The influence of multi-stenosis in the left coronary artery subjected to the variable blood flow rate

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Abstract

Purpose – Coronary artery disease (CAD) is reported as one of the most common sources of death all over the world. The presence of stenosis (plaque) in the coronary arteries results in the restriction of blood supply, leading to myocardial infarction. The current study investigates the influence of multi stenosis on hemodynamic properties in a patient-specific left coronary artery.

Design/methodology/approach – A three-dimensional model of the patient-specific left coronary artery was reconstructed based on computed tomography (CT) scan images using MIMICS-20 software. The diseased model of the left coronary artery was investigated, having the narrowing of 90% and 70% of area stenosis (AS) at the left anterior descending (LAD) and left circumflex (LCX), respectively.

Findings – The results indicate that the upstream region of stenosis experiences very high pressure for 90% AS during the systolic period of the cardiac cycle. The pressure drops maximum as the flow travels into the stenotic zone, and the high flow velocities were observed across the 90% AS. The higher wall shear stresses occur at the stenosis region, and it increases with the increase in the flow rate. It is found that the maximum wall shear stress across 90% AS is at the highest risk for rupture. A recirculation region immediately after the stenosis results in the further development of stenosis.

Originality/value – The current study provides evidence that there is a strong effect of multi-stenosis on the blood flow in the left coronary artery.

Keywords WSS, Atherosclerosis, Stenosis, Hemodynamic

Paper type Research paper

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1. Introduction

Atherosclerosis is a typical CAD disease, which is a leading source of death in advanced countries. Extensive research work has been carried out to predict the locations of plaque progression in recent years. The continuous changes in the hemodynamic and arterial damage result in the progression of stenosis on the inner walls of the coronary artery. An extensive study of literature shows that the plaques are regularly occurring at the bifurcation and the curvature of vessels (Zarins *et al.*, 1983; Asakura and Karino, 1990; Fuster, 1994; Chaichana *et al.*, 2011; Sun and Cao, 2011). The WSS and velocity (local hemodynamic constraints) are alleged to play a decisive role in developing and initiating atherosclerosis diseases (Berger and Jou, 2000; Stone *et al.*, 2003). The direct assessment of WSS and disturbed flow cannot be measured across stenosed coronary arteries. However, the CFD (computational fluid dynamic) simulation provides an alternate way to assess the wall shear stresses and early diagnosis of initiation and progression of stenosis (Shanmugavelayudam *et al.*, 2010; Chaichana *et al.*, 2012). In current centuries, the stenotic flow in arteries using the CFD models and numerical methods has been developed (Fazli *et al.*, 2011; Razavi *et al.*, 2011). The impact of the bifurcation angle, various curvature angles and stenosis shape have been studied by various researchers (Yao *et al.*, 2000; Chen and Lu, 2006; Lorenzini and Casalena 2008; Kamangar *et al.*, 2017a; Ahamad *et al.*, 2018). The behavior of the blood flow was modeled as the laminar flow according to certain research (Boutsianis *et al.*, 2004; Wu *et al.*, 2015), whereas few studies considered the non-Newtonian blood flow in an idealized artery with solo stenosis (Nosovitsky *et al.*, 1997; Varghese and Frankel 2003; Li *et al.*, 2007; Moreno and Bhaganagar, 2013). The flow behavior in the immediate vicinity of idealized stenosed models was experimentally determined in numerous studies previously (Carew and Pedley, 1997; Beratlis *et al.*, 2005; Trip *et al.*, 2012). The patient-specific LCA model was created with the help of a CT scan image to inspect the consequence of stenosis on hemodynamics parameters (Chaichana *et al.*, 2012; Gholipour *et al.*, 2020). The computed velocity and pressure gradient were compared with and without stenosis for patient-specific models. They discovered that at the stenosis, there is a high-pressure gradient and low velocity at the post-stenosis. Several types of plaque arrangement in the patient LCA on hemodynamic were investigated in previously published studies (Chaichana *et al.*, 2013). They revealed a sort of plaque configuration that involves the plaque position in all three left coronary artery branches that had the largest velocity and pressure gradient. The impact of different degrees of stenosis severity on the hemodynamic variables such as pressure, velocity, and the WSS was investigated in real patient-specific LCA (Kamangar *et al.*, 2017c). The computational simulation appears to be a cheaper and more effective method to predict the locations of atherosclerosis diseases. Therefore, in order to properly diagnose and treat the atherosclerosis disease in a multi stenosed coronary artery, a comprehensive understanding of the hemodynamic parameters is essential. In the existing study, an attempt is made to investigate the influence of multi stenosis severity at LAD and LCX branches on hemodynamic variables such as WSS, pressure, and velocity using CFD. It has been a common observation for doctors that the stenosis may develop at multiple places across the flow disturbed region. The existence of multiple stenoses endangers the life of the patient, and it could lead to more severity than single stenosis. Hence, the effect of stenosis located at multiple positions on hemodynamic parameters was investigated by using computational fluid dynamics.

