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Comparative Study on the Wall Shear Stress Distribution in Coronary Bifurcations using Finite Element Analysis

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Abstract

Plaque formation in coronary arteries reduces coronary flow reserve, which can cause myocardial infarction in severe conditions. It is well established that wall shear stress (WSS) and wall shear stress gradient (WSSG) is the dominant factor behind atherosclerosis. Also, the bifurcations are of special interest as both maximum and minimum values of WSS are present in the vicinity. In this study, CFD simulations are performed over a large coronary network with actual spatial geometry developed from CT scan dataset. Lower shear stresses are found at the outer side of more diverging daughter vessel posterior to bifurcations. Murray's exponent and bifurcation angle are found as the dominating factors of shear stress distribution while curvature and spatial geometry played a minor role. The results agree with the previously reported clinical data. This study compares the relative hemodynamic condition over a sufficiently large portion of the coronary tree with actual geometry and predicts the behavior of vulnerable bifurcations. The modelling technique can be used for simulating different diseased conditions and helping physicians to take better judgmental decisions with non-invasive measures.

Keywords
Atherosclerosis, Bifurcation, Coronary Artery, Wall shear stress and Wall Shear Stress Gradient.

1. Introduction
Atherosclerosis in coronary arteries leads to plaque growth, stenosis formation, and blockage of the blood flow supplying the heart tissue. If severe, this can cause heart attack and leads to death. Thus, coronary circulation has been a major research area over recent years.

The cardiovascular system is a network of blood vessels that supplies blood to all the parts of the body. As the cardiac muscles periodically contract and relax the heart acts as the pumping station. Then blood flows through the arteries out of the heart and comes back through the veins periodically. Coronary arteries supply blood to the heart itself. Coronary artery diseases are usually associated with a build-up of fatty deposits inside the arteries (atherosclerosis). When the flow of oxygen-rich blood to the heart muscle is blocked or reduced, it can lead to different moderate to severe conditions such as myocardial infarction.

2. Literature Review
Several studies have shown that hemodynamics plays a significant role in the growth of coronary artery plaques. An important hemodynamic parameter in determining the location and progress of the cardiovascular disease is wall shear stress (Asakura and Karino 1990; Stone et al. 2003; Samadi et al. 2011). This parameter can be obtained by analyzing the variations of the flow in the neighborhood of the wall. The local position of the plaques, where the minimum wall shear stress (WSS) occurs, can be interpreted by simulating the coronary vessels using computational fluid dynamics (CFD) (Stone et al. 2003). Critical shear stress is responsible for the development of arteriosclerosis in arterial bifurcation (Chaichana et al. 2014). In the bifurcation region, a unique flow pattern with local low velocity causes low shear stress. The association of wall shear stress gradient (WSSG) with plaque distribution (Estehardy et al. 2012) and the effect of the properties of viscoelastic walls (Abbas et al. 2018; Owen et al. 2020) on WSS are also simulated using CFD for simplified vessel models. Pulsatile flow simulates more realistic conditions (Abbas et al. 2018). Chatzizisis et al. (2008) pointed out that the magnitude of low WSS can be used to predict the severity of atherosclerotic lesions. Some recent studies have simulated the hemodynamics and plaque growth using shear stress

driven model as well as Newtonian and non-Newtonian models for steady state and transient conditions (Azrani 2020; Johnston et al 2004, Johnston et al. 2006). In addition, it is important to consider the actual spatial geometry of coronary vessels for better hemodynamic results (Rabbi et al. 2020).

Most of the studies have only focused on simple ideal geometry. Some studies considered actual geometry for only one bifurcation. The actual geometry over a substantial region, which include 20 bifurcations from both sides of the coronary tree, is considered in this study (figure. 1). The simulation allows us to directly compare the behavior of different bifurcations. The method can be used to study the effect of atherosclerosis in one or multiple sites in local and distant areas.

3. Methods

The left main coronary artery (LMCA) and right coronary artery (RCA) originate from near the base of ascending aorta. LMCA later divides into left anterior descending (LAD) and left coronary circumflex (LCX) arteries. All these gradually split into narrower branches in similar ways and enter the myocardium (Figure 1). In this study, 14 bifurcations from LMCA and 6 bifurcations from RCA are studied. The bifurcations are named after the mother vessel in this study.

