An MRI-based CFD analysis of flow patterns in the jugular vein

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Target audience: For those interested in the hemodynamics of the jugular vein.

Purpose: Abnormalities of the venous anatomy are considered to play a role in a number of important cardiovascular conditions. These include situations such as arteriovenous fistulas which generate pulsatile jets into the venous anatomy resulting in pulsatile tinnitus, and in the purported link of obstructive venous outflow to the development of multiple sclerosis. Evaluation of the anatomy is complicated by the large variability in venous outflow patterns even in normal subjects where there is often a one-sided dominant flow distribution. Furthermore, conventional imaging modalities, including catheter-based methods, provide little insight into the complex flow patterns in these tortuous vessels. The aim of this study was to use subject-specific CE-MRA determined anatomy, and MRV-based inlet flow conditions to develop CFD models of flow in normal subjects and in subjects with suspected venous abnormalities to investigate how the geometry of the jugular vein affects the flow field.

Methods: 11 jugular veins (6 normal, 5 with suspected venous abnormalities) were imaged with CE-MRA A test bolus run (2cc at 2cc/s) with a 3D time-resolved low spatial resolution acquisition having a 1 sec temporal footprint was acquired to determine optimal timing of the contrast injection for the CE-MRA run. The CE-MRA run was acquired at 0.7mm x 0.7mm x 0.7mm spatial resolution and total acquisition time was 32 secs. 2D PC-MRV was also acquired transverse to the sigmoid sinus to determine inlet flow conditions. A VENC of 100 cm/sec was used in all studies. Surfaces were segmented using VMTK (Orobix, Bergamo, Italy) and Geomagic Design X (Geomagic, Rock Hill, USA). Tetrahedral meshing was also performed in VMTK, using a target edgelength of 0.8mm. CFD simulations were performed in FLUENT (ANSYS, Canonsburg, USA), using flow values obtained from the in vivo measurements.[1] Flow patterns in the jugular vein were characterized by their vortex core-lines, which were extracted from simulation data using Ensight (CEI, Apex, USA). Additional flow-parameters were calculated in MATLAB (Mathworks, Natick, USA) and visualized using Paraview (Kitware, New York, USA).

Results: Patients with suspected venous anomalies had flow patterns with features that were, in general, quite distinct from those in normal subjects. Normal flow was characterized by vortex cores in the jugular bulb (Figure 1, left), which neatly redirected the flow along the curvature of the bulb straight into the jugular vein (Figure 2, left). Abnormal flow was characterized by an inability to form these shunting vortex cores due to the geometrical differences, which forced incoming flow directly into the jugular vein at a perpendicular angle (Figure 2, right), creating larger helical flow structures throughout the proximal jugular vein (Figure 1, right). High flow rates, and even the presence of turbulence, was noted in the distal jugular vein – close to the level of the bifurcation of the extracranial carotid arteries – where there was often pronounced narrowing of the jugular.

Discussion: Our results suggest a link between geometry, flow, and adverse conditions in the jugular vein, which is an important first step toward determining potential disease mechanisms. Additionally, there are "outliers" (control subjects with abnormal jugular veins and vice versa), which imply that beyond the geometry and general flow features, there may be a critical hemodynamic parameter threshold, not yet defined, that determines what constitutes a pathological condition.

Conclusion: The geometry of the jugular vein significantly affects the position, size, and length of the vortex cores. CE-MRA and 2D-PC MRV are convenient tools for building a CFD model on a subject-specific basis. This combination of approaches permits the visualization of flow structures that are not directly accessible using other in vivo imaging modalities. CFD can augment or extend patient-specific analyses by allowing us to assess the sensitivity of flow structure formations to parameters such as blood viscosity, inlet flow, and steady versus unsteady flow conditions.

References

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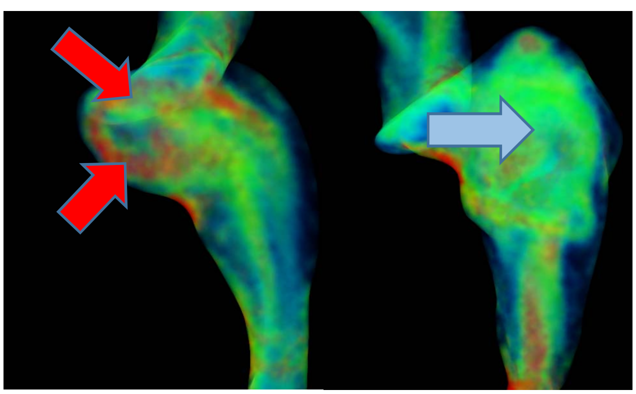

***Figure 1**. Visualization of vortex cores by swirling strength.* **(Left)** Typical normal subject case, with strong vortex cores in jugular bulb (red arrows). **(Right)** Typical patient case, with a larger, more diffuse vortex core encompassing nearly the entire proximal jugular vein (blue arrow).

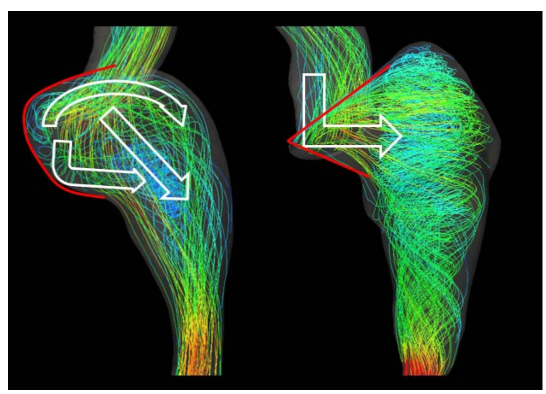

***Figure 2.**. Visualization of Streamlines.* Subjects are the same as in Figure 1. White arrows represent the general re-direction of flow from the sigmoid sinus into the jugular vein. Red lines emphasize the shape of the jugular bulbs, which dictate the flow.