2. Methodology

2.1 3-D reconstruction of the left coronary artery

The 3 dimensional realistic LCA model was recreated by using computed tomographic images of an LCA disease patient. The following practice was implemented in order to

acquire the CT images of the patient by using a 128-multislice scanner. The axial images with 0.6 thickness were obtained by keeping the 0.75 mm increment. The detailed segmentation process of the LCA model is described in references (Kamangar *et al.*, 2017b, c). In order to explore the impact on the hemodynamic variables, 90% AS and 70% AS were introduced at the LAD and LCX, respectively. The left coronary artery model was imported into the 3-Matic software to create the tetrahedral mesh consisting of 317,690, 39,884 and 458,027 elements. The grid independent study was carried out to find the above-mentioned 39,884 number of elements are right choice of mesh size for this particular study. The mesh independent study was performed by using various numbers of elements, as given in Table 1 and Figure 1.

2.2 Governing equation for blood flow

The flow of blood was presumed as incompressible, pulsatile and non-Newtonian. The incompressible Navier–Stokes equations for the blood flow model are as given below.

$$\rho\left(\frac{\partial v}{\partial t} + v \cdot \nabla v\right) = \nabla \cdot \tau - \nabla P \tag{1}$$

The equation for continuity is given as

$$\nabla \cdot v = 0 \tag{2}$$

where P = pressure and τ = stress tensor v = vector of 3D velocity, t = time and ρ = blood density. The Carreau model was considered in this study to predict the blood viscosity.

LCA model	Number of elements	Max velocity m/s	Time (Hr:min:sec)
Grid 1	317,690	0.53	9:38:35
Grid 2	398,884	0.60	11:31:58
Grid 3	458,027	0.56	13:20:03

Table 1.
Mesh independent results

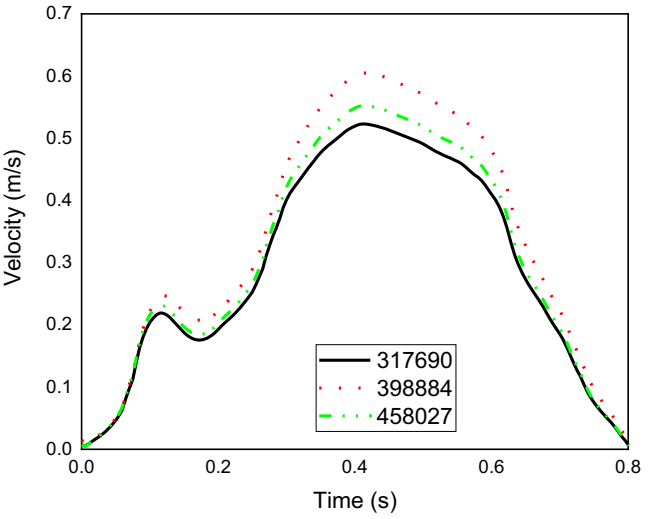

Figure 1.
Mesh dependency during the peak systole

$$\mu = \mu_{\infty} + (\mu_0 - \mu_{\infty})\left[1 + (\lambda\gamma)^2\right]^{(n-1)/2} \quad (3)$$

The blood density (ρ) is = 1,050 kg/m^3 (Peelukhana *et al.*, 2009; Govindaraju *et al.*, 2014; Kamangar *et al.*, 2014; Basri *et al.*, 2020; Johny *et al.*, 2019). The detailed boundary condition prescribed in (Kamangar *et al.*, 2017a, b, c) was used in the current study. The pulsatile coronary flow was applied at the inlet as shown in Figure 2. The CFX was used to carry out the blood flow simulation. The flow rate selected in the current study was to examine the multiple stenosis effect on hemodynamic parameters with variable blood flow rate (50, 100, 125 and 175 ml/min). The flow of blood in the stenosed LCA is a turbulent flow phenomenon. The SST model was considered in the current to account for turbulent velocity. For velocity residuals, the convergence criteria were set as 10^{-4}. Hemodynamic parameters were computed and visualized using ANSYS CFD-postprocessor.

