Three-dimensional Assessment of Wall Shear Stress Distribution in the Carotid Bifurcation

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Introduction: Carotid artery stenosis is a leading cause of ischemic stroke. Detailed pathophysiological insights into the causes for the development of atherosclerosis at this site are necessary to prevent future cerebrovascular events. The development of atherosclerosis in the naturally bulbic ICA is related to anatomical and local hemodynamic conditions such as flow deceleration or recirculation. Particularly, low wall shear stress (WSS) and high oscillatory shear index (OSI) determine the complexity of stenotic lesions and predict the development of high-risk plaques [1, 2]. Since shear forces act on the vessel wall both along the axial and circumferential direction, the calculation of 3D vectorial WSS is desirable [3].

No comprehensive three-dimensional in-vivo analysis of the segmental distribution of normal WSS in the carotid bifurcation has been presented to date. Thus, we aimed to assess these vessel wall parameters in the carotid bifurcation of healthy volunteers using time-resolved phase contrast carotid MRI with three-directional velocity encoding.

Methods: 32 healthy volunteers (25.3±3.4 years) were examined by flow-sensitive 4D-MRI at 3 Tesla (TRIO, Siemens, Germany). Data were acquired in an axial 3D volume using a combined 12-element head and 6-element neck coil and a rf-spoiled gradient echo sequence with interleaved 3-directional velocity encoding (flip angle=15°, TE/TR= 3.6ms/5.7ms, venc=150cm/s, spatial resolution=1.1x0.9x1.4mm³, temporal resolution = 45.6ms) [4].

Data processing included noise filtering, correction for eddy currents and velocity aliasing. A 3D phase contrast (PC) MR angiography was calculated from the 4D MR data and combined with spatially co-registered 3D blood flow visualization (EnSight, CEI, USA, figure 1). For each volunteer seven analysis planes normal to the carotid lumen were extracted from the 4D-MRI data using the 3D PC-MRA for anatomical orientation (EnSight, CEI, USA, see also fig. 1) and were then imported into an in-house analysis tool (MatLab, The MathWorks, USA). Vectorial WSS was directly derived from the flow-sensitive 4D MRI data. First order derivatives of measured velocities were mapped directly onto the segmented lumen contours using cubic b-spline interpolation as described previously [5]. After segmentation of all measured time frames, absolute (WSS_{mag}) and circumferential (WSS_{circ}) were extracted for 12 segments along the vessel circumference (figure 2). The OSI reflected the degree of WSS_{mag} inversion over the cardiac cycle. To identify areas at risk for plaque development (low WSS_{mag} and high OSI), the segments representing the individual upper 15% of OSI and lower 15% WSS_{mag} were determined for each carotid bifurcation.

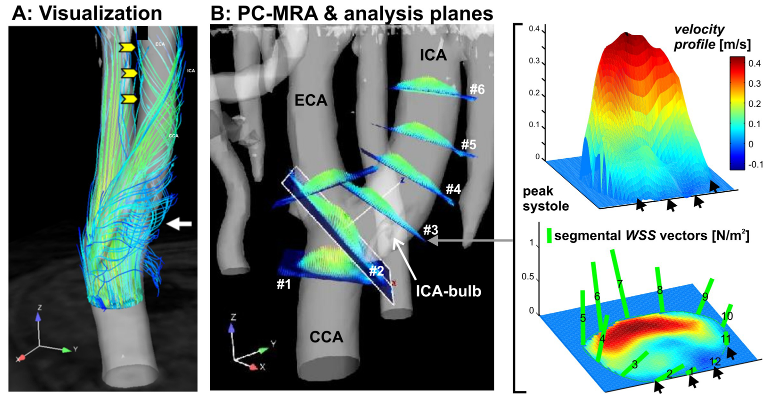
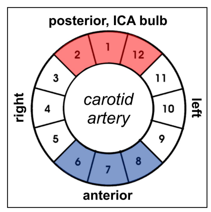


Fig. 1: **A:** 3D PC-MRA and 3D flow visualization in the carotid bifurcation **B:** Analysis planes for WSS quantification (left) and extracted peak systolic flow profile (top right) and derived WSS vectors (bottom right) in 12 angular segments. Reduced and helical flow in the bulb (segments 12, 1, 2) resulted in low WSS and high in-plane components (black arrows). CCA, ICA and ECA = common, internal and external carotid artery.



