Calculation of Wall Shear Stress in Intracranial Cerebral Aneurysms Using High Resolution Phase Contrast MRA (PC-VIPR)

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Introduction:

Cerebral aneurysms are a major cause of morbidity and mortality in the United States, with 60,000 cases and 20,000 deaths per year, and as high as 65% mortality when rupture leads to subarachnoid hemorrhage (SAH).[1] Recent reports suggest that high wall shear stress (WSS) is seen proximal to aneurysms, promoting aneurysm formation, and low WSS is seen in aneurysms, promoting growth.[2,3] Areas of low WSS have also been associated with aneurysm ruptures in several studies.[3-5]

Therefore, WSS analysis may have prognostic value in identifying sites vulnerable to aneurysm formation, progression, and rupture. This has clinical utility in evaluating the risk of SAH second to saccular cerebral aneurysms. Recent advances in 4D phase contrast MR have facilitated WSS analysis in cranial aneurysms based on in-vivo velocity measurements. However, the high demands for obtaining spatial and temporal resolution for hemodynamic assessment in aneurysm in clinically useful scan times remains a challenge. The recently proposed dual-echo phase contrast 3D radial (PC-VIPR[6]) approach has demonstrated the ability to produce high resolution velocity-encoded angiograms of the head and neck of diagnostic quality in as little as 5 minutes.[7] Velocity data from PC-VIPR,[8] along with an automated spline interpolation that allows more accurate visualization of the boundary zone at the vessel wall[9] was used to compare WSS in patients with aneurysms in the internal carotid artery (ICA) to WSS in ICAs of healthy volunteers.

Materials & Methods:

Volunteer studies were performed in compliance with HIPAA using a protocol approved by the local Institutional Review Board (IRB). 10 healthy volunteers (age 19-58, 6 female, 4 male) and six patients (age 28-72, all female) with known aneurysms of the ICS and paraclinoid ICA (3-4mm, verified with DSA, **Figure 1a**) were imaged with a GE HD750 3.0T MR system with an 8-channel head coil. Immediately following contrast enhanced acquisition as part of the PC HYPRFlow[7] protocol, velocity-encoded dual-echo 3D radial phase contrast acquisition (PC-VIPR) was acquired at a spatial resolution of $0.67 \times 0.67 \times 0.67 \text{mm}^3$. Following reconstruction, the images were imported into a visualization software package (Ensight, CEI Inc, Apex, NC) where cutplanes **(Figure 1d)** proximal to the aneurysm and directly through the aneurysm were interactively placed in the patient data, and cutplanes in corresponding areas in the ICAs of volunteers were generated. The time-average velocity data was then imported into custom Matlab runtime environments which used B-spline interpolation with Green's Theorem to calculate WSS.[9] In addition to the cutplanes, surface-rendered WSS maps **(Figure 1b-c)** were generated to provide a global assessment of WSS patterns and to localize areas with abnormal WSS.

Results:

The average WSS for patients in the ICA proximal to the aneurysms was $1.49 \pm 0.21 \text{ N/m}^2$. The WSS inside the aneurysms was $0.56 \pm 0.08 \text{ N/m}^2$. In healthy volunteers, the WSS in five segments of the ICA ranged from $0.97\text{-}1.19 \text{ N/m}^2$ with an average of $1.08 \pm 0.13 \text{ N/m}^2$; this was statistically different from both proximal WSS (p=0.004) and WSS inside the aneurysms (p < 0.001). These results are consistent with results in recent studies that suggest that high proximal WSS contributes to aneurysm formation and low WSS is prevalent in aneurysms, promoting progression.[2,3] WSS maps also allow flow patterns to be visualized; higher proximal WSS, lower WSS in the aneurysm, and abnormal distal WSS patterns are seen on the WSS map in **Figure 1b** (arrows). WSS analysis may also be useful for aneurysm detection by looking for areas in the brain with abnormal WSS.

Figure 1: a) top left: DSA image of the aneurysm. b) top right: WSS map of the aneurysm. c) bottom left: WSS map of the ICS in a normal volunteer. d) bottom right: cutplanes on magnitude and velocity images.

