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CORRELATION BETWEEN GEOMETRIC PARAMETERS OF LEFT CORONARY ARTERY AND PLAQUE DEPOSITION IN LEFT ANTERIOR DESCENDING ARTERY

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ABSTRACT

The present work assess, through a statistical study, the correlation between geometric parameters of the left coronary artery of eight patients and the potential effect to atherosclerotic plaque deposition in both left anterior descending artery (LAD) and proximal artery LAD, allowing a better clinical practice. The tendency to develop atherosclerosis appearance is evaluated through the relative residence time (RRT) descriptor. Fluid-structure interaction (FSI) simulations were performed for a hemodynamic study in non-simplified *in-vivo* geometries of eight healthy patients. RRT increases in LAD and proximal LAD (prone regions of atherosclerosis appearance) when the left main steam (LMS) cross-sectional area, the tortuosity between LMS-LCx and the angles LMS-LAD / LAD-LCx increase. RRT also increases when the proximal LAD length and the curvature of LMS decrease.

Keywords: left coronary artery, plaque deposition, geometric measurements, relative residence time, fluid-structure interaction, statistical study

INTRODUCTION

Cardiovascular diseases are the main cause of human death, globally corresponding to 31% of all deaths worldwide (Mozaffarian *et al.*, 2015). The clinical practice has shown that specific locations in human circulatory system are more propitious to atherosclerosis development - accumulation of lipoproteins near the artery wall. This disease disturbs the normal circulation of blood. The computed tomography (CT) scans of patient coronary arteries provide the necessary information about the geometry and the site of the disease; however do not explain with detail the hemodynamics. By this way, numerical simulations of blood flow can contribute as an auxiliary tool for the prevention and treatment of this disease.

The left coronary artery (LCA), with diameter lower than 4 mm, is a complex artery with many bifurcations, curvatures and roughness. As far as we know, no study in the literature has assessed a statistically relevant study on the LCA geometric parameters and their influence in the hemodynamic descriptors, using a numerical code which simulates blood flow as close as possible to the reality. Malvè *et al*. (2014) performed a statistical analysis where the tortuosity was correlated with low wall shear stress using several simplifications like rigid wall of the artery (CFD) and a simplified reconstructed geometry. Authors of the present paper go ahead using a fluid-structure interaction (FSI) analysis for a hemodynamic study in non-simplified *in-vivo* geometries of eight healthy patients. Therefore, the goal is to assess whether or not the most relevant geometric parameters - cross-sectional areas, proximal LAD length, tortuosity, curvature, angles between the branches - are correlated with the risk assessment of atheroma plaque formation in both LAD and Proximal LAD, allowing a better clinical practice.

STUDY POPULATION

Healthy subjects with right-dominant coronary circulation were selected to be part of this study: total of 8 cases - 5 males and 3 females (Figure 1). The database was kindly provided by the Cardiovascular R&D Unit of the Medicine Faculty of the University of Porto.

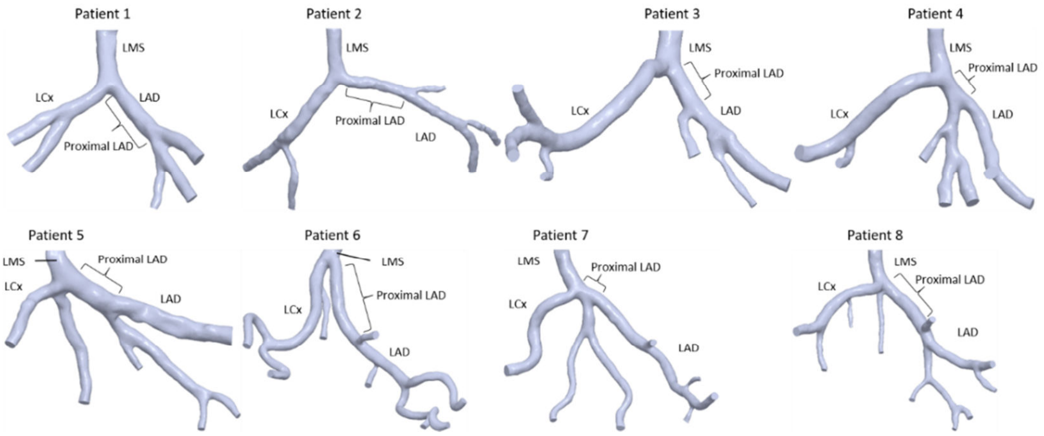

Fig. 1 - 3D patient-specific LCA geometries reconstructed through MIMICS® software from CT scans. Left main steam (LMS), Left Anterior Descending Artery (LAD), Left Circumflex Artery (LCx).

