Automatic Intracranial 3D Wall Shear Stress Vessel Segmentation and Localization

Eric Schrauben[1,2], Anders Wåhlin[2,3], Khalid Ambarki[2,4], Jan Malm[5], Oliver Wieben[1,6], and Anders Eklund[2,4]

[1]Medical Physics, University of Wisconsin - Madison, Madison, Wisconsin, United States, [2]Radiation Sciences, Umeå University, Umeå, Sweden, [3]Umeå Center for Functional Brain Imaging (UFBI), Umeå University, Umeå, Sweden, [4]Center for Biomedical Engineering and Physics, Umeå University, Umeå, Sweden, [5]Clinical Neuroscience, Umeå University, Umeå, Sweden, [6]Radiology, University of Wisconsin - Madison, Madison, Wisconsin, United States

TARGET AUDIENCE: Physicists and clinicians interested in fast, automated segmentation and quantification of intracranial WSS from 4D flow MRI.

PURPOSE: Wall shear stress (WSS) describes the drag force on the endothelial surface of vessels induced by the movement of blood. Historically, high WSS correlates with outward vascular remodeling, particularly in aneurysm impingement zones, while low WSS has been used as a biomarker for atherosclerotic development[1]. In MR, the calculation of WSS is often based on the assumption of a parabolic blood velocity profile, and is typically only measured in 2D cut planes[2]. While 3D approaches have been presented before, their calculation is time-consuming, requiring volumetric manual segmentations of vessel regions for WSS comparison[3]. This analysis has only been performed on large or straight vessels, which allows for relatively easy labeling of vessel wall regions. This type of segmentation is not practical in tortuous vessels, such as the siphon of the internal carotid artery (ICA). Computer fluid dynamic simulations have shown WSS to be perturbed in ICA siphon curves, with higher outer-wall WSS and lower inner-wall WSS[4]. Here we present an extension to the algorithm proposed in [3] for improved usability in cranial flow analysis by adding an automatic vessel segmentation and wall region labeling method to localize WSS calculations. It is evaluated in vivo in the ICA siphon.

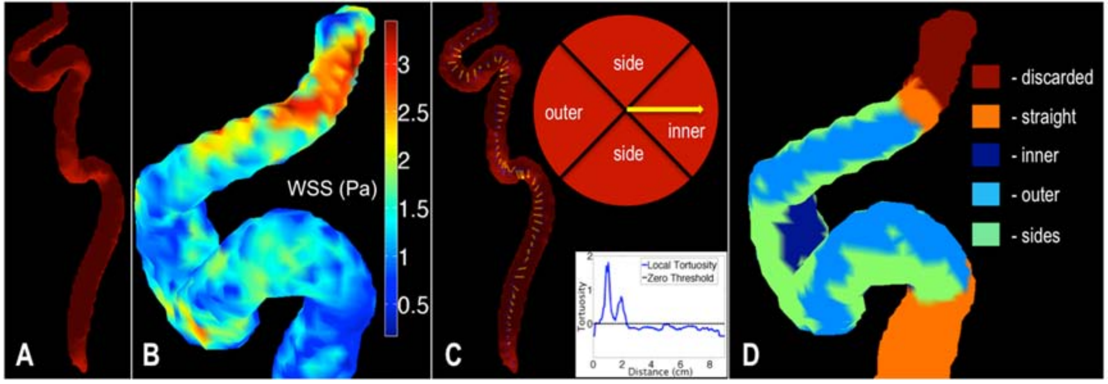


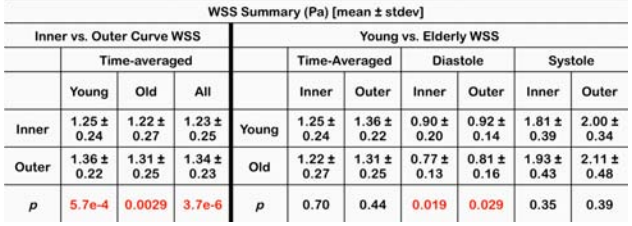
Figure 1. A: automatic isosurface right ICA segmentation B: zoomed siphon with WSS calculations at each vertex. C: background – vessel with calculated centerline normals (yellow arrows); inset top – pictorial view of cross-sectional quadrants to sort WSS measurements; inset bottom – tortuosity calculation for determination of curved and straight vessel segments D: final representation of vessel regions of fluid dynamic interest.

