Flow simulation in coronary artery models: An investigation of the effect of variable angulations at the left coronary artery

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Abstract

This study was designed to investigate the hemodynamics in the left coronary artery with the aim of identifying the relationship between angulations of left coronary bifurcation and development of atherosclerosis. Six 3D left coronary models were simulated for computational fluid dynamic analysis. The left coronary model was composed of left main stem, left anterior descending and left circumflex branches. The angulations at the left bifurcation were simulated with angles ranging from 90°, 75°, 60°, 45°, 30° to 15°. The computational fluid dynamic was used for analysis of flow velocity, wall pressure and wall shear stress. Our results showed that apparent low shear stress and high wall pressure was noticed at the left coronary bifurcation regions with wide angled models. Flow pattern was also changed with angled becoming wide in the simulated models. Our analysis shows direction relationship between coronary angulation and development of atherosclerosis. Future studies are required to perform computational fluid dynamic analysis in coronary models from patients' data with different degree of coronary stenosis.

Key words
Coronary artery disease, Angulation, Blood flow, Flow velocity, Plaque, Simulation.

1. Introduction

The Coronary artery disease (CAD) is the leading cause of death in western countries. Early detection and diagnosis of CAD is particularly important for reduction of the mortality and subsequent complications [1]. The most common cause of CAD is atherosclerosis which is caused by the presence of plaques on the artery wall, resulting in the lumen stenosis. Plaques have been particularly involved in blood clot and blocks blood stream to myocardium. This occurs when the coronary plaques suddenly rupture; if a clot cannot be treated in time, then the heart muscle will be impaired due to ischemic changes, leading to ischemia or myocardial infarction or necrosis [1].

Atherosclerosis is primary cause of CAD and the presence of plaques is widely distributed along the coronary arteries. However, the situation of plaques is not equally distributed within the coronary artery compared with the other risk factors. This is due to the fact that there are other local conditions that induce the plaques formation and progression [2, 3]. Studies have shown that plaques tend to form in areas of low shear stress or regions of turbulent flow. According to the coronary anatomy, the plaques most frequently occur in the left coronary bifurcation [4].

Computational fluid dynamic (CFD) allows for efficient and accurate computations of hemodynamic features of both normal and abnormal situations in the cardiovascular system, in vivo simulation of coronary artery flow changes [5]. CFD is different from medical imaging visualisation as medical imaging techniques such as coronary angiography or computed tomography angiography provide anatomic changes of the coronary artery wall due to presence of plaques, thus assessing the degree of lumen stenosis. In contrast, CFD analysis enables hemodynamic changes of the coronary artery, even before the plaques are actually formed in the artery wall or occlude the vessels. Therefore, to some extent, CFD allows an early detection of coronary artery disease and improves understanding the progression of plaques which are considered paramount importance to clinical treatment. This study aims to investigate hemodynamic characteristics in simulated coronary models with variable angulations. It is expected that different angles in the left coronary bifurcation will provide variable effect on flow analysis to the coronary artery, thus the proposed study will serve the purpose of identifying patients with potential risk of developing coronary artery disease

2. Materials and Methods

2.1 Information about Left Coronary Artery

The computed tomographic (CT) data of left coronary artery anatomy was used in this study to generate the mathematical models. The left coronary artery (LCA) branches consist of the left main stem (LMS), left anterior descending (LAD) and left circumflex (LCx), as shown in Figure 1. The LCA has an angulation between the LAD and LCx, showing the perpendicular angle (Figure 1). Thus changing the angles to various degrees will affect the subsequent hemodynamic flow patterns. Simulation of different angles between these two branches was performed in this study. Figure 2 shows the variable angles that were simulated in left coronary artery models.