	slice	Posterior- Segments [12,1,2] OSI [%]	WSS_{mag} [N/m²] 10^3	WSS_{circ} [N/m²] 10^3	Anterior Segments [6,7,8] OSI [%]	WSS_{mag} [N/m²] 10^3	WSS_{circ} [N/m²] 10^3
CCA	#1	11.2	125.8	18.4	4.1	199.8	10.2
	#2	12.6	100.6	13.2	8.8	127.6	13.6
ICA	#3	12.6	123.6	19.4	2.1	240.5	0.6
	#4	5.2	226.4	7.3	1.3	273.9	1.8
	#5	2.2	320.1	4.5	1.4	294.2	7.4
	#6	1.5	391.4	0.9	1.5	307.9	8.8
ECA		7.0	206.8	14.1	6.0	186.7	0.5

Fig. 2: Orientation of segments within the analysis planes. Segments 12,1,2 (red) were located at the posterior wall of the ICA, i.e. within the physiologically dilated ICA bulb, segments 6–8 were located opposite the bifurcation. **Table 1:** Anterior (blue) and posterior (red) segmental WSS averaged over all analyzed 64 carotid bifurcations.

Results: 3D blood flow visualization could be used to identify flow deceleration and right-handed helical flow in the carotid bulb and distal ICA (figure1, arrows) indicating altered shear stress compared to straight flow without any rotational component (figure 1, right).

Figure 2 and Table 1 summarize the WSS and OSI distribution of all volunteers. Table 1 compares mean WSS_{mag}, WSS_{circ}, and OSI in anterior regions with values obtained at the ICA bulb (segments 12,1,2 and slices 1-3, gray shaded area in table 1). For the bulb, a marked reduction of WSS_{mag} in comparison to anterior regions was evident. In the same posterior region, a substantially enhanced WSS_{circ} and OSI can be observed which is consistent with the helical flow pattern illustrated in figure 1. Identification of segments potentially predisposed to the development of atherosclerosis (individual 15% thresholds) is illustrated in figure 3. A very high incidence of low WSS_{mag} and high OSI was found in slices 1-3 and posterior segments (11,12,1-3) in almost all 64 carotid arteries. These results indicate a very high inter-individual consistency in segments experiencing atherogenic WSS.

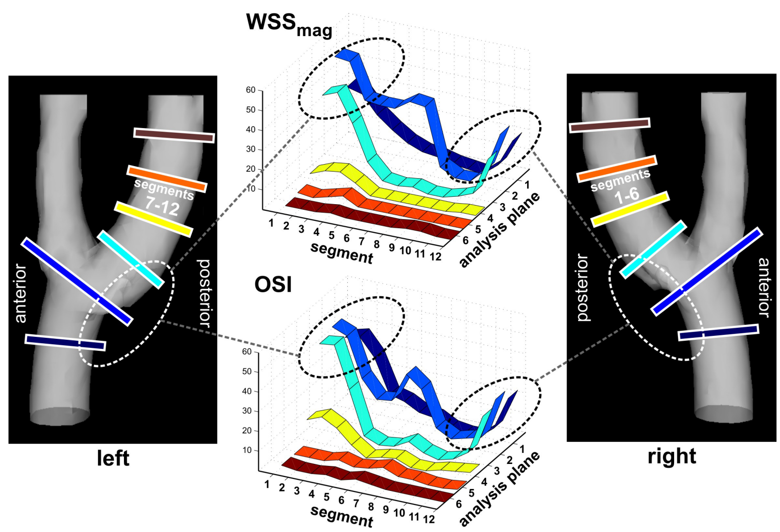


Fig. 3: Segmental distribution of the individual upper 15% of OSI and lower 15% of WSS_{mag} in all analyzed 64 carotid arteries and 6 analysis planes in the CCA and ICA. The segmental distribution in the central graphs represents the number of volunteers who had potentially atherogenic low WSS_{mag} or high OSI in the respective carotid region.

Discussion: Flow sensitive 4D MRI in the carotid bifurcation provides visual 3D information of blood flow which can be directly combined with absolute velocities or local wall shear stress at the individual site of interest, i.e. within the carotid bulb or ICA stenosis. The marked reduction of flow and thus absolute and circumferential wall shear stress in the ICA bulb compared to other segments can help explaining why ICA stenosis predominantly develop and progress at this location. The results presented here provide a reference standard for the distribution of normal WSS which is an important perquisite for the examination of patients with high-grade ICA stenosis. Future patient studies will evaluate the potential of WSS analysis to independently predict the individual risk for the development of ICA stenosis.

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