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A METHOD FOR THE ASSESSMENT OF THE MULTIDIRECTIONAL NATURE OF DISTURBED FLOW IN REALISTIC COMPUTATONAL HEMODYNAMICS ARTERIAL MODELS

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Fluid forces are thought to stimulate the endothelium to produce factors that can inhibit or promote inflammatory events. Studies on endothelial cells (ECs) have shown contrasting effects between unidirectional laminar and ‘‘disturbed’’ shear flow [1]. Wall shear stress (WSS) can change the morphology and orientation of the endothelial lining: ECs subjected to unidirectional shear flow tend to elongate and align in the direction of flow, whereas in areas of low and oscillatory shear, ECs look without a clear orientation, with a lack of organization of the cytoskeleton and junctional proteins. While it is widely accepted that the multidirectional nature of WSS impacts on the mechanosensitive ECs, descriptors to quantify the contribution of multidirectional components of the shear forces at the wall in arteries with complex geometry have been proposed only very recently [2]. Here we propose a method to project the local WSS vector into its axial and secondary (lying on a plane containing the cross-section of the vessel, analogous to secondary (in-plane) velocities) components. The method is applied to computational hemodynamic models of complex vascular districts. Image-based models of a carotid bifurcation and of a human aorta were reconstructed into the Vascular Modeling Toolkit (VMTK) environment. CFD was adopted to solve the governing equations of fluid motion under unsteady flow conditions and ultimately to calculate WSS surface distribution. Centerline **C** extraction in the form of a set of discrete points in space and calculation of its attributes were performed into VMTK. Attributes were used for surface parameterization: by applying a patching strategy, the Cartesian coordinates and the curvilinear abscissa as defined on its centerline of superficial mesh points were extracted. From the discrete and noisy observations of curves **C**, we need a representation in closed form. The reason for this choice is related to the need for calculating derivatives for **C** at each curvilinear abscissa S. The 3D free-knot regression splines were selected as a basis of representation. The analytical expression for $\mathbf{C}(S)$ allows to easily obtain the coordinates of curve **C** at each curvilinear abscissa S and the vector tangent at **C** in each point, $\mathbf{C}'(S)$, by derivation [3]. For a generic point P_k at the wall, we need to identify the cross-sectional surface of the vessel the point P_k belongs to (plane Π_k, defined by point P_k and the vector aligned with $\mathbf{C}(S)$ at abscissa S_k). By identifying plane Π_k we identify the local direction of vector $\mathbf{C}'(S)$, which is needed for projecting vector $\mathrm{WSS}(P_k)$ along with and orthogonal to **C**. The algorithm implemented for multidirectional WSS components calculation is presented in Fig. 1. We define as axial and secondary components of vector WSS at point P_k, $WSS_a(P_k)$, the projection of vector WSS along the direction of **C’** at the curvilinear abscissa S_k, and $WSS_s(P_k)$, lying onto the cross-sectional plane orthogonal to $\mathbf{C}'(S_k)$, respectively (Fig. 1):

$$WSS_a(P_k) = \frac{\mathbf{WSS}(P_k)\cdot\mathbf{C}'(S_k)}{\left|\mathbf{C}'(S_k)\right|} \qquad WSS_s(P_k) = \sqrt{\left|\mathbf{WSS}(P_k)\right|^2 - \left(WSS_a(P_k)\right)^2} \tag{1}$$

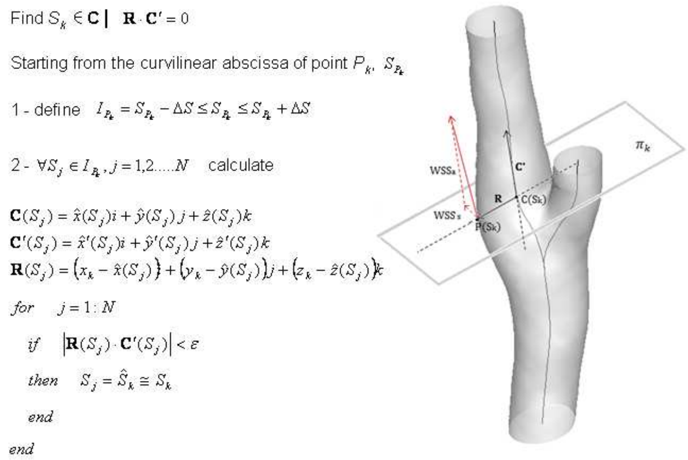

Fig. 1 – pseudocode of the algorithm for axial and cross-sectional WSS components calculation

As an example of the information that can be extracted from WSS decomposition, Fig. 2 shows the mutual contribution of the axial and secondary time-averaged WSS components at the luminal surface of a model of carotid bifurcation and of aorta.

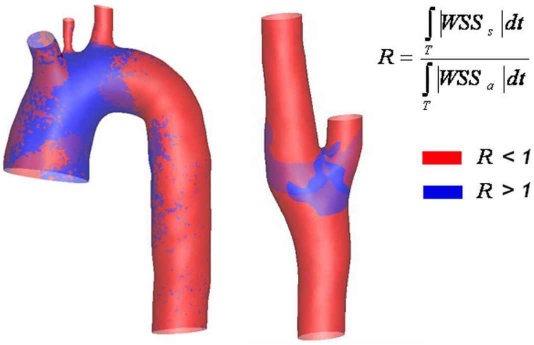

Fig. 2 - mutual contribution of the time-averaged multidirectional WSS vector components at the luminal surface of a model of carotid bifurcation and of aorta.

By visual inspection of Fig. 2, it is possible to appreciate the location of those regions where, e.g., WSS_s predominates over WSS_a. Currently "axial" is typically defined as the direction of the time-averaged WSS, which becomes ill-defined in regions of disturbed flow. Although it could be argued that using time-averaged WSS for “axial” makes sense from an EC-sensing point of view, the example in Fig. 2 emphasizes that the axial WSS definition proposed here is "geometric" and, for this reason, it is more generalizable for cardiovascular flows, since it doesn't rest a nominal EC-sensing mechanism. In the future, the approach proposed here for the analysis of the multidirectional character of disturbed flow in realistic computational hemodynamic models could be helpful for a more in depth investigation of the relation between the localization of atherosclerosis and hemodynamic factors.

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