METHODS: All processing is completed using an in-house tool developed in commercial software (Matlab, *Mathworks*, MA, USA). After reconstruction of a high resolution 4D MR flow dataset, centerline extraction for the entire vascular tree is performed on the PC MR angiogram, labeling each vessel with a unique branch number. The user interacts to select a vessel of interest, in this case the ICA, which is automatically segmented into a 3D isosurface (Figure 1a) built from triangular faces connected by vertices. Inward unit normal vectors are computed for each vertex, from which WSS is estimated (Fig. 1b) using the equation $WSS = \mu \frac{\partial v}{\partial n}$, where μ is blood viscosity (assumed to be constant 4.0 cP), v is velocity, and n is the inward surface normal. Quadratic (parabolic) polynomial interpolation of velocity at and adjacent to the surface is used for WSS calculation. To localize WSS calculations, isosurface vertices are assigned to each centerline point: 3D vessel centerline normals are calculated, and the resulting angle between inward surface normal and centerline normal determine if each WSS calculation was part of inner-, outer-, or side-wall regions (Fig. 1c). Lastly, to determine segments of the vessel that are straight or curved, local tortuosity is calculated at each centerline point. Points above zero are considered part of the vessel curve, while points below are considered straight segments (Fig. 1c-bottom). This process assigns WSS values to either curved or straight segments, and to inner-, outer-, or side-wall regions of these segments (Fig. 1d).

Ten healthy young (7M, age 37 ± 9 years) and ten healthy elderly (6M, age 67 years) subjects were imaged after informed consent with a 4D radially undersampled flow MRI technique[5] on a 3T magnet (Discovery MR750, *GE*, WI, USA). Scan parameters: 32 channel head coil, FOV = 22 x 22 x 22 cm^3, $(0.7\ mm)^3$ isotropic spatial resolution, scan time = 9.5 min, Venc = 110 cm/s, 20 reconstructed cardiac time frames. Cardiac time-averaged, diastolic, and systolic WSS measurements were performed on forty ICA siphons. Differences between inner and outer curves as well as between young and elderly individuals were tested with paired (between vessel wall regions) and unpaired (between age groups) student t-tests.

RESULTS and DISCUSSION: Table 1 presents results of mean wall region WSS values and statistical comparisons between regions and groups. Red numbers indicate statistical significance ($p < 0.05$). In curves, inner-wall WSS is significantly lower than outer-wall WSS across young, old, and combined time-averaged measurements. Comparing young and old, significant differences occur only for inner- and outer-walls during diastole. This lower WSS in the ICA siphon may be a normal result of the aging process, caused by altered arterial compliance and vascular resistance as one ages[6]. Automatic segmentation of the vessel wall into curved versus straight segments as well as inner-, outer-, or side-wall regions provides a reduction in post-processing times and user dependent segmentations while giving WSS measurements in locations with relevant fluid dynamics.

CONCLUSION: 4D flow MRI in conjunction with a novel 3D WSS post-processing method exhibits significant differences in inner versus outer-wall vessel regions in curves as well as differences between healthy young and elderly diastolic WSS. Further studies into the optimization of post-processing settings and pathologies in which to use this method are warranted.



WSS Summary (Pa) [mean ± stdev]										
Inner vs. Outer Curve WSS				Young vs. Elderly WSS						
	Time-averaged				Time-Averaged		Diastole		Systole	
	Young	Old	All		Inner	Outer	Inner	Outer	Inner	Outer
Inner	1.25 ± 0.24	1.22 ± 0.27	1.23 ± 0.25	Young	1.25 ± 0.24	1.36 ± 0.22	0.90 ± 0.20	0.92 ± 0.14	1.81 ± 0.39	2.00 ± 0.34
Outer	1.36 ± 0.22	1.31 ± 0.25	1.34 ± 0.23	Old	1.22 ± 0.27	1.31 ± 0.25	0.77 ± 0.13	0.81 ± 0.16	1.93 ± 0.43	2.11 ± 0.48
p	5.7e-4	0.0029	3.7e-6	*p*	0.70	0.44	0.019	0.029	0.35	0.39

Table 1. Summary of WSS measurements in curved regions.

Acknowledgements: We gratefully acknowledge funding by Swedish Research Council grant number 221-2011-5216, the Swedish Brain Foundation, NIH grant 2R01HL072260 and GE Healthcare for their assistance and support.

REFERENCES: **1**. Dolan JM, et al. *Annals of Biomedical Engineering*. 2013. **2.** Box FMA, et al. *Invest Radiol.* 2003. **3.** Bieging E, et al. *JMRI.* 2011. **4.** Zhang C, et al. *Surg Radiol Anat.* 2013. **5.** Gu T, et al. *AJNR*. 2005. **6.** O'Rourke MF and Hashimoto J, *JACC*. 2007.