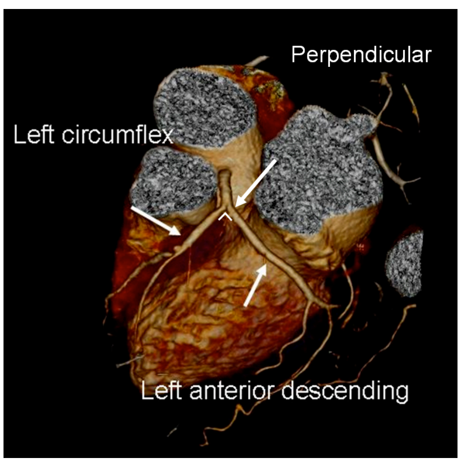

Figure 1. LCA branches on 3D CT visualisation image

2.2 Measurement of CT volumetric data

The DICOM (digital imaging and communication in medicine) images of CT scan from a sample patient data were transferred to a computer workstation equipped with Analyze version 7.0 (AnalyzeDirect, Inc., Lexana, KS, USA) for creation of three-dimensional left coronary artery (LCA) models. The volume model was segmented by using the semi-automatic method with a CT number thresholding technique by Sun et al [6, 7] and manual editing was used in some slices to delete the bony structures and soft tissues. The three-dimensional volumetric of LCA model was used to measure the dimensions of the left coronary artery and its branches, as shown in Table 1.

Table 1
The measurements of a normal LCA model

Diameter of LCA (mm)		Distance between bifurcation to distal/proximal (mm)	
LMS	3.0	Proximal LMS	35
LAD	2.0	Distal LAD	25
LCx	1.5	Distal LCx	20

LMS-left main stem

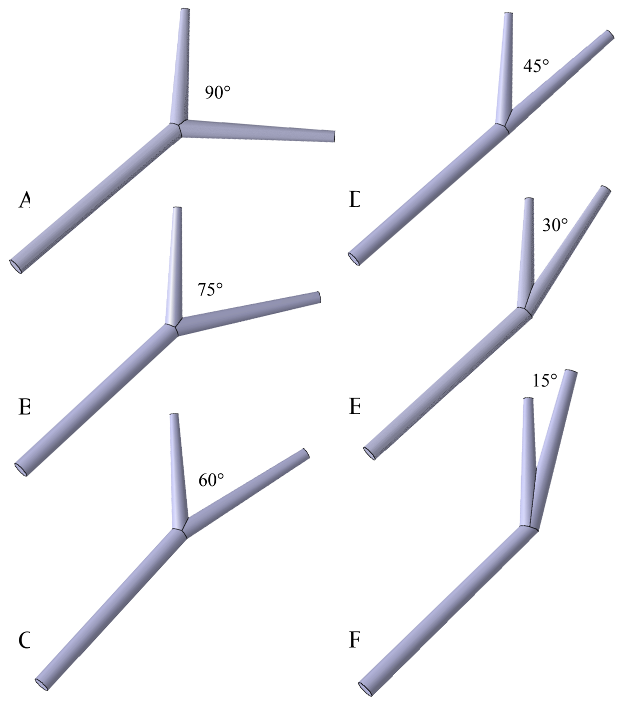

Figure 2. Diagrams showing variable angles of LCA, 90° (A), 75° (B), 60° (C), 45° (D), 30° (E) and 15° (F)

2.3 Generation of left coronary models

The surface model was generated based on the anatomic details of LCA in Section 2.1 and 2.2, referencing the LCA anatomy in Figure 1 and the parameters in Table 1 by using CATIA V5 R18 (Dassault Systemes, Inc., Suresnes, France). The surface model was then converted into the solid model, as shown in Figure 3. According to the 90° model, other five models were generated by varying the degree of the 90° model between LCX and LAD, as shown in Figure 2 and all of models were saved as STP type to generate mesh models.

