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A numerical investigation of the functionality of coronary bifurcation lesions with respect to lesion configuration and stenosis severity

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ABSTRACT

The intervention of coronary bifurcation lesions is associated with higher rates of peri- and post-procedural clinical events compared to the treatment of isolated lesions. Overall, the factors that influence the dynamics of these types of configurations are still not well understood. A geometric multiscale model, consisting of a 3D representation of the left main coronary artery bifurcation and a 0D representation of the rest of the cardiovascular system, was developed. Computational fluid dynamics simulations of the 3D domain were executed by implementing the multiscale algorithm, in order to characterize the functionality of different multilesional configurations as a function of stenosis severity. The investigation found that coronary branch steal has a significant impact on the functionality of the disease and can render a two-lesion configuration more severe compared to a three-lesion configuration. As a result of the complexity of this phenomenon, it was also suggested that certain lesion configurations could result in false negatives in diagnosis when employing a pullback pressure recording across the tandem lesions. In conclusion, this study showed that coronary bifurcation lesions are subject to intricate haemodynamic interactions which render the characterization of their functionality complex and could have significant clinical implications with regards to their diagnosis and prognosis.

1. Introduction

Atherosclerotic plaques tend to form in areas of disturbed flow such as vessel bifurcations (Bijari et al., 2014). Coronary bifurcation lesions (CBLs), defined as luminal narrowings that include a significant side branch, constitute 15–20% of cases treated by percutaneous coronary interventions (PCIs); their intervention is associated with higher rates of peri- and post-procedural clinical events, restenosis and thrombosis compared to their isolated counterparts (Levine et al., 2011; Windecker et al., 2014). In order to improve interventional strategies and reduce risks associated with their treatment, a good understanding of the factors that affect their dynamics must be obtained.

Clinical studies have shown that for isolated lesions with intermediate diameter reductions (50–70%), a functional haemodynamic assessment is required to guide cardiologists with the decision to revascularize. This assessment is made using the fractional flow reserve (FFR, Eq. (1)):

$$\mathrm{FFR} = \frac{Q_d}{Q_n} \approx \frac{P_d}{P_{ao}} \tag{1}$$

where Q_d and Q_n are the diseased and theoretically normal flow in the myocardium respectively and P_d and P_{ao} are the distal stenosis pressure and aortic pressure respectively (at maximum hyperaemia), which measures the percent of healthy hyperaemic myocardial blood flow that is preserved when the supplying artery is diseased (Yong et al., 2011). Clinical studies have shown that FFR values between 0.75 and 0.8 correspond to the threshold for the onset of ischemia (De Bruyne et al., 1995; Pijls et al., 1995a). By using FFR, interventions can be safely deferred for physiologically insignificant but angiographically significant lesions (Tonino et al., 2010). Due to procedural costs, FFR is executed in less than 10% of lesions undergoing PCI (Li et al., 2013; Morris et al., 2013). Consequently, the computation of FFR using numerical methods with patient-specific anatomic coronary data (Min et al., 2012; Morris et al., 2013; Taylor et al., 2013; Zarins et al., 2013) has recently become of great interest. Central to these works is the use of geometric multiscale modelling, which allows numerical simulations to be executed without assigning predefined flows or pressures at the model boundaries. Instead, patient-specific models are coupled to 0D patient-tailored models of surrounding cardiovascular domains,

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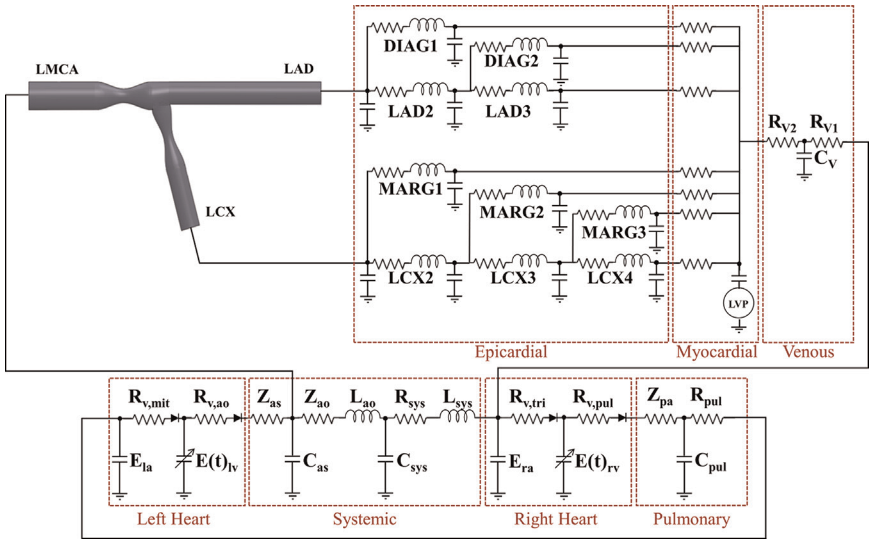