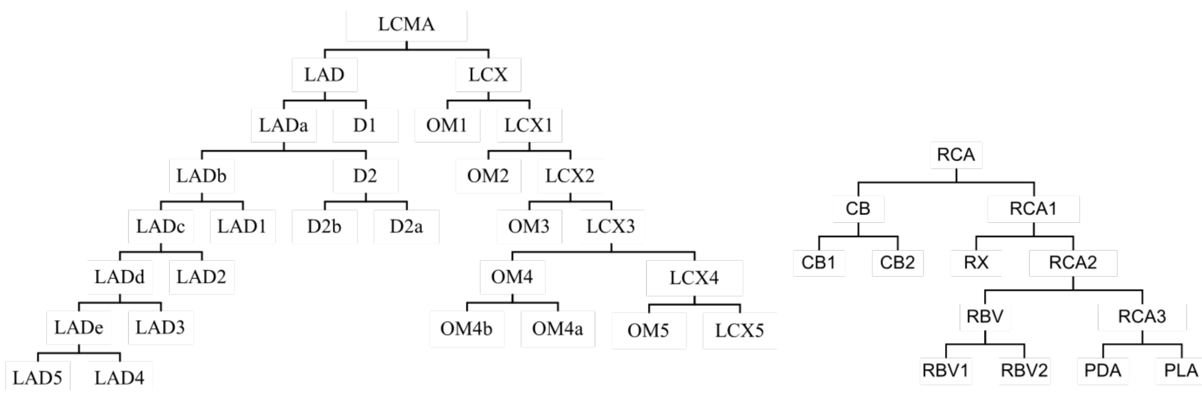

Figure 1. Coronary Artery network analyzed in this study. Left main coronary artery tree with 14 bifurcations (left) and Right coronary artery tree with 6 bifurcations (right).

Solanki et al. (2021) have shown that there is a good variation in the hemodynamic results from the analysis of the simplified model and actual irregular spatial geometry of coronary bifurcations. Simpler geometry results in a significant decrease in WSS and WSSG (Pinto and Campos 2016). The vessel models, as narrow as 0.5mm, constructed from the CT scan dataset are dependable for numerical study (Gijsen et al. 2014). In our study, CT scan dataset of a healthy human was used. The coronary artery tree is first segmented and then converted to an STL file using SimVascular (Updegrove et al. 2017), an open-source image segmentation software.

This STL file is then used to develop a 3D solid model of the coronary tree in ANSYS SpaceClaim (figure 2). Standard procedures were followed in the construction of geometry (Gijsen et al 2014). The mesh was generated using tetrahedral elements (4747881 nodes and 3238729 elements).

Angles were calculated at the point of significant perimeter change of the mother vessel with the normal to the plane across daughter vessels containing minimum the shear stress points. Pflederer et al. (2016) showed that there is a good variety of bifurcation angles between patients which indicates the importance of patient-specific analysis.

Murray's law based on the minimum energy hypothesis is widely used for analyzing simple arterial bifurcation that states the summation of cubes of daughter vessels and the cube of mother vessel should be equal (Murray 1926). However, different bifurcations in the coronary arterial tree have different power values. The average diameter of each vessel segment of both left and the right coronary artery was calculated from the developed geometry. For each bifurcation, the following equation was solved for m,

$$D_0^m = D_1^m + D_2^m$$

Here, D_0 is the mother vessel diameter; D_1 and D_2 are the daughter vessel diameters. The diameter values were verified by existing literature (Dodge et al. 1992).

Using a modified exponent value for Murray's law, the flow ratio of branch vessels was found. Thus, fractional flow output in each final segment was obtained. These values were used as the outlet boundary conditions.

