MR-based, subject-specific computational fluid dynamics modeling of the vertebro-basilar system

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Introduction. Intimal hyperplasia (IH) is a common cause of coronary artery bypass graft failure, and previous studies have demonstrated a correlation between IH and hemodynamic factors (e.g., wall shear stress) and used this correlation to influence graft design [e.g., 1-4]. The vertebro-basilar system is one of the few locations in the human arterial tree where two major arteries (vertebral arteries) merge into a single vessel (basilar artery). Since this is a native merge, investigating the hemodynamic features of this system in healthy subjects can be used to improve vascular graft design for ensuring graft/vessel patency. Our study uses high field MR and phase contrast MR (PCMR) to characterize vertebro-basilar system hemodynamics in a healthy, adult subject for the goal of identifying flow patterns (e.g., low wall shear stress) relevant to graft failure.

Methods. Geometry and velocity data were obtained using a Philips Achieva 3T MR scanner (Philips, Netherlands). Three-dimensional time-of-flight (TOF) angiography was used to determine cerebrovascular geometry of the vertebro-basilar system and to define acquisition planes for PCMR measurement. Scan parameters: FOV=160 mm x 90 mm x 60 mm; voxel size=0.5 mm x 0.5 mm x 0.6 mm; TR=23 ms; TE=3.5 ms; SENSE factor=1.5. Measurement planes were oriented perpendicular to the direction of flow, and the through-plane velocity was measured across the lumen of the vessel using retrospectively ECG-triggered PCMR. Scan parameters: FOV=100 mm x 100 mm; voxel size=0.4 mm x 0.4 mm x 5 mm; TR=15 ms; TE=7 ms; SENSE factor=2; VENC=110 cm/s; time-points=21. The time-varying velocity distribution across the right and left vertebral arteries was measured at 21 time-points throughout the cardiac cycle (Figure 1). Lumen geometry was segmented from the TOF data and reconstructed using MATLAB (Mathworks, Inc.). The resulting arterial geometry was imported into Gambit (Ansys, Inc.), where it was discretized (~12,000 tetrahedral elements). A commercially available computational fluid dynamics (CFD) code, FLUENT (Ansys, Inc.), was used to solve for steady flow at a time-point just prior to peak systole.

Results and Discussion. Regions of high WSS (WSS > 2.8 Pa) are seen in the distal left vertebral artery (LV) and on the anterior surface of the proximal basilar artery (BAS) (Figure 2). The intersection point of the two arteries is an area of locally low WSS (WSS < 1.3 Pa), as is the posterior surface of the BAS. The volumetric flow rate of the LV is slightly less than that of the right vertebral artery (RV) (1.2:1.6), and the LV diameter is smaller than that of the RV. The combination of the flow division and the relative size of the vertebral arteries contributes to the high WSS region in the LV. The locally high WSS values on the anterior face and the low WSS region on the posterior surface of the BAS are due to the curve in the BAS. The vertebro-basilar system curves in the anterior-posterior plane (i.e., the outer curve of the vessel is anterior), which would cause the velocity profile to skew towards the anterior; thus, the WSS is higher on the outer curve of the vessel than on the inner curve of the vessel. The geometry and flow division predominantly influence the WSS distribution in this simulation; however, physiologic flow is pulsatile. The pulsatility (and the fluctuating flow divisions in the feeder arteries) likely will influence WSS distributions.

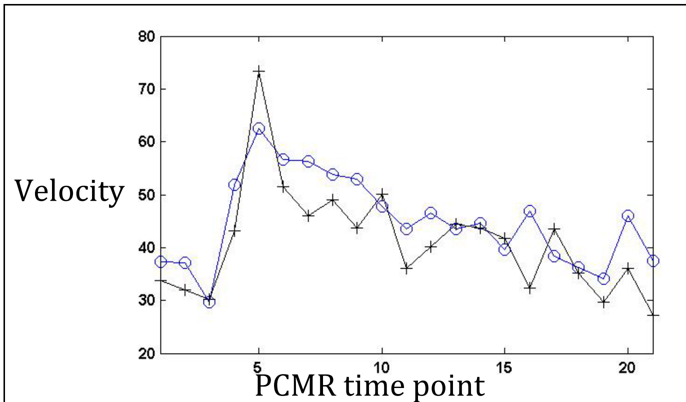

Figure 1. PCMR-measured maximum velocity (cm/s) values over time for the right vertebral artery (o, blue line) and the left vertebral (+, black line).

Conclusion. The flow field of the vertebro-basilar system has been investigated for several pathologies (e.g., aneuerysms); however physiologic flow in this system is not well characterized. Understanding the nature of flow in this system will be directly relevant to the improved design of arterial bypass grafts. These results highlight the geometric and flow contributions to WSS in the vertebro-basilar system that will yield useful insight into vascular bypass graft design. In the near future we will construct subject-specific, pulsatile CFD models that will describe the time-varying flow field, and data from additional subjects will be analyzed.

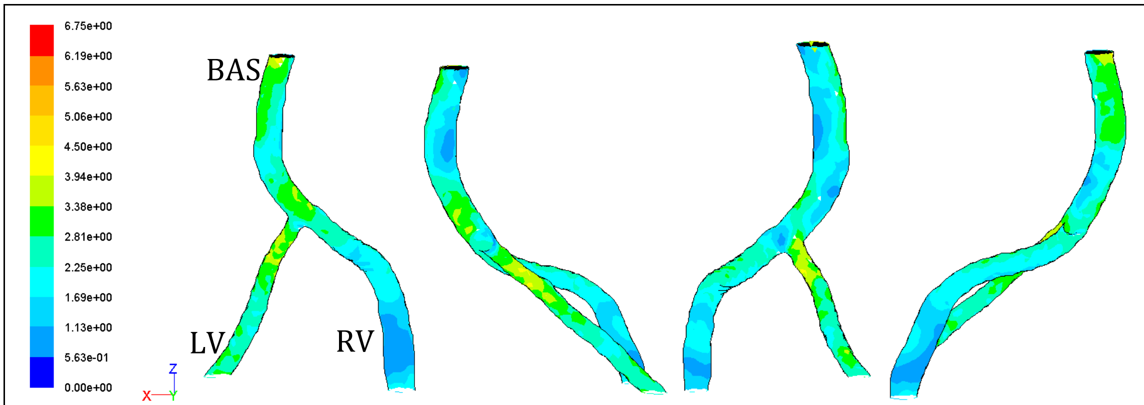

Figure 2. Wall shear stress (WSS) (Pa) results calculated for the vertebro-basilar system at a time point immediately prior to peak systole. Vertebrobasilar system is shown rotated at 90° increments. BAS=basilar; LV=left vertebral; RV=right vertebral.

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