Linking wall shear stress topological skeleton to near-wall transport in aortic flow

G. De Nisco[a1], V. Mazzi[a], K. Calò[a], R. Ponzini[b], G. Rizzo[c], D.A. Steinman[d], D. Gallo[a], U. Morbiducci[a]

[a] *PoliToBIOMed Lab, Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Turin, Italy;* [b] *HPC Department, Cineca, Milan offices, Milan, Italy;* [c] *Institute of Biomedical Technologies, National Research Council, Segrate (MI), Italy;* [d] *Biomedical Simulation Laboratory, Department of Mechanical & Industrial Engineering University of Toronto, Toronto, Canada.*

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1. Introduction

Several studies have suggested that high plasma levels of low-density lipoproteins (LDL) are involved in the atherosclerosis process [1]. In the last decade, computational fluid dynamics has been proposed to elucidate the links (if any) among disturbed shear, atherogenesis and LDL transport in the human aorta [2][3]. However, modelling blood-wall mass transfer requires the use of high-resolution grids, with high computational costs [4]. To overcome this limitation, a marked interest has recently emerged on WSS Lagrangian Coherent Structures (WSS LCS), aiming at providing a template for near-wall transport [5]. In addition, previous studies have proven the ability of LCS in identifying WSS topological skeleton features [5]. We briefly remind that the WSS topological skeleton is composed by fixed points, points where WSS vanishes, and stable/unstable connection lines (manifolds), identifying WSS expansion/ contraction regions. The use of LCS as a template of near-wall mass transport might have some practical limitations mainly because of the Lagrangian nature of the method. Moving from this consideration, a Eulerian method has been recently proposed to analyse WSS topological skeleton, based on the divergence of the WSS vector [6]. The aim of the present study is to test the ability of the proposed Eulerian method to provide a template of the LDL blood-wall transfer in patient-specific computational hemodynamic models of human aorta.

2. Methods

An overview of the study methods is provided in Fig. 1. The MRI image acquisition of the healthy human aorta and the geometry reconstruction are extensively described elsewhere [4].

2.1 Computational hemodynamics

The finite volume method was applied to solve the coupled Navier-Stokes and advection-diffusion equations in their discretized form, using Fluent

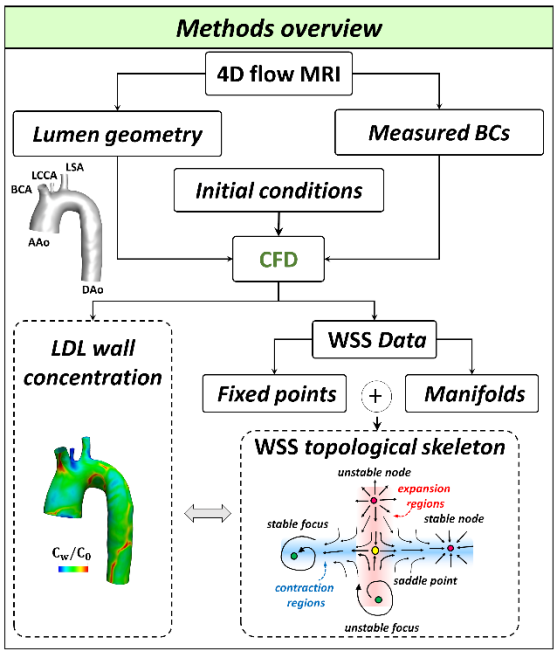

Figure 1: Overview of the proposed approach

(ANSYS Inc., USA) on a computational mesh-grid with 30 layers of high-quality prismatic cells near the wall [4]. A constant LDL concentration C_0 (equal to the average LDL concentration in whole blood) was applied at the inlet section, and the stress-free condition at the outlets. The LDL blood-to-wall transfer was modelled as follows:

$$C_W v_W - D_{LDL} \left.\frac{\partial C}{\partial n}\right|_W = 0, \qquad (1)$$

where C_W is the LDL concentration at the vessel wall, v_W the water filtration velocity through the wall, D_{LDL} is the diffusivity of LDL in blood $\partial C/\partial n$ is the concentration gradient normal to the wall.
Measured 4D flow MRI data were used to prescribe 3D velocity profiles at the inflow boundary and flow-splits at the outflow boundaries of the aortic model. A null LDL concentration was applied as initial condition in the whole domain. Details on the applied numerical schemes are extensively provided elsewhere [4].