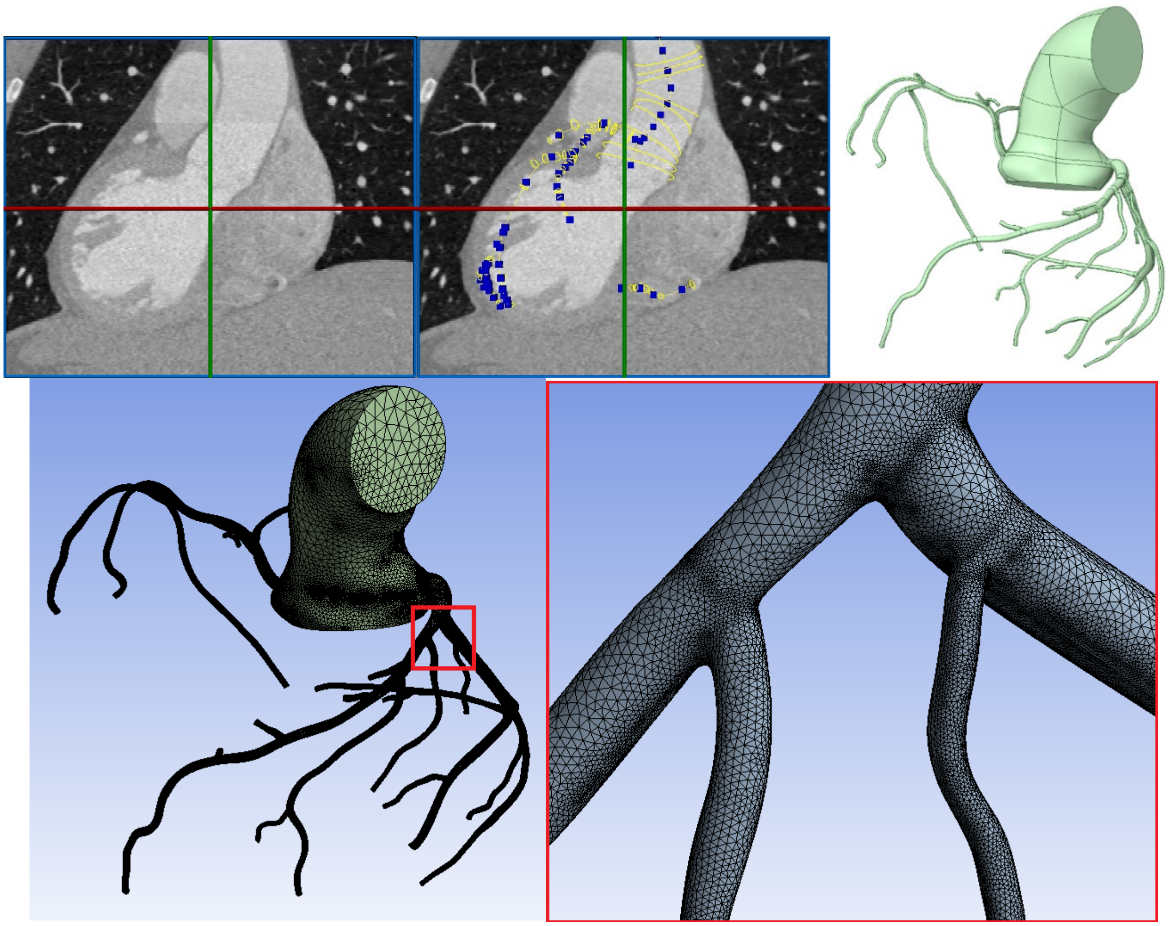

Figure 2. Steps of developing Solid Model from CT scan dataset (top) and creation of 3D mesh for FE analysis (bottom)

ANSYS Fluent was used to model blood flow through the coronary artery tree. As fluid, blood was defined with a density of 1060 kg/m3 and viscosity of 0.0035 Ns/m2. For viscous SST modeling, the surface roughness was taken as 1.04×10-6 m (Owen et al. 2020). For maximum and minimum pressures of the aorta as 120mmHg and 80mmHg respectively, the weighted mean average pressure is 93mmHg. Taking the cardiac output as 83mL/s with a heart rate of 75 beat per minute. As for a healthy person, the coronary output should be 4% of the total cardiac output. The ratio of left coronary and right coronary volume flow rate is taken as 7:3. Viscous SST k-omega model was adopted to account the turbulence (Figure 2).

