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Numerical flow analysis of coronary arteries through concentric and eccentric stenosed geometries

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ABSTRACT

In this study, the flow characteristics through specific concentric and eccentric plaque formations are investigated via Large Eddy Simulation (LES) turbulence technique considering pulsatile flow conditions adjusted for a single frequency-sinusoidal motion (SIN) and for the coronary arteries namely the Left Anterior Descending (LAD) and Right Coronary Artery (RCA). This specific plaque formation is a combination of a highly eccentric shape with triangular-like cross-section for which the flow behaviour has not been studied before.

The pulsatile flow behaviour in conjunction with non-Newtonian blood model for SIN, RCA and LAD is found to have considerable effect on formation of separation bubbles and jets, coherent structures associated with vortex rings and horseshoe vortices, wall shear and pressure drop. It should be stated that the quantitative outcome from this study has been the extra pressure load estimated on the heart which was approximately 17% of eccentric model and 9% of concentric model both in RCA or LAD case for a 75% occlusion scenario.

1. Introduction

Numerical and experimental studies regarding the shape of eccentricity for stenotic flows are limited by circular-cross sections and plaques are usually assumed as to be oriented concentrically or eccentrically with low index level. These studies include the work of Ahmed and Giddens (1983, 1984), Solzbach et al. (1987), Dunmire et al. (2001), Varghese et al. (2007a, 2007b), Griffith et al. (2010) and many others. However, in real life, the flow is much more complex than that studied in the past since the plaque formation is mostly eccentric and non-circular (Mintz et al. (1996) and Enrico et al. (2009)). The flow is mostly dictated by plaques located asymmetric and the cross-section at the throat of the plaque is not always in a circular shape. In fact, some open literature shows that this cross-section is a sector of a circular shape and looks like mostly a triangular as seen in Fig. 1. In this manner, this study aims to address the laminar and turbulent pulsatile flow characteristics subjected to the three-dimensional ideal concentric and eccentric plaque models incorporating the pulsatile velocity inlet boundary condition adapted by the changes in flow rates of a single frequency sinusoidal motion (SIN) and coronary arteries, including RCA (Right Coronary Artery) and LAD (Left Artery Descending). These coronary arteries are of concern in this study mostly because clinical studies indicate that coronary artery plaques are most common in RCA and LAD as tabulated in Table 1.

2. Problem formulation

2.1. Stenosed geometry

The geometry for the concentric stenosed model is a duplicate geometry of Ahmed and Giddens (1983) (see Fig. 2a). The eccentric model as seen in Fig. 2b, on the other hand, is employed in such a way that the cross-section at throat is similar to the real geometries (Fig. 1) and the eccentricity index (EI), which was described by Yamagishi et al. (2000) as the ratio of the difference between the maximum and minimum plaque thickness to the maximum thickness ($EI=(pt_{max}-pt_{min})/pt_{max}$), is greater than 0.5 in order to be considered medically significant. The stenotic region is characterised by a cosine function in primary flow direction and the length of this region is two-fold of the artery diameter. The occlusion ratio of both plaques at the throat is kept as 75%.

2.2. Computational grid

The computational domain ranges from $-4D$ to $18D$ in axial direction (X), $-0.5D$ to 0.5 in normal (Y) and spanwise (Z) directions.

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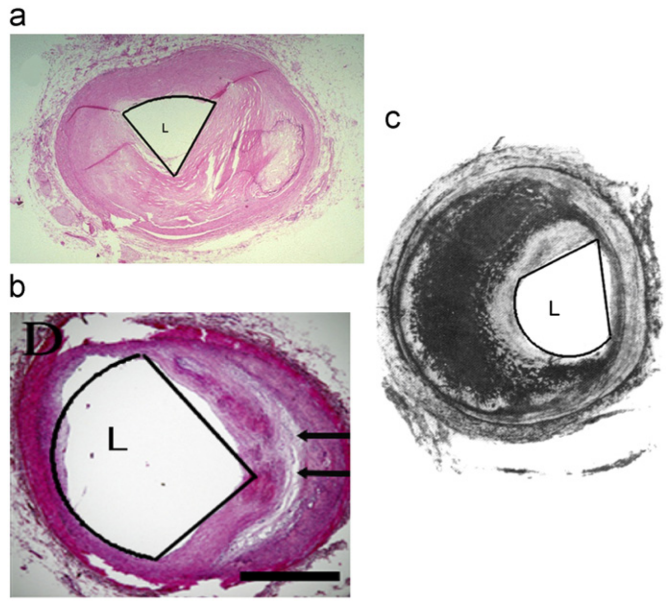

Fig. 1. Examples of sector-type luminal configurations of eccentric atherosclerotic plaques. Images are modified with borders of lumen. (a) An image processed after optical coherence tomography of a coronary artery from meduweb.com. (b) Another image from a patient who died without clinical evidence of coronary artery disease (Kume et al., 2008) and (c) an intravascular ultrasound image of a diseased human coronary artery from alexandria.healthlibrary.ca. Reproduced by the permission of the publishers.

