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

Giuseppe De Nisco (1), Eline Hartman (2), Valentina Mazzi (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 that have been 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 to predict the temporal evolution of coronary artery plaque burden (PB), a hallmark of atherosclerosis development, in 49 patient-specific computational models of human coronary arteries.

Methods

A non-culprit coronary segment for 48 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]:

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

PB growth was evaluated as the difference between PB measurements (100*plaque area/total vessel area) at T2 and T1 averaged over 3mm/45° luminal sectors. 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 PB growth measurements.

Results

Figure 1 reports (1) the luminal distribution of TAWSS and TSVI for two explanatory cases (panel A), and (2) the average PB growth values for low, mid, or high values of these two hemodynamic descriptors (panel B). Overall, sectors exposed to high TSVI at T1 exhibited PB growth in the T2-T1 time interval significantly higher than sectors exposed to low or mid TSVI at T1. A significant association emerged also for the exposure to low TAWSS at T1 and PB growth. An association also emerged between PB growth in the T2-T1 time interval and WSS multidirectionality at T1. However, the very low values of OSI (<0.01) and transWSS (<0.15 Pa) suggest a secondary role of the WSS multidirectionality in promoting aggravating biological events.

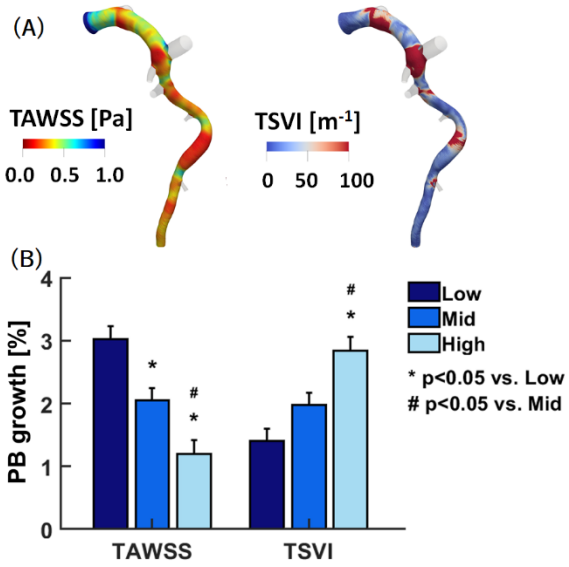

Figure 1: (A) TAWSS and TSVI luminal distributions; (B) TAWSS and TSVI vs. estimated PB growth.

Discussion

Here we demonstrate that luminal exposure to high TSVI was associated with significant PB growth. Physically, TSVI quantifies the variability of WSS contraction/expansion action 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 clinical trials for a translation of this concept into clinical practice.

References

1. Brown AJ et al., Nat Rev Cardiol, 13:210-220, 2016.
2. Morbiducci U et al., Ann Biomed Eng, 48:2936-49, 2020.
3. Candreva A et al., Atherosclerosis, 2021.
4. Mazzi V et al., Biomech Model Mechanobiol, 19(5):1403-23, 2020.