GEOMETRIC MEASUREMENTS OF THE LCA

The selected geometric parameters for the assessment are:

- Cross-sectional area of the LMS, LAD and LCx;
- Length of the proximal LAD (*l*), Figure 2(a);
- Bifurcation angles ($\alpha_{\mathrm{LMS-LAD}}$, $\alpha_{\mathrm{LMS-LCx}}$, $\alpha_{\mathrm{LAD-LCx}}$), Figure 2(b);
- Angle between a branch and the septum ($\alpha_{\mathrm{LAD-Septum}}$, $\alpha_{\mathrm{LCx-Septum}}$), Figure 2(b);
- Curvature at the beginning of each branch (κ_{LMS}, κ_{LAD}, κ_{LCx}), Figure 2(b);
- Tortuosity between branches ($\tau_{\mathrm{LMS-LAD}}$, $\tau_{\mathrm{LMS-LCx}}$, $\tau_{\mathrm{LAD-LCx}}$), Figure 2(c).

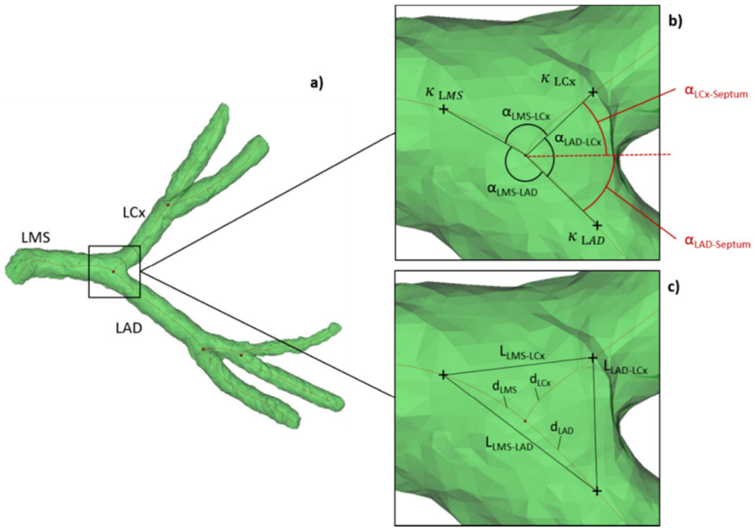

Fig. 2 - (a) 3D mask of Patient 1 and its centerline; (b) Angles ($\boldsymbol{\alpha}_{\mathbf{LMS-LAD}}$, $\boldsymbol{\alpha}_{\mathbf{LMS-LCx}}$, $\boldsymbol{\alpha}_{\mathbf{LAD-LCx}}$, $\boldsymbol{\alpha}_{\mathbf{LCx-Septum}}$, $\boldsymbol{\alpha}_{\mathbf{LAD-Septum}}$) and curvature ($\boldsymbol{\kappa}_{\mathbf{LMS}}$, $\boldsymbol{\kappa}_{\mathbf{LAD}}$, $\boldsymbol{\kappa}_{\mathbf{LCx}}$); (c) tortuosity definition ($\boldsymbol{\tau}$).

The main bifurcation region, where measurements were obtained, was considered quasi-coplanar since the sum of all the bifurcation angles was close to 360º (360.5º ± 0.9º). The tortuosity parameter was calculated between two points of interest in the study branches (Malvè *et al*., 2014, Zakaria *et al*., 2008):

$$\tau\,(\%) = \left(1 - \frac{L_{i-j}}{d_{i-j}}\right) \times 100 \qquad (1)$$

d_{i-j} is the distance along the centerline and L_{i-j} is the corresponding shortest distance between i and j, Figure 2(c).

