An in vivo MRI and computational fluid dynamic simulation of cerebrospinal fluid hydrodynamics in the third ventricle

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Overview In this study, we performed 7D flow measurements and geometry-based computational fluid dynamic (CFD) analysis of the ventricular system of a healthy volunteer and made comparison of the two techniques in the aqueduct of Sylvius and third ventricle.

Introduction Accurate quantitative measurements of cerebrospinal fluid (CSF) flow velocities are difficult to obtain with conventional magnetic resonance methods due to long longitudinal relaxation time and limited inflow enhancement. In order to maximize the inflow effect, the commonly used technique is through-plane phase contrast MRI based on spoiled gradient echo (SPGR), which is only sensitive to velocity in one direction. Phase contrast balanced steady-state free precession (PC-bSSFP) can be used to measure CSF velocities with higher signal levels and therefore it enables a three-directional, three-dimensional time-resolved (7D) mapping of the velocity field (Santini, Wetzel et al. 2009).

Methods 7D PC-bSSFP CSF velocity measurements of the ventricular system of the brain were performed on a healthy 25 year-old male volunteer on a 3T Siemens scanner, with an encoded velocity of 15 cm/s, TR/TE 13/6.5 ms, flip angle 45°, and 1.03x1.03x1.40 mm resolution. The 7D MRI data set were pre-processed using a custom software tool (Bock, Frydrychowicz et al.), and visualized with EnSight (CEI, Apex, NC) and Matlab (The Mathworks, Natick, MA) software.

A morphological high-resolution trufi sequence, with a resolution of 1.04*1.04*1 mm, was used to define the brain ventricle geometry for the CFD simulation. The MR geometry scan of the ventricles was manually segmented using ITK Snap (Yushkevich, Piven et al. 2006) to obtain a three-dimensional representation of the ventricles, and adapted to form inlet and outlet locations using the software Rhinoceros (McNeel, Seattle, WA). Conventional through-plane phase contrast SPGR velocity mapping scans, with 10 cm/s velocity encoding and 0.62x0.62x4.50 mm resolution, were used to acquire CSF velocity at the aqueduct of Sylvius for the flow boundary condition of the CFD model. The measured velocity profiles were manually phase-unwrapped, and processed with the Segment software Segment version 1.8 R1145 (http://segment.heiberg.se) (Heiberg, Sjogren et al.). A rigid wall computational mesh was formed based on the MR geometry scan using the software ICEM CFD. CSF velocity was imposed at the aqueduct of Sylvius with the CSF modeled as an incompressible Newtonian fluid with the same density and viscosity as water at body temperature. The outlet pressure was set to zero at the foramina of Monro. Computations were performed using the commercial finite volume CFD solver CFX (Ansys, Canonsburg, PA). Different meshes were utilized in different runs, with an average of $2*10^3$ nodes which approximately correspond to 10^6 tetrahedral cells. The total simulation time of every run was sufficient for temporal periodicity to be established.

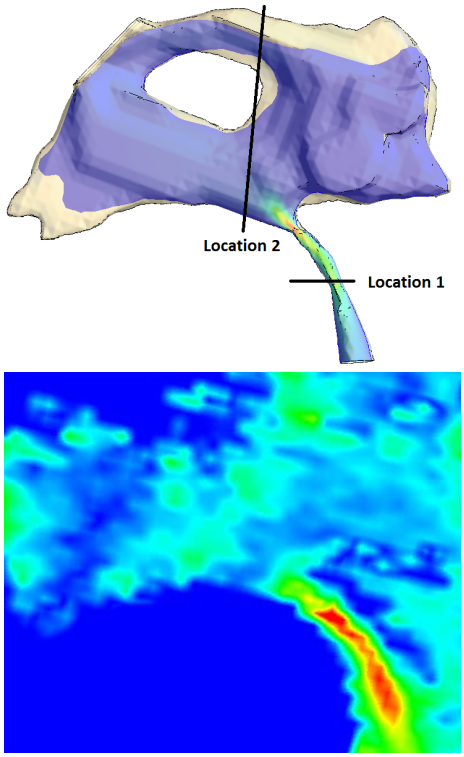

Figure 1. Comparison of peak CSF velocity magnitude in the mid-sagittal plane for CFD (top) and 7D MRI (bottom).

	Velocity min/max [mm/s]	Stroke volume [µL]
7D MRI – location 1	-8.50/12.5	-110
CFD - location 1	-34.9/28.4	-168
7D MRI – location 2	-11.1/13.6	-227
CFD - location 2	-0.967/1.73	-181

Table 1. Comparison of CFD and 7D MRI results.

Results The 3D CFD and 7D MRI measurements agree qualitatively and qualitatively in the aqueduct of Sylvius in terms of stroke volume and to a lesser extent in peak and minimum velocity (Table 1). In the 3rd ventricle, the CFD results did not match the 7D MRI measurements, with large differences in velocity distribution and magnitude, particularly where the CSF velocity is low at locations further away from the aqueduct of Sylvius (Figure 1).

Conclusion The 7D MRI measurements were useful to quantify CSF flow velocity in the aqueduct of Sylvius, but not in the 3rd ventricle, where CSF velocities are lower. CFD simulation is time consuming and requires many pre-and post processing steps to obtain flow results. Each of these steps can introduce error to the result. Thus, the 7D MRI measurement technique has an inherent advantage over CFD techniques that are highly sensitive to boundary conditions. The 7D MRI technique can be improved by 1) optimization of the velocity encoding value in different areas of the flow field, 2) reduction of noise due to breathing, and 3) streamlining data visualization and processing to obtain quantitative results for use in clinical settings.

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