Fig. 1. Multiscale model of the bifurcation of the LMCA into the LAD and LCX. *la* left atrium; *lv* left ventricle; *v,mit* mitral valve; *v,ao* aortic valve; *as* aortic sinus; *ao* aortic; *sys* systemic; *ra* right atrium; *rv* right ventricle; *v,tri* tricuspid valve; *v, pul* pulmonary valve; *pa* pulmonary artery; *pul* pulmonic; *DIAG* diagonal; *MARG* marginal; *V* venous; *LVP* left ventricular pressure.

allowing for boundary flows and pressures to be determined through the interaction of the two models. Although work is ongoing regarding the optimization of multiscale models (Pant et al., 2014), their use is becoming more prominent; they have been implemented for various applications including disease progression (Balossino et al., 2009), and modelling/optimization of surgical/interventional procedures (Lagana et al., 2005; Moghadam et al., 2012; Morlacchi et al., 2011).

For isolated lesions, the onset of ischemia is influenced by various factors including lesion morphology and location, the size and dynamics of the perfused myocardium and the extent of collateral circulation (Pijls and Sels, 2012; Yong et al., 2011). For CBLs, the development of ischemia is more complex because there are both local (within the diseased bifurcation) and global (between different myocardial beds) haemodynamic interactions that render the overall dynamics of the system more complex (Daniels et al., 2012; Gould, 1999; Yong et al., 2013). Only few studies have investigated the dynamics of CBLs; however, focus was put on disease progression and not on physiologic impact (Binu and Kumar, 2012; Chaichana et al., 2013, 2014; Zarandi et al., 2012).

It is important that the various global and local factors that could affect the haemodynamic impact of CBLs be studied based on the FFR. As an initial study, it was hypothesized that the configuration of the lesions alone significantly impacts the haemodynamic interactions between the stenoses in the bifurcation and therefore plays a central role in the physiological severity of CBLs. Thus, the objective of this study was to characterize and compare the functional impact, as quantified by the flow- and pressure-based FFR, of different CBL configurations as a function of lesion severity; as such, computational fluid dynamics (CFD) simulations of 3D diseased left main coronary artery (LMCA) bifurcations were performed and the flow- and pressure-based FFR were obtained by implementing a geometric multiscale algorithm.

2. Methods

A closed-loop geometric multiscale model consisting of a 3D simplified representation of the bifurcation of the LMCA into the left anterior descending artery (LAD) and the left circumflex artery (LCX) (Zarandi et al., 2012) coupled to a 0D model or lumped-parameter model (LPM) of the rest of the cardiovascular system was developed (Fig. 1).

2.1. 3D model of the diseased bifurcation

Four multilesional CBL configurations based on the Medina classification (Medina et al., 2006) were considered in the study (Fig. 2). The Medina classification is a binary system that denotes either the presence (1) or the absence (0) of a stenosis with a diameter reduction $\geq 50\%$ in each of the vessels of the bifurcation. Dimensions and morphological characteristics of the geometry (Dodge et al., 1992; Wang et al., 1989) are provided in Fig. 2.

All stenoses were modelled by an axis-symmetric cosine profile (Young and Tsai, 1973); the base length of the stenosis was constant at 10 mm. Intermediate lesions, with diameter reductions of 41%, 50%, 61% and 68% were considered for each configuration. All stenoses within a given configuration had a uniform severity; as such, a total of 17 multiscale CFD simulations were executed, including the healthy case.

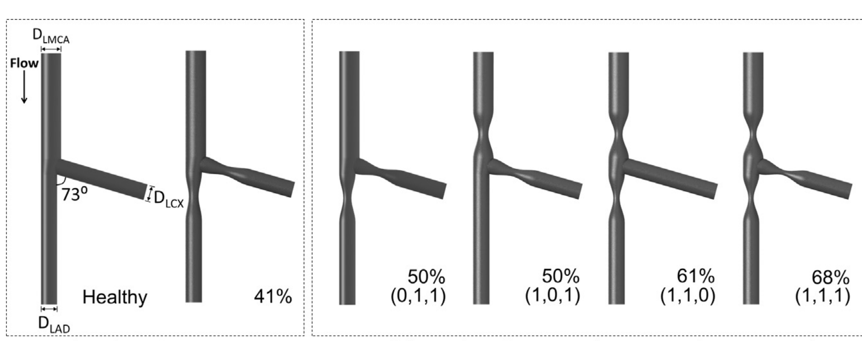

Fig. 2. Bifurcation lesion configurations, based on the Medina classification, considered in the study. $D_{LMCA}=4.5$ mm, $D_{LAD}=3.4$ mm, $D_{LCX}=3.2$ mm.

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