Table 1
Percentage of stenosis observed in LAD and RCA.

Study	Case	LAD	RCA	LAD (%)	RCA (%)
Mintz et al. (1996)	1349	618	542	45.8	40.2
Kürüm et al. (2000)	519	269	205	51.8	39.5
Enrico et al. (2009)	382	177	99	46.3	25.9

Three type of grid resolution is used; namely the coarse grid (CG, 1.4×10^6 cells), medium grid (MG, 2.8×10^6 cells, twice the size of CG) and fine grid (FG, 5.6×10^6 cells, twice the size of MG). CG has approximately 2.7×10^5 and 7.8×10^5 cells for upstream and downstream regions of the stenosis, respectively. The rest are employed in the constricted region (see Fig. 2).

The convergence of grid resolution and phase-averaging are shown in Fig. 3a and b. In Fig. 3a, phase-averaged axial velocity profiles are shown at certain axial stations on $Z/D=0$ plane. Results of coarse grid (CG) deviate significantly from those of other grids. MG and FG results are seen to produce almost same results, suggesting that grid convergence is achieved. Fig. 3b is the same as Fig. 3a, but the labels represent the number of phase-averaging. There are very small differences between the results of 54, 92 and 130 samples, indicating that the pulsatile averaging is also converged.

2.3. Numerical implementation

Details of all numerical implementation, flow model and averaging are the same as pulsatile flow case of Varghese et al. (2007a,b). As for the turbulence model, LES is employed here to accurately predict the pulsatile turbulent flow behaviour dictated by sinusoidal pulsatile motion with single frequency (SIN) as Varghese et al. (2007b) employed, and the realistic pulsatile motion in RCA and LAD. LES is a numerical technique based on resolving the larger scales and modelling the smaller ones. It is not as costly as DNS (Direct Numerical Simulation) and the prediction capability is better than RANS (Reynolds-Averaged Navier–Stokes) models provided that required grid resolution for LES is employed. The details of the LES theory, its implementation and validation for an engineering flow can be found in Guleren (2010).

A considerable effort is devoted to establishing the inlet boundary condition which would satisfy both the *in vivo* measurements of mass flow rates in RCA and LAD as seen in Fig. 4a

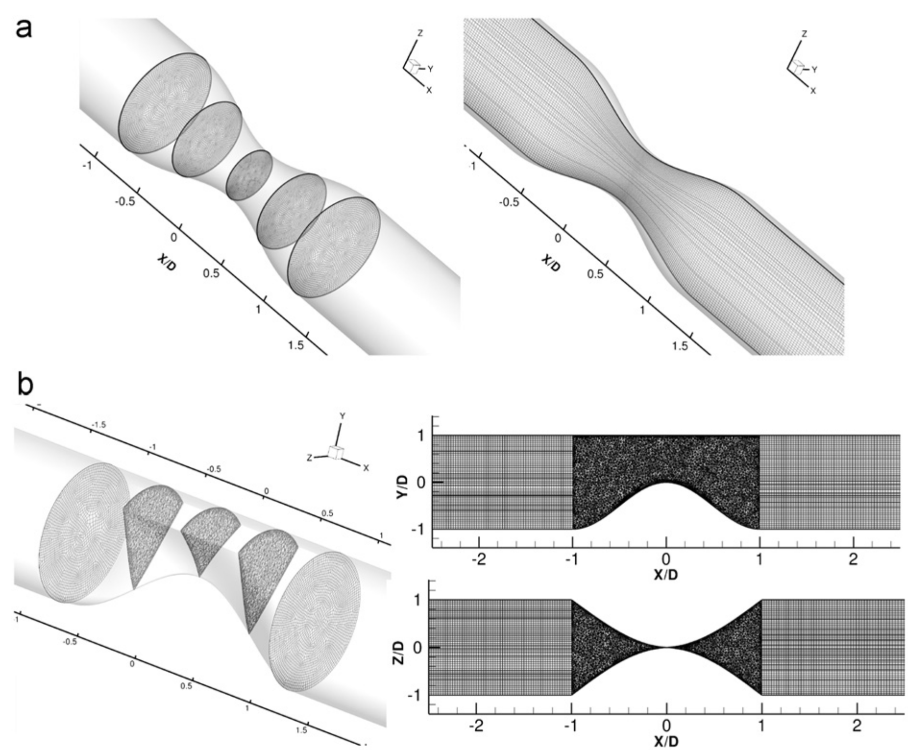

Fig. 2. Three-dimensional flow model with mesh examples. Mesh shown at certain cross sections and side planes for concentric plaque (a) and eccentric plaque (b).