WALL SHEAR STRESS TOPOLOGICAL SKELETON VARIABILITY PREDICTS PLAQUE PROGRESSION IN HUMAN CORONARY ARTERIES

Giuseppe De Nisco (1), Eline Hartman (2), Elena Torta (1), Diego Gallo (1), Claudio Chiastra (1), Joost Daemen (2), Jolanda Wentzel (2), Umberto Morbiducci (1)

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

Introduction

Although low wall shear stress (WSS) has become the consensus hemodynamic mechanism for coronary atherosclerosis, the exact biomechanical stimulus affecting atherosclerosis evolution is still undetermined [1]. Aiming at bridging this gap of knowledge, recently the WSS topological skeleton (TS) is receiving increasing interest, because of (1) its link with flow features associated with vascular dysfunction [2], and (2) its capability to concur to the description of the complex biomechanical stimulus affecting atherosclerosis evolution [3]. Briefly, the WSS TS is composed by fixed points, where the WSS vanishes, and unstable/stable manifolds connecting them, where WSS exerts a contraction/expansion action on the endothelium [4]. Here we test the ability of WSS TS, solely or synergistically with plaque phenotypes, to predict the temporal evolution of coronary artery plaque atheroma volume (PAV), a hallmark of atherosclerosis development, in 38 patient-specific computational models of human coronary arteries.

Methods

A non-culprit coronary segment for 37 hemodynamically stable patients was imaged at baseline (T1) and at 1 year follow-up (T2). Vessel geometries were reconstructed at T1, and computational hemodynamic simulations were carried out prescribing patient-specific boundary conditions. Widely adopted descriptors of WSS magnitude and multidirectionality were tested (i.e., TAWSS, OSI, RRT, and transWSS). Additionally, a Eulerian method was applied to analyse the WSS TS [4], identifying WSS contraction/expansion regions at the coronary luminal surface by the divergence of normalized WSS vector field (DIV_{WSS}). The amount of variation in WSS contraction/expansion action along the cardiac cycle T was quantified by the Topological Shear Variation Index (TSVI) [2]:

$$TSVI = \left\{\frac{1}{T}\int_0^T [DIV_{WSS} - \overline{DIV_{WSS}}]^2 dt\right\}^{1/2} \quad (1)$$

Plaque progression was evaluated as the difference between PAV measurements (100*plaque volume/total vessel volume) at T2 and T1 averaged over 3mm/45° luminal sectors. Additionally each sector was classified as lipid rich, fibrous or plaque free based on OCT images. Hemodynamic descriptors were averaged over 3mm/45° luminal sectors and divided into artery-specific low, mid and high tertiles to perform a statistical analysis on the associated ΔPAV, solely or in combination with plaque phenotype.

Results

The luminal distribution of TAWSS, TSVI and ΔPAV are reported in Figure 1A for an explanatory case. Overall, sectors exposed to high TSVI at T1 exhibited ΔPAV in the T2-T1 time interval significantly higher than sectors exposed to low or mid TSVI at T1 (figure 1B). A clear trend emerged also for the exposure to low TAWSS at T1 and high ΔPAV. Plaque phenotype acted synergistically with TAWSS or TSVI regarding plaque progression: at low TAWSS or high TSVI sectors in combination with lipid rich plaque, ΔPAV values were significantly higher ($p<0.01$) than expected based on the individual contribution of hemodynamics.

Low values emerged for OSI (<0.01) and transWSS (<0.15Pa) suggesting a minor role of WSS multidirectionality in promoting aggravating biological events.

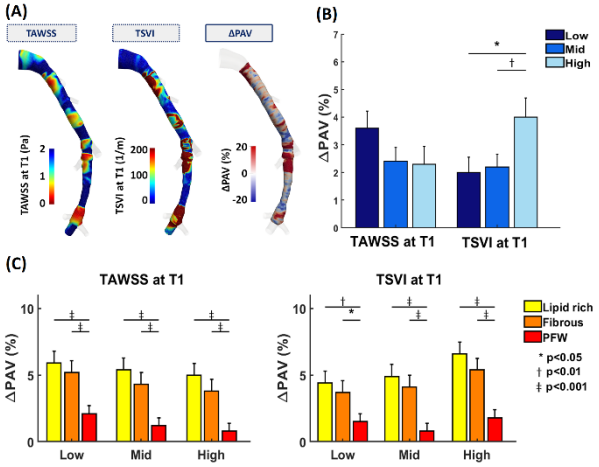

Figure 1: (A) TAWSS, TSVI and ΔPAV luminal maps; (B) TAWSS and TSVI vs. estimated PAV: (B) solely; (C) in combination with OCT-derived plaque phenotypes.

Discussion

Here we demonstrate that luminal exposure to high TSVI, solely or combined with lipid rich plaque phenotype, was associated with plaque progression. Physically, TSVI quantifies WSS contraction/expansion action variability on the endothelium, describing a different hemodynamic stimulus with respect to low TAWSS. This study confirms recent findings on TSVI as biomechanical marker of vascular disease, encouraging further trials for its translation to clinics.

References

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4. Mazzi V et al., Biomech Model Mec, 19(5):1403-23, 2020.