Discussion:

In this study, we demonstrate that PC-VIPR has sufficient spatial resolution to visualize, obtain velocity measurements, and calculate velocity derivatives such as WSS in aneurysms as small as 3-4mm in diameter. Our results found high WSS was prevalent in arteries immediately proximal to aneurysms and low WSS was seen inside the aneurysms, when compared to WSS in corresponding segments in normal volunteers. This is consistent with published reports that implicated high WSS proximal to aneurysms in promoting aneurysm formation and suggested that low WSS was associated with the growth and rupture of cerebral aneurysms. PC-VIPR can be used to identify areas potentially vulnerable to aneurysm growth, detect cerebral aneurysms in patients presenting with clinical signs/symptoms, characterize morphology with surface-rendered 3D segmentation and flow characteristics with stream/path lines,[10] and evaluate the risk of aneurysms in the whole brain by monitoring WSS maps, with scan times as short as 5 minutes. WSS analysis of PC-VIPR data provides an attractive alternative to time-consuming CFD analysis with clinical potential.

References: 1) de Rooij et al, JNNP 2007 2) Hoi et al, JNS, 2004 3) Shojima et al, Stroke, 2004 4) Jou et al, AJNR 2008 5) Li et al, IFMBE, 2009 6) Johnson et al, MRM 2008 7) Wu et al, ANJR 2010 8) Chang et al, AJNR 2010 9)Stalder et al, MRM 2008 10)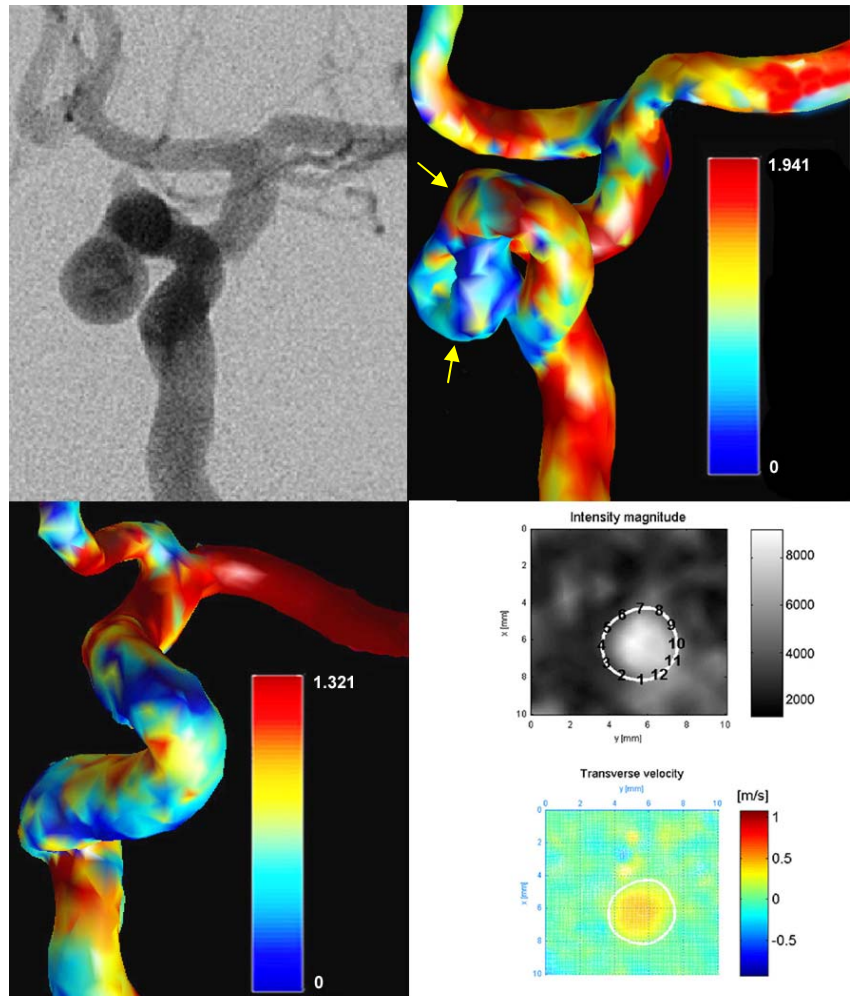 Johnson et al, IEEE EMBS, Minneapolis, 2009