3D quantification of wall shear stress and oscillatory index using finite-element interpolations in 4D flow MR data of the thoracic aorta.

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PURPOSE:

Actual methods quantify wall shear stress (WSS) parameters in one or several 2D planes from data obtained from 2D or 3D CINE PC-MRI acquisitions[1]. This approach however, does not provide the whole distribution of the WSS or oscillatory index in the entire vessel of interest. Moreover, the process of locating the 2D planes manually is dependent on the user and may lead to results that have low reproducibility. A few methods based on computational fluid dynamics (CFD) have been studied to obtain the WSS in 3D[2,3]. These methods provide the WSS and oscillatory distributions from realistic vascular geometries, and from several boundary conditions, such as wall stiffness, in-flow velocity profiles, and non-Newtonian blood models, which may not necessarily coincide with real conditions. In this work, we propose a 3D finite-element based methodology to compute the WSS of whole thoracic aorta from 3D CINE PC-MRI.

METHODS:

The domain of interest is discretized using tetrahedral elements, and the velocities at each node are interpolated from 3D CINE PC-MRI using a cubic approximation. The shear stress tensor (Eq.1) over whole aortic vessel is obtained from a global least-squares stress-projection method, from which the WSS vector is calculated using the inward unit normal vector at each node in the surface. We computed the WSS distribution in whole aortic vessel from 15 healthy volunteers and from one aortic coarctation phantom (Elastrat Sàrl, Geneva, Switzerland) using a pulsatile MR-compatible flow pump (Simutec, London, Ontario, Canada). To showcase the applicability of our method, we report and compared the WSS in three 2D cutting planes of the aorta along the cardiac cycle. We compare 2D WSS reformatted from the calculated 3D WSS versus 2D WSS calculated directly on 2D velocity data reformatted from 3D PC MRI. For the 2D WSS case we implemented a similar method based on finite element interpolations, but for 2 dimensional data, making all the red components of the stress tensor in red in Eq1. equal to 0.

$$\overleftrightarrow{\tau} = \frac{1}{2}\cdot\begin{pmatrix} \left(\frac{\partial v_x}{\partial x}+\frac{\partial v_x}{\partial x}\right) & \left(\frac{\partial v_x}{\partial y}+\frac{\partial v_y}{\partial x}\right) & \left(\frac{\partial v_x}{\partial z}+\frac{\partial v_z}{\partial x}\right) \\ \left(\frac{\partial v_x}{\partial y}+\frac{\partial v_y}{\partial x}\right) & \left(\frac{\partial v_y}{\partial y}+\frac{\partial v_y}{\partial y}\right) & \left(\frac{\partial v_y}{\partial z}+\frac{\partial v_z}{\partial y}\right) \\ \left(\frac{\partial v_x}{\partial z}+\frac{\partial v_z}{\partial x}\right) & \left(\frac{\partial v_y}{\partial z}+\frac{\partial v_z}{\partial y}\right) & \left(\frac{\partial v_z}{\partial z}+\frac{\partial v_z}{\partial z}\right) \end{pmatrix} \qquad \text{Eq. 1}$$

RESULTS:

The 3D WSS distribution can be appreciated in figure 1-A, obtained in 1 volunteer and in figure 2-A obtained in the arotic coarctation phantom. The 3D WSS contour mean and standard deviation values obtained with our method were lower than the 2D WSS values as can be seen in Figure 1 and 2 from B-C. We also found that, in general, the OSI contour mean values were also lower. The Bland-Altman plot showed a systematic bias between both methods with an average WSS contour mean difference of 0.069±0.03 N/m^2.

DISCUSSION:

Our results showed that the distribution shape of the 3D WSS was similar than the 2D WSS, however, the proposed method showed lower values. We believe this is because in the 3D quantification we used the complete deformation tensor (Eq. 1), and for the 2D analysis there are some component of the tensor matrix (Eq.1 red), which are omitted and the third column was eliminated with the normal vector in 2D. Those component are the derivatives of the through plane velocity along z which is not available when a single plane is used.

CONCLUSION:

We have developed a novel methodology to calculate 3D WSS based on FE interpolations and 3D PC MRI data, which provides an excellent approximation of local WSS values in the entire vessel of interest.

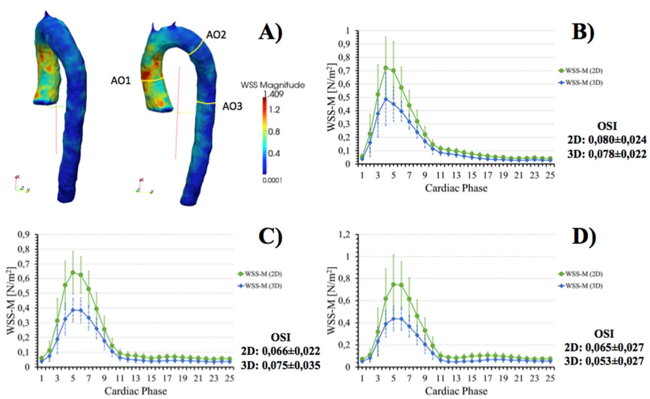

Figure 1. A) WSS magnitude for one volunteer in 3D, in B), C) and D) shows the magnitude of WSS and standard deviation between the volunteer group, for the AO1, AO2 and AO3 section respectively.

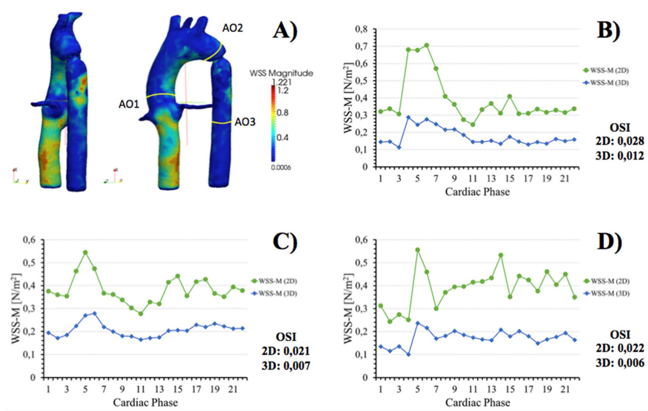

Figure 2. A) WSS magnitude for the Phantom in 3D, in B), C) and D) shows the magnitude of WSS for the AO1, AO2 and AO3 section respectively.

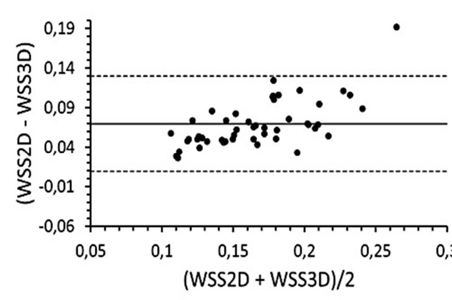

Figure 3. Bland-Altman plot of cardiac phase averaged of magnitude of wall shear stress contour mean comparing the proposed method in 3D and the 2D method from volunteer data.

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