4. Results and Discussion

From the post-processing, the minimum WSS, and its distance from the beginning of the daughter vessels along the centerline were obtained (Gijsen et al. 2014). The higher the value of WSSG, the more quickly the WSS would be normal. Lower WSSG at an area with low WSS value would increase the area of the potential risk zone. The low WSS distribution over the whole coronary tree is shown in three sections in Figure 3. Angulation, Murray's exponent, minimum WSS value with distance from bifurcation for all 20 nodes are listed in Table 1.

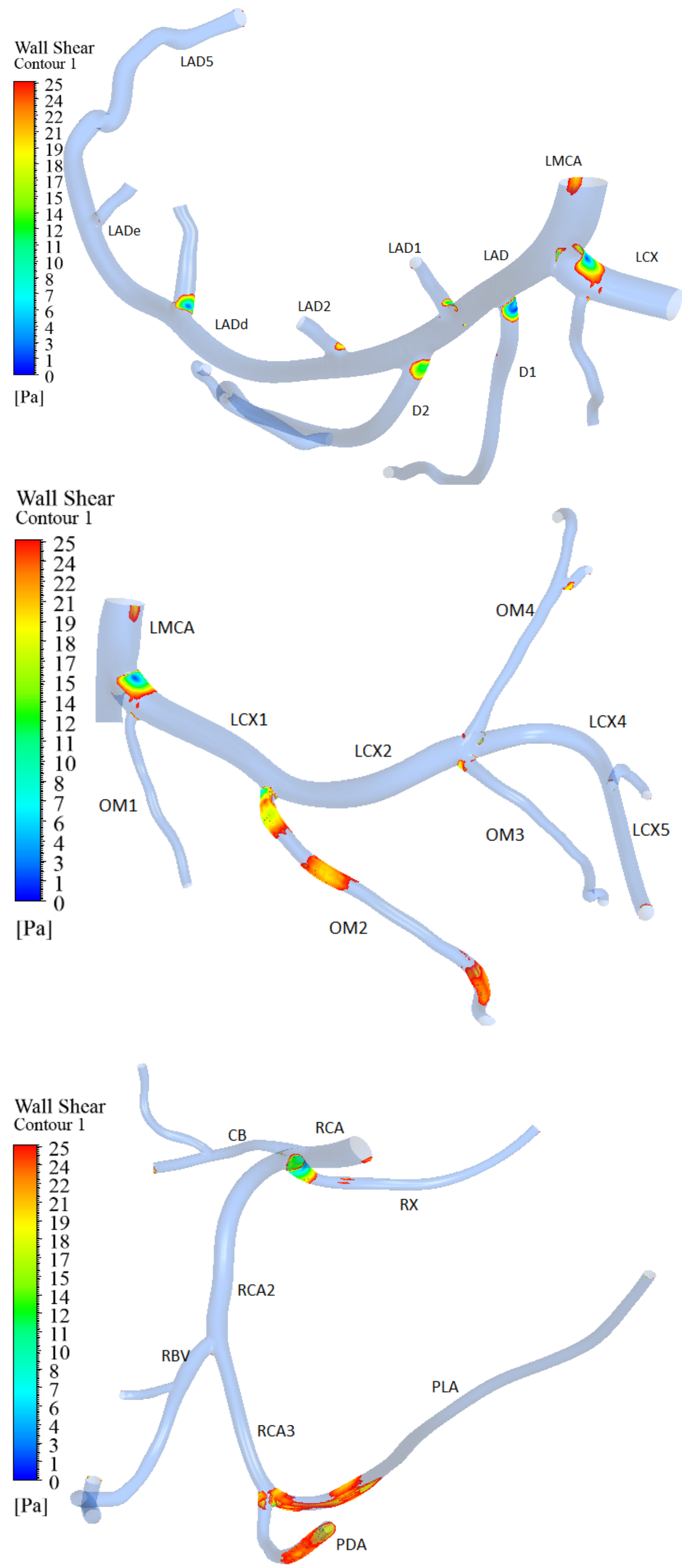

Figure 3. Low wall shear stress distribution over the coronary tree; LAD and its branches (top left), LCX and its branches (top right) and RCA and its branches (bottom)