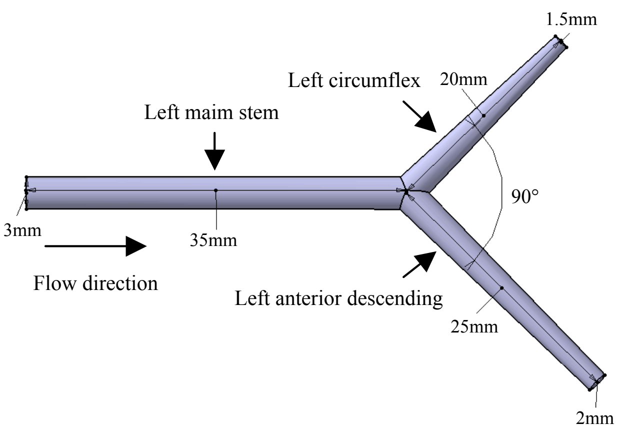

Figure 3. The 90° model based on the anatomic details

2.4 CFD simulation in left coronary artery

2.4.1 Generation of Mesh Models

The six three-dimensional computer aided design (CADD) models of left coronary artery were used for generation of mesh models for performance of CFD simulation. In addition, the CADD models were produced using the tetra-meshing and three prism layers method, which is suitable for the actual computation. Details of meshing elements are shown in Table 2. The mesh models were generated with the ANSYS ICEM CFD version 12 (ANSYS, Inc., Canonsburg, PA, USA) [8, 9, 10]. Finally, the six mesh models were saved as CFX5 type to be use for CFD computation.

Table 2
The details of meshing elements

The 6 LCA models		
Angled models	Tetra-mesh	3 Prism layers
90°	354827	97677
75°	357502	99153
60°	366925	103941
45°	364552	104106
30°	358038	98988
15°	330427	92517

2.4.2 Application of physiological parameters

In order to ensure that our analysis reflects the realistic simulation of in vivo conditions, application of the physiological parameters should be considered for the three-dimensional numerical analysis. The transient simulation was performed, and accurate hemodynamic rheological and material properties were used in this study, as referred to in previous studies [11].

According to Bertolotti et al [12], we have reconstructed the flow rate graph at LCA by developing algorithm using Matlab (MathWorks, Inc. Natick, MA, USA) for creation of Fourier series graph as shown in Figure 4. The boundary conditions were determined by pulsatile velocity at left main stem (inlet) and opening pressure with left anterior descending (outlet) and left circumflex (outlet). Accurate physiological parameters were applied with a blood density of 1060 kg/m3, blood viscosity of 0.0027 Pa s. The blood flow and wall were assumed to be Laminar flow and no-slip conditions. Blood was assumed to be a Newtonian [13, 14] and income-pressible fluid [15].

2.4.3 Performance of CFD computation

To ensure that our results are valid, we performed the simulation using ANSYS CFX version 12 (ANSYS, Inc.) which was equipped with the Microsoft Windows XP 32-bit, 4 MB RAM and running on the dual core 2.4 GHz CPU. A left coronary artery in normal flow situation is governed by the Navier-Stokes equations. The CFD solution was fully converged by 32 time steps, each 0.05 step within 1.6 second of pulsatile velocity flow. The computed time consumption for each LCA model was approximately one and half hour. This computation was performed similar to an in vivo condition by referring to previous experiments [8, 9, 10]. The flow pattern, flow velocity, wall pressure, and wall shear stress were calculated and measured in this study by using ANSY CFD-Post version 12 (ANSYS, Inc.).

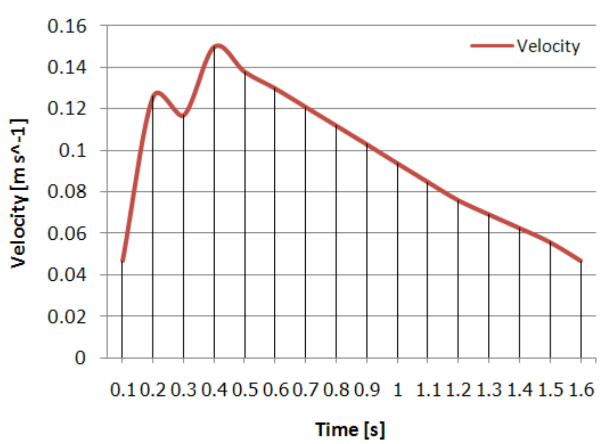

Figure 4. Pulsatile velocity at the left coronary artery

3. Results

CFD simulation was successfully performed in six coronary models under realistic physiological condition during systolic and diastolic phases. Our results showed direct relationship between CFD analysis and the simulated angulations in these models. Peak velocity reached the highest during systolic at 0.4 sec (Figure 4). A laminar flow was noticed at small angled models, and it became turbulent at wide angled models, as shown in Figure 5.