NUMERICAL METHOD AND BOUNDARY CONDITIONS

A fluid-structure interaction (FSI) analysis, through ANSYS® software, was used to obtain the hemodynamics and wall shear stress-based descriptors, in non-simplified *in-vivo* geometries of healthy patients.

To simulate the hemodynamic behaviour, as real as possible, transient velocity and pressure profiles were imposed (Dong *et al*., 2015). At the inlet, a Womersley velocity profile was considered, allowing a variable velocity along the time of the cardiac cycle and according to the vessel radius (Pinto *et al*., 2018). At the outlets, the transient and uniform pressure profile allowed to mimic the pressure pulse, essential to the vessel deformation. Structurally, all degrees of freedom from all nodes at the inlets and outlets faces were constrained.

Blood was considered an isotropic, incompressible ($\rho_f = 1060$ kg/m^3) and non-Newtonian fluid obeying to the shear-thinning Carreau model (Pinto et al. 2016).

Arterial wall was considered an isotropic, homogeneous, incompressible ($\rho_w = 1120$ kg/m^3) and non-linear material described by the 5-parameter Mooney-Rivlin hyperelastic constitutive model (Karimi, *et al*., 2014).

RESULTS AND CONCLUSIONS

Figure 3 shows the relative residence time (RRT) spatial distribution, a commonly used wall shear stress hemodynamic descriptor, for each patient case in study. Regions closer to 8 Pa^{-1} are considered prone to atherosclerotic plaque formation (Pinto *et al*., 2016). Generally, higher RRT are found near bifurcations and at LAD branch.

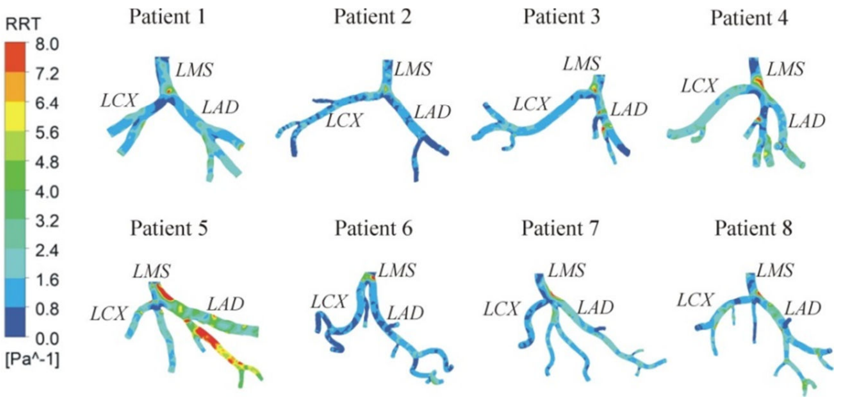

Fig. 3 - RRT spatial distribution for each heathy patient-specific LCA artery - front view - determined through FSI simulation.

A linear regression was performed to study the dependence of the RRT descriptor in each geometric parameter: cross-sectional area of the LMS, proximal LAD length, tortuosity, curvature and angles between the branches. The statistical relevance and significance of each parameter was evaluated through the Pearson correlation coefficient (r).

A higher LMS cross-sectional area shows an upper RRT, increasing the probability for atherosclerosis plaque formation in LAD (r = 0.85) and proximal LAD (r = 0.88). Also, a lower proximal LAD length induces a higher turbulence, increasing RRT (r = -0.41). However, a higher tortuosity between LMS-LAD implies a reduction of the RRT descriptor (r = -0.56) in LAD. Oppositely, when tortuosity increases between LMS-LCx, RRT growths in LAD (r = 0.64), increasing the prone regions to atherosclerosis appearance.

A high curvature in LMS reports a reduction of LAD flow (r = -0.87) and a decrease of RRT in LAD (r = -0.52) and in proximal LAD (r = -0.60), reducing the prone regions to atherosclerosis. Nevertheless, a higher angle LMS-LAD and LAD-LCx increases RRT in proximal LAD (r = 0.49 and 0.57) and the tendency to atherosclerosis.

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