Table 1. Data obtained from the model geometry and CFD simulation

Tree Section	Bifurcation Nodes	Murray's Exponent, m	Bifurcation Angle (degree)	Minimum WSS (Pa)	Location of minimum WSS from bifurcation (mm)
	LMCA	2.74	76	3.1	3.54
LAD	LAD	1.39	56	4.1	3.33
	LADa	3.28	58	11.3	2.01
	LADb	3.26	50	11.5	2.04
	D2	3.22	55	41.4	4.85
	LADc	3.01	42	21.1	2.7
	LADd	3.4	64	5.3	2.38
	LADe	2.44	70	36.1	1.74
LCX	LCX	1.21	71	3.2	0.41
	LCX1	2.18	80	21.3	2.73
	LCX2	1.9	45	17.6	2.55
	LCX3	2.55	56	18.9	2.6
	OM4	2.65	41	18.6	2.8
	LCX4	2.67	82	35.5	2.3
RCA	RCA	1.38	35	26.13	3.292
	CB	2.51	55	35	1.86
	RCA1	1.77	80	4.8	0.256
	RCA2	3.19	55	27	2.7
	RBV	2.9	48	31.7	1.8
	RCA3	3.54	72	18.1	0.14

4.1 Validation

According to Murray's law, the exponent value should be 3 for the least frictional resistance. However, the value for the first bifurcation of three major parts LAD, LCX and RCA are the lowest among all indicating that larger arteries tend to deviate the most from this law (Kassab and Fung 1995; Beier et al. 2015). These lower values indicate that there is a larger area available next after the bifurcation. Consequently, the WSS magnitudes are lower at the inner side of the posterior region of LAD, LCX and RCA1 bifurcation. Previous studies showed that areas with WSS less than 1.5 Pa can be considered as vulnerable for plaque formation (Peiffer et al. 2013). Higher exponent values are present at lower branches of LAD and RCA2, RCA3. All of those has high minimum WSS values.

Results of simulation showed good agreement with experimental studies regarding the effect of mother vessel diameter and curvature (Beier et al. 2016). Larger diameter vessels tend to be lower in minimum WSS but higher in WSSG with more flow separation tendency in larger bifurcation angle. It points out the significance of earlier bifurcations over the later ones. Comparing LADa and LADb with D2, all of them have almost same Murray's exponent and angulation with similar spatial geometry. LADa has higher mother vessel diameter and larger bifurcation angle than LADb, thus slightly higher minimum WSS. But D2 has a larger WSS and lower WSSG at most distant location.

Another dominating factor behind shear stress distribution is the bifurcation angle of both the daughter branches relative to the mother vessel (Sun and Cao 2011; Chaichana et al. 2011; Guiying et al. 2015). Entrance of coronary both left and right coronary arteries both have high angulation. But due to higher velocity of flow the WSS was not much low. High angulation of RX with RCA1 together with low Murray's exponent value caused a low WSS area with low local WSSG. However, WSS was higher at LCX4 despite higher angulation value as the exponent value was moderate. This clarifies that Murrays's exponent is a better parameter in describing the minimum WSS value at bifurcations. The effect of low value of bifurcation angle was prominent at RCA where the WSS value was significantly higher though the value of Murray's exponent value was low. On the other hand, the effect of higher bifurcation angle was much less. At node LADd and RCA3 both the daughter vessels were noticeably diverging with high angle to mother vessel. This lowered the value of minimum WSS at that bifurcation. This paired with high value of Murray's exponent caused the location of minimum WSS unusually close to bifurcation with exceptionally low WSSG at RCA3.

The WSSG primarily depends on bifurcation angle. Wider bifurcation angle promotes atherosclerosis with lower WSSG causing minimum WSS over larger wall area as confirmed with clinical results (Chaichana et al.2014; Soulis et al. 2014). Lower bifurcation angle at LAD, D2 and RCA node was responsible for the comparatively distant location of minimum WSS. At node LCX1 and LCX4 the WSSG was fairly low, causing a larger wall area with low WSS. Also, LCX and RCA1 had the minimum WSS extremely close to the origin of more diverging daughter vessel due to high angulation with low value of Murray's exponent.

Spatial structure of bifurcation plays a noteworthy role in some cases. The non-planarity swerves the flow from the outer to inner side to form separation to lowers both the minimum WSS and its gradient at the outer side of the bifurcated branch and to raise the maximum WSS and it gradient at the inner side making the inner side of more diverging non-planer daughter vessel (Johnston et al. 2004; Arjmandi et al. 2011). WSSG was low at nodes LCX1, RCA, RCA3 due to spatial structure as discussed earlier.