3. Results

The existing study aims to explore the presence of more than one stenosis in the LCA with various degrees of stenosis placed at various locations across the bifurcation by varying the flow rate. The impact of these stenoses with the flow rate on the hemodynamic variables, such as velocity, wall pressure and WSS for the systole period (1.2 s) during the cardiac pulse, was investigated.

Figure 3 shows the wall pressure distribution in multi-stenosis of the left coronary artery located at LAD (90% AS) and LCX (70% AS) for various flow rates at the systole period of the cardiac cycle. As expected, the pressure drops to a greater extent at LAD than at the LCX. Thus, the blood encounters relatively lesser resistance in LAD than LCX in the current model. It is found that the wall pressure drops across the 90% AS at the LAD branch are 7072, 8053, 8473 and 8836 Pa for the flow rate of 50, 100, 125 and 175 ml/min, respectively. Whereas the drop-in pressure across the 70% AS at the LCX branch is 7310, 8504, 9029 and 9577 Pa for the flow rate of 50, 100, 125 and 175 ml/min, respectively. It is observed that the pressure drops higher for the 90% AS at the LAD branch as compared to the 70% AS at the LCX branch.

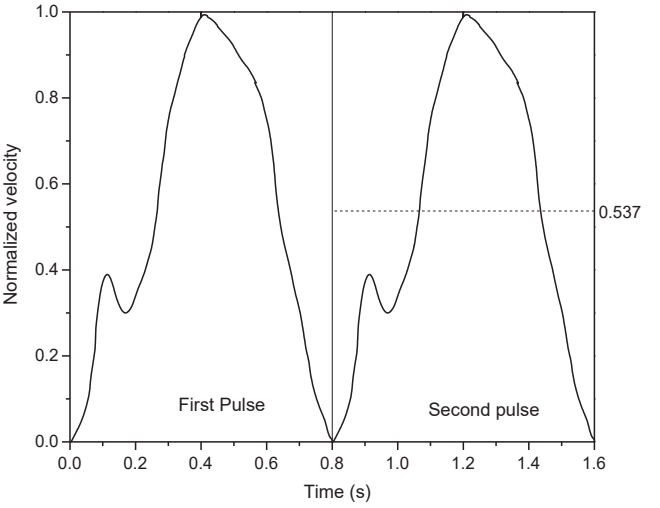

Figure 2.
The pulsatile coronary flow was applied at inlet

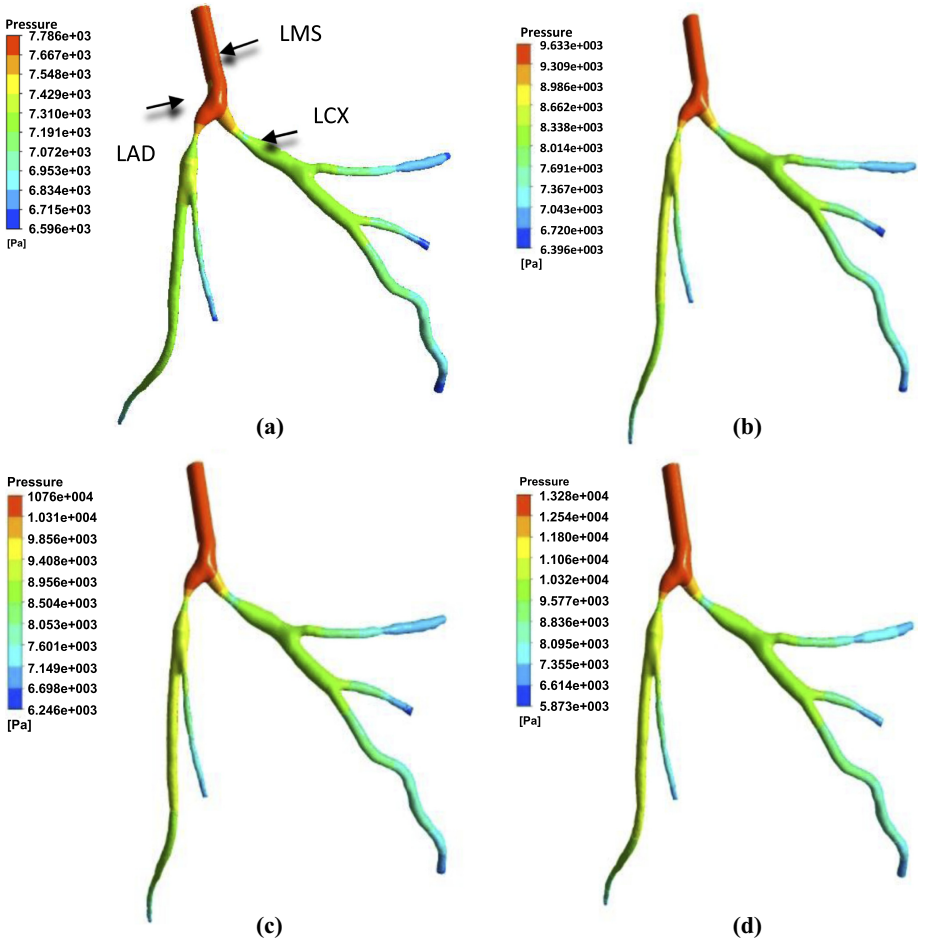

Figure 3.