The wall shear stress (WSS) was found to decrease in wide angled models when compared to narrowed models. This is especially obvious in the systolic phase as shown in Figure 6. Low WSS occurred at the bifurcation location where the left coronary main stem divides into LAD and LCx. The low WSS extended from the coronary bifurcation to the proximal segment of LAD and LCx, as shown in Figure 6.

The wall pressure also changes with the variation of angulations in different models. Wall pressure decreased from wide angled models to narrow angled models, as shown in Figure 7. This is especially apparent in the model with 15° angulation as the results showed that the wall pressure reduced significantly when the blood flows through from the left main stem to the LAD and LCx braches.

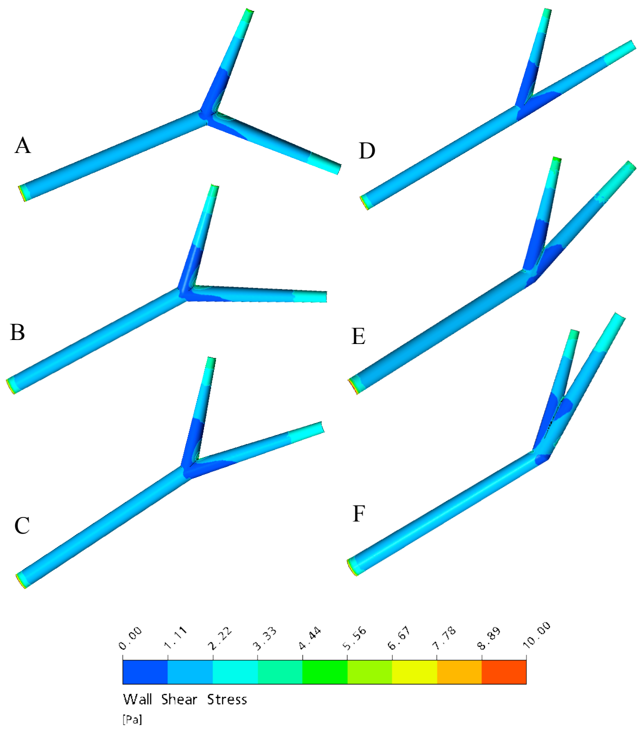

Figure 6. Wall shear stress showing variable angles: 90° (A), 75° (B), 60° (C), 45° (D), 30° (E) and 15° (F)

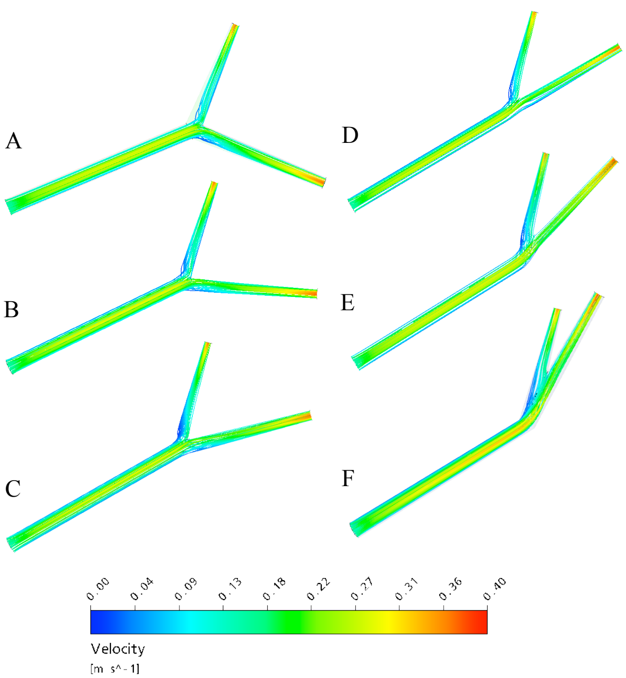

Figure 5. Velocity showing variable angles of LCA, A-F: measured at systolic peak 0.4 sec

