TENDENCY TO ATHEROSCLEROTIC PLAQUE FORMATION IN THE RIGHT CORONARY ARTERY OF HEALTHY CASES - FSI SIMULATIONS

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ABSTRACT

The present work assesses, statistically, the correlation between geometric parameters of the right coronary artery (RCA) of ten healthy individuals and the potential effect to atherosclerotic plaque formation, allowing a better clinical practice. The tendency to develop atherosclerosis is evaluated through the wall shear stress (WSS) based-descriptors. Fluid-structure interaction (FSI) simulations were performed for a hemodynamic study in non-simplified in-vivo RCA geometries. The right-ventricular branch shows an important role in the hemodynamic behavior. Higher values of the angle between the right-ventricular and the RCA tree are strongly correlated with lower WSS values, which, by consequence, tends to a high predisposition to atherosclerosis formation. Lower values of the tortuosity and/or curvature at the beginning of the right-ventricular are associated with lower WSS magnitude, favoring the tendency to atherosclerosis formation. No noteworthy correlations were found between the hemodynamic descriptors and the geometric parameters of the sinu-atrial, the conus and the acute marginal branches in the whole RCA.

Keywords: Right coronary artery, plaque formation, geometric measurements, relative residence time, fluid-structure interaction, Pearson correlation coefficient.

INTRODUCTION

Cardiovascular diseases are the leading cause of mortality in developed countries [1]. The clinical practice has shown that specific locations in the human circulatory system are more propitious to atherosclerosis development. Atherosclerosis develops due to the accumulation of lipoproteins in the arterial wall and the migration of smooth muscle cells to the intima and leukocyte infiltration, thereby forming plaques in the arterial wall. When the progression of atherosclerotic lesion exceeds the compensatory wall response, plaques protrudes into the lumen causing stenosis and obstructs blood flow to the distal myocardial bed. The computed tomography (CT) images of patient coronary arteries provide the information about the geometry and the location of the disease; however, do not explain in detail the hemodynamics. Numerical simulations of blood flow can contribute as an auxiliary tool for the prevention and treatment of such disease.

The right coronary artery (RCA), with a diameter lower than 4 mm, is a complex artery with many side-branches, curvatures and roughness. The main side-branches of the RCA are sinu-atrial, conus, right-ventricular and acute marginal. In most part of the numerical studies [2-5],
authors have been neglected the side-branches of the RCA. However, Liu et al. [6] and Wellnhofer et al. [7] concluded that the geometry of curvature and angulation of the side-branches must not be neglected in numerical flow simulations. The side-branches have a significant effect on the wall shear stress (WSS) in the RCA hemodynamics and, consequently, in the atherosclerosis lesion. The simulations [6, 7] were performed through computational fluid dynamics (CFD) and Liu et al. [6] used simplified models of the RCA.

As far as we know, no study in the literature has assessed a statistically relevant study on several RCA geometric parameters and their influence in the WSS hemodynamic descriptors, using a numerical code which simulates blood flow closer to the reality. Authors of the present paper go ahead using a fluid-structure interaction (FSI) analysis, between blood and the arterial wall, for a computational hemodynamic study in non-simplified in-vivo geometries of ten healthy individuals. Therefore, the goal is to assess whether or not the geometric parameters - cross-sectional area of the main RCA (ostium); angles between the RCA and the side-branches; tortuosity, curvature and cross-sectional area in each side-branch - are correlated with the risk assessment of atheroma plaque formation in the global RCA; allowing a better clinical practice.

METHODOLOGY

Healthy individuals were selected to be part of the study; a total of 10 cases. The database was kindly provided by the Cardiovascular R&D Unit of the Medicine Faculty of the University of Porto. The CT image sequence of each subject has a slice thickness \( (h) \) of 0.6 mm, obtained with an exposure of 452 ± 157 mAs, during 219 ±114 ms. The CT images were analyzed through the image processing software for 3D design and modeling, the Materialise Mimics® software (Materialise NV, Wilfried, Leuven, Belgium).

Blood was considered an isotropic, incompressible \( (\rho_f = 1060 \text{ kg/m}^3) \) and non-Newtonian fluid following the shear-thinning Carreau model [8]. The arterial wall was also assumed as isotropic, incompressible \( (\rho_w = 1120 \text{ kg/m}^3) \), homogeneous and non-linear material. The hyperelastic constitutive model 5-parameter Mooney-Rivlin was considered [9].

