applied at the wall and the wall was assumed to be rigid. The FIELDVIEW software (Version 10.0, Intelligent Light, Lyndhurst, NJ) was used for the visualization of flow patterns and the quantification of wall shear stress. Post processing was done with VMTK and MATLAB.

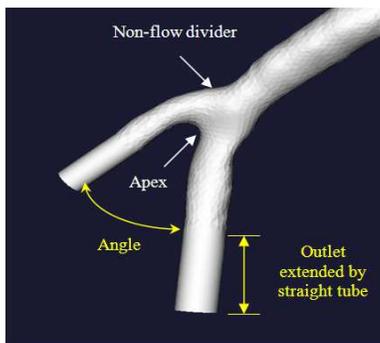


Fig. 3: Extension the inlet and outlets by straight tubes

RESULTS AND DISCUSSION

Steady blood flow in the 9 reconstructed models of the coronary artery was simulated using the CFD program FIDAP.

Influence of angle of side branch at the bifurcations on the WSS distribution: Figure 4 shows the wall shear stress distribution in the Right Coronary Artery (RCA). In this case angle of side branch at the bifurcation is larger than 90° . Low shear stress regions present at non-flow divider. Absolute values of WSS at the non-flow divider are smaller than 0.28 (Pa). Opposite the non-flow divider, near the apex a small region with low shear stress is present (Fig. 4). Absolute values of WSS at this region are larger than 0.4 (Pa). For angle larger than 90° , low shear stress regions only at the non-flow divider.

In the 2 RCA models that the angle of side branch at the bifurcation was larger than 90° , we observed that low shear stress region present only at the non-flow divider area. Absolute values of WSS at the non-flow divider varied between 0.26-0.35 (Pa). In the apex region this value is larger than 0.5 (Pa) (Table 1).

Table 1: Absolute values of WSS at the non-flow divider and apex for different angle of side branch at the bifurcation

	SB angle	Apex WSS	Non-flow divider WSS
RCA-59 MB-SB1	>90	0.40	0.28
RCA-59 MB-SB2	>90	>0.50	0.35
RCA-89 MB-SB2	>90	>0.50	0.26
RCA-44 MB-SB1	90	>0.50	0.33
RCA-89 MB-SB1	<90	0.26	0.36
LAD-72 MB-SB1	<90	0.26	>0.50
LCX-59 MB-SB2	<90	0.37	0.34

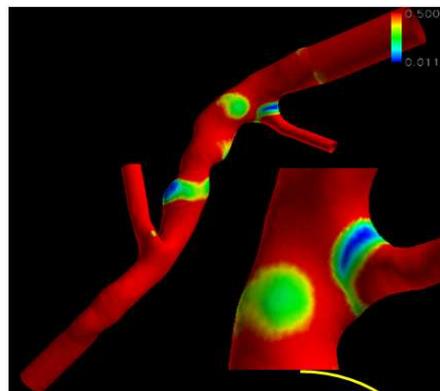


Fig. 4: WSS distribution in the right coronary artery with side branch angle larger than 90°

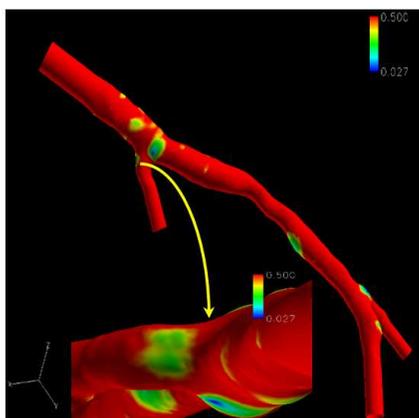


Fig. 5: WSS distribution in the LAD coronary artery with side branch angle smaller than 90°

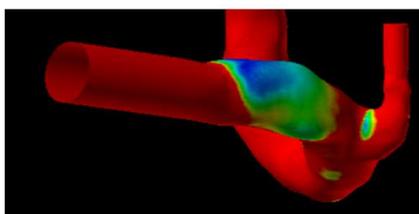


Fig. 6: WSS distribution in the right coronary artery with side branch angle approximately 90°

Table 2: Absolute values of WSS at the non-flow divider and apex for different diameter of side branch at the bifurcation

	SD/MD	Apex WSS	Non-flow divider WSS
LAD-72 MB-SB1	Small	>0.5	>0.50
LAD-59 MB-SB1	Large	>0.5	0.40
LAD-72 MB-SB2	Small	>0.5	0.4, >0.5
LAD-59 MB-SB2	Large	>0.5	0.25
LCX-72 MB-SB2	Small	>0.5	>0.50
LCX-59 MB-SB2	Large	>0.5	0.30

Figure 5 illustrates the wall shear stress distribution in the left anterior descending of coronary artery (LAD). In this case angle of side branch at the bifurcation is smaller than 90°. The results show that for angle lower than 90°, low shear stress regions are observed at the non-flow divider and the apex. Absolute values of WSS at the non-flow divider varied between 0.36-0.5 (Pa). In the apex region this value is varied between 0.26-0.37 (Pa).

When the angle of the side branch at the bifurcation is approximately 90° (Fig. 6), we observed that a small region of low shear stress present only at the non-flow divider area. Absolute value of WSS at the non-flow divider is 0.33 (Pa). In the apex region this value is larger than 0.5 (Pa) (Table 1).

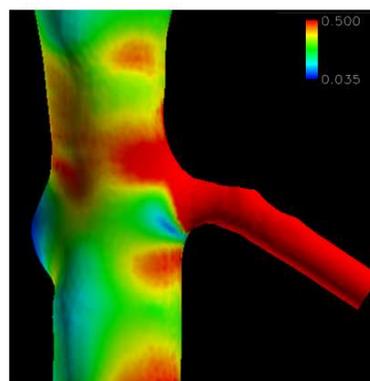


Fig. 7: WSS distribution in the LAD coronary artery with small side branch

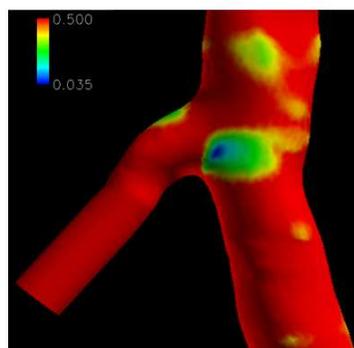


Fig. 8: WSS distribution in the LAD coronary artery with large side branch

Influence of diameter of side branch at the bifurcations on the WSS distribution: WSS distribution in the LAD coronary artery with small side branch was shown in Fig. 7. In this case shear stress in the side branch is larger than 0.5 Pa, both at the apex and the non-flow divider.

WSS distribution in the LAD coronary artery with larger side branch was shown in Fig. 8. In this case low shear stress regions in the side branch appear at the non-flow divider. Absolute values of WSS at the non-flow divider varied between 0.25-0.4 (Pa). In the apex region this value is larger than 0.5 (Pa) (Table 2).

CONCLUSION

If the angle is lower than 90°, low shear stress regions are observed at the non-flow divider and the apex. For angle larger than 90°, low shear stress regions only at the non-flow divider and shear stress at the non-flow divider seem to be lower than bifurcation with angle smaller than 90°.

By increasing the ratio of side branch diameter to main branch diameter (D_s/D_m), low shear stress regions in the side branch appear at the non-flow divider

We concluded that not only angle and diameter, but also the overall 3D shape of the artery are important. More research is required to further quantify the effects angle and diameter on shear stress patterns in coronaries.

The current results confirm and extend our previous observations and further demonstrate the importance of artery geometry on the intravascular fluid dynamics.

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