Wall pressure field on the left coronary artery of 90% and 70% AS located were at LAD and LCX, respectively, for the systole period of the cardiac cycle at various flow rates a) 50 ml/min b) 100 ml/min c) 125 ml/min d) 175 ml/min

The velocity distribution in the multi-stenosed left coronary artery for the various flow rates is depicted in Figure 4. It can be clearly seen from Figure 4 that the velocity increased across the stenosis, the 70% and 90% AS. The velocity was observed in the range from 0.22 to 0.44 m/s, 0.67–0.89 m/s, 1.33–1.56 m/s and 1.78–2 m/s at the stenosis for 50, 100, 125 and 175 ml/min, respectively. It is found that the velocity across the higher degree stenosis increases with the increase in the blood flow rate from 125 to 175 ml/min. It is also observed that a recirculation zone immediate to the stenosis and across the bifurcation was noticed, which results in further progression of the stenosis.

The WSS distribution in the multi-stenosed left coronary artery for the various flow rates is shown in Figure 5. The maximum WSS is found across the stenosis present at the LAD and LCX branches. The WSS across the 70% AS at the branch LCX is in the range from 5.56 to 11.11 Pa, 16.67–22.22 Pa, 44.4–50 Pa and 44.4–50 Pa for 50, 100, 125 and 175 ml/min, respectively. The increase in the area of WSS across stenosis was found as the flow of blood increased from 50 to 175 ml/min. The maximum WSS area was noted for 90% AS as compared to the 70% AS. It is obvious that the LAD has a higher risk as