For a twisted single vessel, higher curvature reduces the magnitude of minimum WSS as well the WSSG (Kassab and Fung 1995; Guiying et al. 2015). In our study, the effect of curvature was prominent in the distal portion of LCX5, OM2 and LCX branches. Note that, in these areas the minimum values of WSS were higher and WSSG values were lower than average WSS and WSSG value of all bifurcations.

The most vulnerable areas found in this study are LMCA and LAD bifurcation that agrees with clinical record (Chang et al. 2018). Also, WSSG at LAD bifurcation was less than in LCX. RCA was found to be comparatively in lower risk of atherosclerosis.

4.2 Proposed Improvements

This study had several limitations .Blood was assumed to have a Newtonian viscosity model. Johnston showed that the magnitude of wall shear stress changes especially at low velocity (Rabbi et al. 2020) in non-Newtonian modelling. Newtonian model underestimates the WSS. However, the pattern of wall shear stress remains the same irrespective of curvature and vessel diameter. Johnston et al. (2006) concluded that, Newtonian model is a quite reasonable approximation for transient conditions as well despite the fact that regions of slow flow exist at various points of the cardiac cycle.

The simulation was based on steady state condition and averaged flow rate and pressure was considered. Oscillating WSS would be found if periodic boundary conditions were set (Soulis et al. 2014). The effect of heart rate and fractional flow reserve in critical hemodynamic conditions would be studied in that case. However, in terms of determining the wall shear stress distribution over the coronary tree, steady state is a reasonable approximation (Arjmandi and Razavi 2012). Analysis of the particle paths suggests that within the flow there are differences which have insignificant effect on WSS distribution. However, to accurately analyze the plaque formation and growth states transient condition is necessary.

Due to the location of the coronary arteries, being embedded into the myocardium, the contraction of the heart influences coronary hemodynamics (Zinemanas et al. 1993). This results in the unique feature that blood is supplied during diastole, while coronary epicardial pressure is high in systole. The myocardial contractility and coronary perfusion pressure together regulate coronary flow independent of left ventricular loading conditions (Kim et al. 2010). Thus, setting the outlet boundary conditions with appropriate pressure would influence the flow pattern and fractional flow reserve and it is important for simulating atherosclerotic conditions also.

The vessel walls were considered rigid but in realistic physiological condition they show varying elasticity during cardiac cycle. The elastic property is important to calculate the fractional flow reserve. The time varying elastance concept was first applied to the coronary circulation by Krams, where flow is impeded due to a varying stiffness of the cardiac wall (Krams et al. 1989).

Surface roughness was considered constant. Previous studies showed that cconsidering variation of surface roughness results into wider range of WSS but the average value and pattern remains almost same (Owen et al. 2020).

Due to complex geometry and imaging accuracy limitations considering more branches with perfect geometry was computationally expensive (Gijsen et al. 2013). Also, studying more samples would generate more reliable conclusion.

The model can be used for analysis of probable risk-location in stenosis conditions at different level. The change of parameters in different diseased conditions can be analyzed. Analysis in atherosclerotic condition will help understanding the shear stress distribution. The difference can be significant, as atherosclerotic human coronary arteries bear 44% more stress (Karimi et al. 2013). Also, comparing normal and hypertension condition with oscillatory WSS is important (Bahrami and Norouzi 2018). Transient analysis with viscoelastic wall properties should be used also to simulate more realistic healthy and stenosed condition.

5. Conclusion

The geometry constructed was verified with clinical data. The effect of different parameters of bifurcation on WSS and WSSG distribution were studied and a comparative analysis of different bifurcations over both the left and right coronary tree were conducted. LMCA and LAD were identified as the most potential risk zones for atherosclerosis. The results generated from the simulation were in good agreement with previous studies. Although actual geometry was considered, several limitations were present in material properties and boundary conditions. Therefore, the results of this analysis would underestimate the true magnitude of error compared with real-world clinical use.

Data Accessibility

The image-based coronary artery model used in this study is available athttp://simvascular.github.io/

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