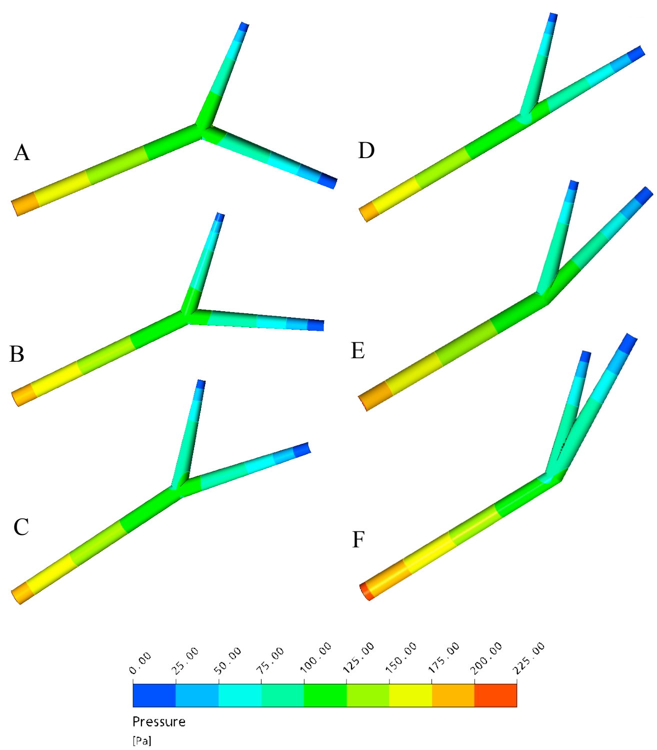

Figure 7. Wall pressure showing variable, 90° (A), 75° (B), 60° (C), 45° (D), 30° (E) and 15° (F)

4. Discussion and Conclusion

Our preliminary study based on coronary models with different angulations shows direct relationship between angulations and change of wall shear stress and flow pattern. This is valuable for improving understanding the development of atherosclerosis of coronary artery disease.

Atherosclerosis is a chronic, inflammatory and fibroproliferative disease mainly involving large- and medium-sized arteries [16, 17]. It has been reported that atherosclerotic lesions form at specific regions of the arterial tree, such as in the vicinity of branch points, the outer wall of bifurcation, and the inner wall of curvatures, where disturbed flow occurs [18]. Local factors such as hemodynamic forces play a major role in the regional localization of atherosclerosis [19]. These local hemodynamic forces include flow-generated shear stress and wall pressure with wall shear stress playing the most fundamental role in atherosclerosis, This is confirmed in our study as low wall shear stress occurred at wide angled models, indicating the tendency to form atherosclerosis.

Current methodologies such as coronary CT or invasive coronary angiography cannot provide adequate information about the microenvironment of the coronary arteries, especially the local hemodynamic changes. In contrast, CFD analysis offers opportunities to study the effect of variable situations such as different angles at left bifurcation and subsequent flow changes. Therefore, we believe our preliminary study provides insight into the development of atherosclerosis of coronary artery disease.

The main limitation of this study is lack of realistic models. Thus, future studies are required to study the local hemodynamic environment responsible for individual plaque behaviour and natural history of coronary artery disease based on patient-specific models.

In conclusion, our results show that there is a strong relationship between the wide angulation in the left coronary bifurcation and development of atherosclerosis. Further studies based on realistic models are needed to verify our initial results.

5. Acknowledgement

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