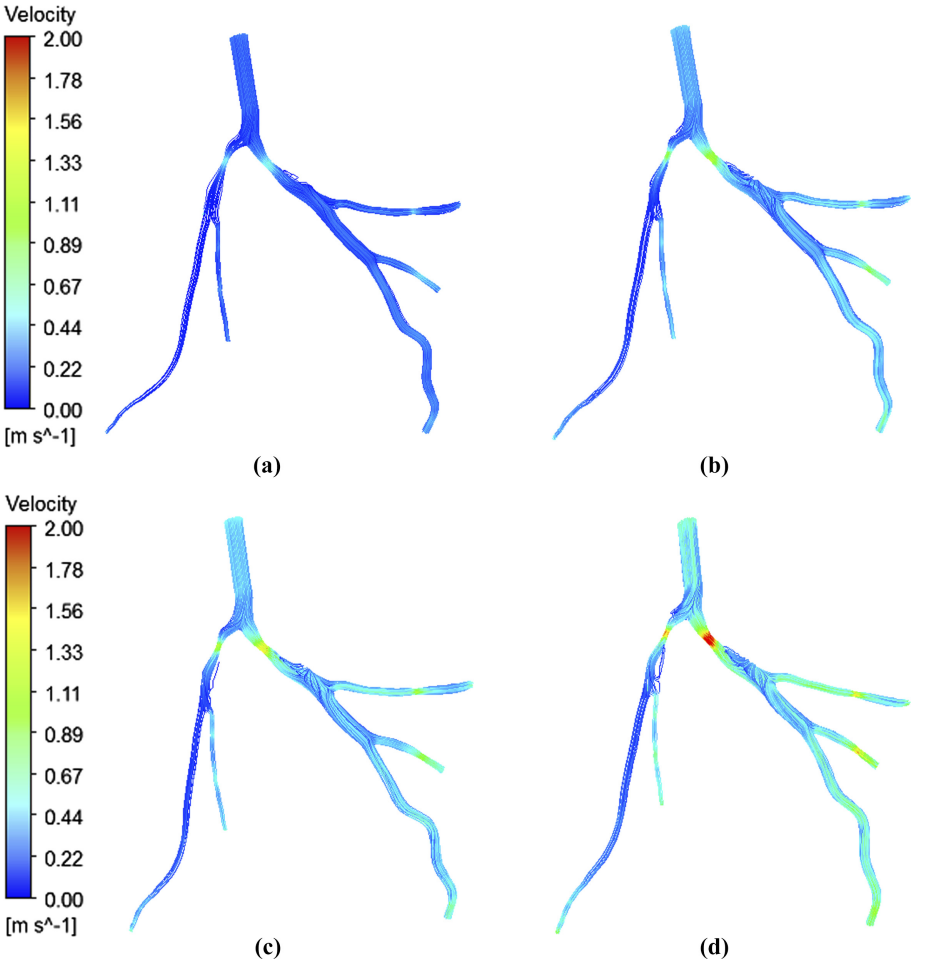

Figure 4.
Velocity distribution in the left coronary artery of 90% and 70% AS were located at LAD and LCX, respectively 1.2 s during the cardiac cycle for various flow rates a) 50 ml/min b) 100 ml/min c) 125 ml/min d) 175 ml/min

compared to LCX. However, the low WSS in the non-stenotic region of the artery was found. The higher WSS may lead to rupture of the artery. However, the low WSS areas immediate to the stenosis are prone to stenosis development (Dobrin *et al.*, 1989; Delfino *et al.*, 1997; White *et al.*, 1993).

4. Discussion

The current study focuses on the investigation of hemodynamic parameters in the LCA with multi- stenosis placed at various locations across the bifurcation by varying the flow rate. It is observed that LCA geometry and, thus, the pattern of flow in this artery are very intricate, involving separation of the flow, secondary flow and high and low WSS regions. This study offers additional evidence about the impact of multi coronary stenoses on hemodynamic; hence, it improves our knowledge of atherosclerotic stenosis progression and development during various flow rates. In the last few years, development in the field of medical imaging techniques (Gijsen *et al.*, 2007; Sun and Cao, 2011), such as MRI, CTA and IVUS, has made it possible to

