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Original

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EULERIAN-BASED WALL SHEAR STRESS TOPOLOGICAL SKELETON AS A TEMPLATE OF NEAR-WALL MASS TRANSPORT IN ARTERIES

Giuseppe De Nisco (1), Valentina Mazzi (1), Karol Calò (1), Maurizio Lodi Rizzini (1),
Claudio Chiastra (1), Jolanda J. Wentzel (2), David A. Steinman (3),
Diego Gallo (1), Umberto Morbiducci (1)

1. PoliTo^{BIO}Med Lab, DIMEAS, Politecnico di Torino, Italy; 2. Department of Cardiology, Biomedical Engineering, Erasmus MC, Netherlands; 3. Biomedical Simulation Laboratory, University of Toronto, Canada

Introduction

Several studies have suggested that mass transfer and transport (e.g., of high plasma levels of low-density lipoproteins, LDL) are involved in the atherosclerosis process [1]. In the last decade, computational fluid dynamics has been largely adopted to elucidate how flow disturbances, mass transport and atherogenesis are linked in human arteries [2]. However, modelling mass transfer in cardiovascular flows requires high computational costs [3]. To overcome this limitation, a marked interest has recently emerged on the Lagrangian-based features of the wall shear stress (WSS) topological skeleton (TS), able to provide a template for near-wall transport [4]. Briefly, the WSS TS is composed by fixed points, points where WSS vanishes, and stable/unstable manifolds, identifying WSS expansion/contraction regions. Here, a recently proposed Eulerian-based method for WSS TS analysis [5] is used to provide a reliable template of near-wall mass transport in patient-specific computational hemodynamic models of three distinct vascular regions. The capability of the proposed approach to depict an affordable picture of the near-wall mass transport is tested against LDL polarization distributions simulated solving the coupled Navier-Stokes (NS) and advection-diffusion (AD) equations.

Methods

The 3D geometries of a human thoracic aorta, a carotid bifurcation, and a right coronary artery were reconstructed from medical images. The finite volume method was applied to solve the coupled NS and AD equations on high-quality mesh-grids [3]. Subject-specific flow measurements were prescribed as boundary conditions. LDL boundary conditions, in particular blood-to-wall transfer were modelled as proposed elsewhere [3]. A recently proposed Eulerian-based WSS TS analysis [5] was here considered. Based on theory and according to [5], the divergence of the WSS unit vector field τ_u , defined as:

$$DIV_W = \nabla \cdot \left(\frac{\tau}{\|\tau\|_2} \right) = \nabla \cdot \tau_u \quad (1)$$

represents a template of the WSS vector field manifolds, identifying WSS expansion/contraction regions. The Poincarè index and the Jacobian analysis were then used to identify and classify fixed points [5]. In addition, the canonical descriptors of flow disturbances, i.e., TAWSS, OSI, and RRT, were evaluated. The surface areas (SAs) exposed to high local LDL uptake (LDL90), WSS contraction regions (DIV10), and disturbed

hemodynamics (TAWSS10, OSI90, RRT90) were identified, and their co-localization was quantified [3].

Results

DIV_W and LDL luminal distributions are provided in Fig. 1. WSS contraction/expansion regions are coloured in blue/red (negative/positive DIV_W , Fig. 1A). A marked co-occurrence of WSS contraction regions and LDL concentration polarization on the vessels wall clearly emerges. These observations are confirmed by quantitative analysis (Fig. 1C), reporting that WSS contraction regions co-localize with high LDL concentration regions at least the 40% more than canonical WSS-based descriptors.

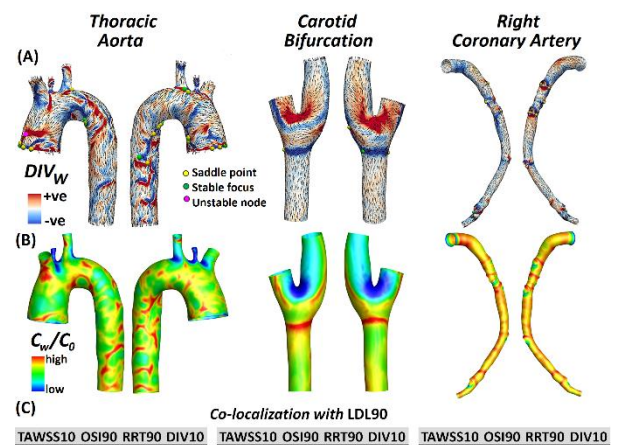


Figure 1: A) Cycle-average WSS TS. B) LDL wall concentration. C) SAs co-localization.

Discussion

Our findings clearly indicate that the Eulerian-based method for analysing the WSS TS [5] provides an effective template of WSS manifolds, which in turn co-localize with LDL polarization areas at the luminal surface. This means that the DIV10-based approach: (1) identifies high LDL polarization areas at the luminal surface better than canonical WSS-based descriptors; (2) reduces computational costs and methodological complexity with respect to classical mass transport simulations.

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