A fluid-structure interaction (FSI) between blood and the arterial wall was assumed. The ANSYS® software was used to obtain the hemodynamics, WSS-based descriptors, in non-simplified in-vivo geometries of healthy individuals. The side-branches of the RCA - sinus-atrial, conus, right-ventricular and acute marginal - were taken into account.

Transient velocity and pressure profiles were imposed [10] in order to simulate blow flow as real as possible. At the inlet, a Womersley velocity profile was imposed. The profile depends on the velocity along each time of the cardiac cycle and depends on the vessel radius [11]. At the outlets, a transient and uniform pressure profile allowed to mimic the pressure pulse, essential to the vessel deformation.

Several geometric parameters - cross-sectional area of the main RCA (ostium); angles between the RCA and the side-branches; tortuosity, curvature and cross-sectional area in each side-branch - are represented in Figure 1 in order to correlate with the risk assessment of atheroma plaque formation in the global RCA.
Fig. 1 - Geometric parameters of an individual RCA. $\alpha_{RV}$ (angle between the RCA tree and the right ventricular); $\tau_{RV}$ (tortuosity of the right ventricular); $\kappa_{RV}$ (curvature at the beginning of the right ventricular); $\kappa_{RV,middle}$ (curvature between the right ventricular and the middle segment); $A_{RV}$ (cross-sectional area of the right ventricular); $A_{ostium}$ (cross-sectional area in the main RCA - ostium). The other side-branches are defined with the same analogy.

RESULTS AND CONCLUSIONS

Figure 2 shows the relative residence time (RRT) spatial distribution, a commonly used WSS hemodynamic descriptor, for each case study. Grey regions represent zones until the mean RRT value plus 2 times deviation ($\bar{RRT} + 2\sigma_{RRT}$) while white regions show RRT values higher than $\bar{RRT} + 2\sigma_{RRT}$. This metric was used in order to uniform the results of different RCA cases. Zones with values higher than $\bar{RRT} + 2\sigma_{RRT}$ (represented at white) mean prone regions to atherosclerosis appearance relative to the global RCA. Generally, higher RRT are found in the middle segment, in the distal segment of the RCA and in the opposite location of the bifurcation of the side-branch. Moreover, some punctual prone regions relative to the global RCA can also be achieved in the proximal segment.
A linear regression, for the global RCA, was attained to study the dependence of the WSS-based descriptors in each geometric parameter - cross-sectional area of the main RCA (ostium); angles between the RCA and the side-branches; tortuosity, curvature and cross-sectional area in each side-branch. The statistical relevance and significance of each parameter were evaluated through the Pearson correlation coefficient ($r$).

A decrease in $A_{\text{ostium}}$ means a global decrease in the WSS magnitude ($r = 0.74$) and a global tendency to atherogenesis.

The right-ventricular branch (RV) shows an important role in the hemodynamic behavior. Higher values of $\alpha_{RV}$ are strongly correlated with lower WSS values ($r = -0.99$) and, consequently, higher predisposition to atherosclerosis formation ($r = 0.61$). Moreover, lower values of $\tau_{RV}$ ($r = 0.98$) and $\kappa_{RV}$ ($r = 0.65$) are associated with lower WSS magnitude, favoring the tendency to atherosclerosis formation.

The same conclusions were obtained for the geometric parameters $\kappa_{RV,middle}$ and $A_{RV}$. A decrease in their values leads to a more turbulent flow ($r = -0.86$ and $r = -0.47$) and an increase to the risk of plaque formation ($r = -0.46$ and $r = -0.84$).

No noteworthy correlations were found between the WSS hemodynamic descriptors and the geometric parameters of the sinu-atrial, the conus and the acute marginal branches in the whole RCA.
ACKNOWLEDGMENTS

The authors gratefully acknowledge the Foundation for Science and Technology Portugal (FCT), the Research Unit of LAETA-INEGI, Engineering Faculty of University of Porto, and the Cardiovascular R&D Unit of the Medicine Faculty of University of Porto.

REFERENCES