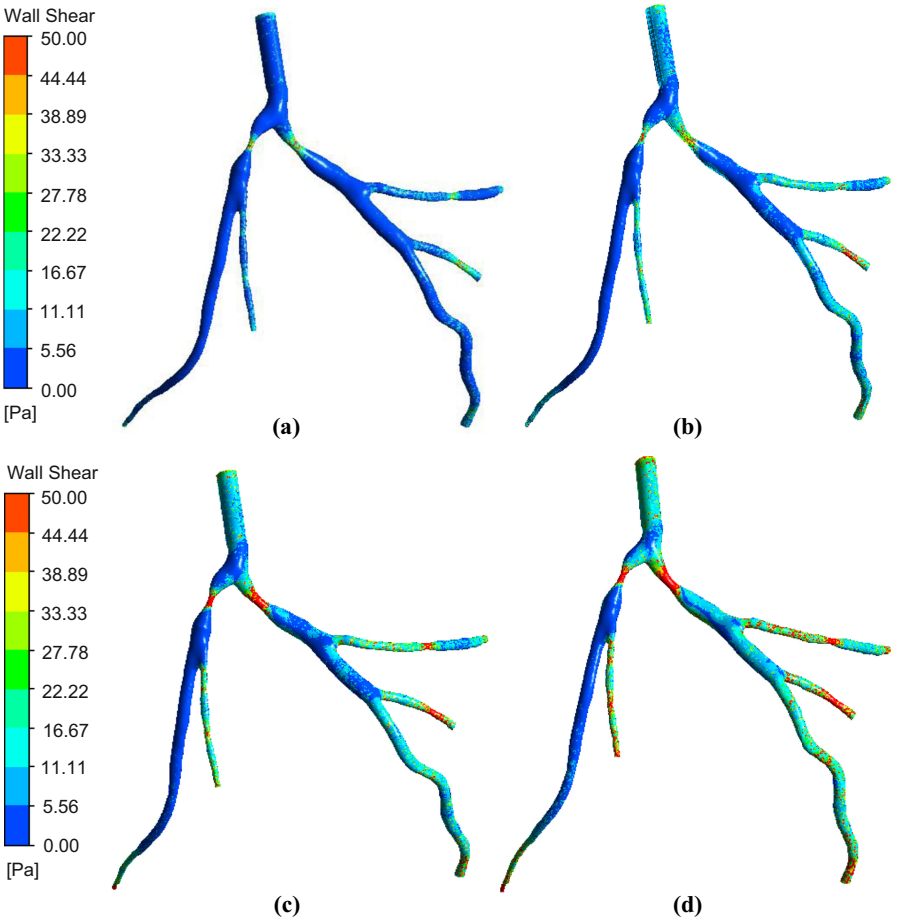

Figure 5.
WSS in the left coronary artery of 90% and 70% AS were located at LAD and LCX, respectively for 1.2 s during the cardiac cycle for various flow rates a) 50 ml/min b) 100 ml/min c) 125 ml/min d) 175 ml/min

differentiate between the wall of a coronary artery and the undesirable deposition on the wall of coronary arteries. These inventive clinical imaging procedures give the remodeling structures of the wall yet are restricted to the examination of the flow characteristics in the coronary arteries. Conversely, CFD offers to visualize blood flow behavior and hemodynamic factors. It is found that the multi-stenosis can significantly affect the hemodynamic factors in the realistic LCA, causing the discrepancy in hemodynamic variables such as wall pressure, velocity and WSS. Figure 3 shows the increase in the wall pressure as the flow rate increases. It was found that the highest WSS occurs at the higher degree of stenosis, and it also increased as the flow rate of the coronary increased. As evident from Figure 4, the velocity elevated across stenosis present at the LAD and LCX branches and increases with the increase in the flow rate. The recirculation area was created within a short distance from the stenosis due to the low blood flow velocity. We found that the abnormal wall shear and fluctuating velocity at the post stenosis region lead to the future progression and development of the stenosis. There was some constraint of this study, which should be addressed in the future. In the current study, the wall of a patient-specific LCA was considered rigid rather than flexible. Hence, the numerical simulation does not replicate the realistic conditions as the coronary artery wall

moves during the cardiac pulse. The study was conducted with limited data of the patient; therefore, a large number of patients should be included.

5. Conclusion

The impact of multi-stenosis for hemodynamic parameters at the positions of stenosis, as well as before and after the stenosis regions in the LCA with varying flow rates, was investigated. The current numerical simulation was performed by using finite element-based software ANSYS CFX. The simulated results reveal that there is a severe consequence of multi-stenosis in the LCA on hemodynamic variables such as wall pressure, recirculation flow, velocity and WSS. The higher wall pressure drop was observed across the 90% AS at the LAD branch, which could lead to the failure of atherosclerosis disease. A higher WSS was found across the stenosis, which increases the risk of stenosis rupture. The section of recirculation immediate to the stenosis due to the low velocity increases the progression and development of stenosis. The greater degree of stenosis at LAD may require an immediate interventional technique in the treatment of the disease. Further study with a greater number of patient data with varying stenosis degrees located at different branches of LCA is required to validate the current study.

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