2.2 WSS topological skeleton

A recently proposed Eulerian method to analyse the WSS topological skeleton [6] was here

[1] Corresponding author. Email: giuseppe.denisco@polito.it

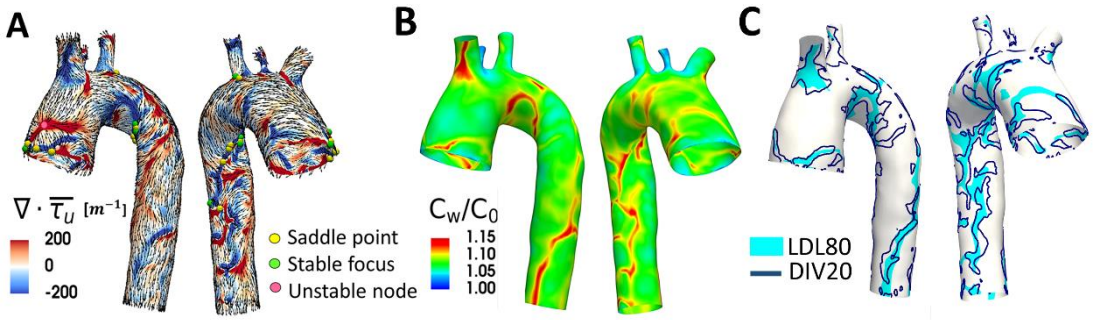

Figure 2: A: Cycle-average WSS topological skeleton. Blue and red color define the contraction and expansion regions; B: LDL wall concentration; C: LDL80 and DIV20 luminal SAs

considered. Briefly, based on Volume Contraction theory, it was demonstrated that the divergence of the WSS unit vector field $\boldsymbol{\tau}_u$, defined as:

$$\mathrm{DIV} = \nabla \cdot \tau_u = \nabla \cdot \left(\frac{\tau}{\|\tau\|_2}\right), \qquad (2)$$

allows to identify WSS expansion/ contraction regions on the arterial luminal surface.
To complete the WSS topological skeleton analysis, the Poincarè index and the Jacobian analysis was carried out to identify and classify fixed points, according to the scheme proposed in [6]. The Eulerian-based WSS topological skeleton analysis was here applied to the cycle-average WSS vector field at the aortic luminal surface.

2.3 Co-localization analysis

The analysis of the co-localization between WSS contraction regions as identified by DIV, and local LDL uptake, was carried out according to schemes proposed elsewhere [4]. Briefly, (1) the surface area (SA) exposed to normalized LDL concentration values (C_W/C_0) higher than the 80th percentile was quantified and denoted as LDL80, and (2) the SA exposed to DIV values lower than 20th percentile was identified and denoted as DIV20.

3. Results and discussion

Figure 2 provides a comparison between WSS topological skeleton and normalized LDL distribution. It clearly emerges that the regions at the luminal surface where DIV is negative co-localize with LDL concentration polarization at the wall. This marked co-localization is particularly evident in the inner part of the brachiocephalic artery, in the inner wall of the aortic arch and in the descending aorta. The marked overlap of LDL80 and DIV20 SAs clearly emerges by visual inspection of Figure 2C. The analysis of Figure 2 (1) suggests that WSS contraction regions are a robust template of high LDL uptake, in accordance to previous findings based on WSS topological skeleton identification based on LCS [5].

4. Conclusions

The findings of this study candidates the recently proposed Eulerian-based method to identify WSS topological skeleton [6] to be an effective template of the LDL blood-to-wall transfer, with a reduction both of computational costs and methodological complexity with respect to classical mass transport simulations and Lagrangian-based techniques, respectively.

6. References

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