Numerical Modeling of CSF Flow in Patient - Specific Anatomical Models

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INTRODUCTION

The Chiari I malformation of the brain is characterized by the cerebellar tonsils extending into the upper cervical spinal canal. The position of the tonsils impedes cerebrospinal fluid (CSF) flow in the foramen magnum. Hypothetically, the altered fluid dynamics in the Chiari I malformation cause the development of neurological signs and symptoms, including a cyst in the spinal cord, called syringomyelia. *In vivo* CSF flow measurements with flow-sensitive magnetic resonance (MR) have demonstrated significant differences between CSF flow in Chiari I patients and normal controls [1]. In the presence of the malformation, the CSF flow waveform is more complex and CSF velocities are increased. Better analytical and numerical techniques are needed to differentiate CSF flow patterns that produce symptomatology from those that do not. With better techniques, selection of patients for surgical management may improve. In this work, a method is presented to generate a computational fluid dynamic model of CSF flow from a high resolution 3D MR acquisition.

MATERIALS AND METHODS

CSF flow dynamics may be analyzed by means of the Navier-Stokes equations [2] if CSF is assumed to be incompressible and a Newtonian fluid. Several numerical techniques have been developed to achieve approximate solutions to the Navier-Stokes equations in the CSF flow phenomena, either for physiological or pathological conditions. Here, we choose the boundary element method (BEM), which requires discretization of the domain surfaces only [3].

A multi-echo 3D radial acquisition (VIPR) was used for fully refocused SSFP imaging with isotropic spatial resolution and fat/water separation [4]. A 20x20x20 cm^3 image volume of 256x256x256 voxels was acquired in a five-minute scan time. The high contrast between CSF and the surrounding tissues and the high spatial isotropic submillimeter resolution (Figure 1) are ideally suited for the creation of an accurate model. A 3D geometry was built with commercial software (Mimics 9.0, Materialise Ann Arbor, MI, USA) using semi-automatic segmentation. The BEM implementation was performed by discretization of the boundary into a series of elements over which velocities and tractions are assumed to vary according to interpolation functions. In the computational fluid dynamics (CFD) model, the elements were defined by a number of nodes where the unknown values of the velocity are sought. The boundary conditions for inlet and outlet geometry were defined from velocity measurements computed from the images produced by the VIPR acquisition. A non-slip boundary condition was used for the canal walls. Velocities and pressures were calculated for the internal points located within the flow domain (subarachnoid space) based on the conditions predetermined by the boundary elements. Velocity contour maps were created from the data (MATLAB 6.0, The MathWorks Inc., Cambridge, MA, USA). Velocity results were normalized to the peak velocity and plotted as contours together with the geometry constructed from MR scans.

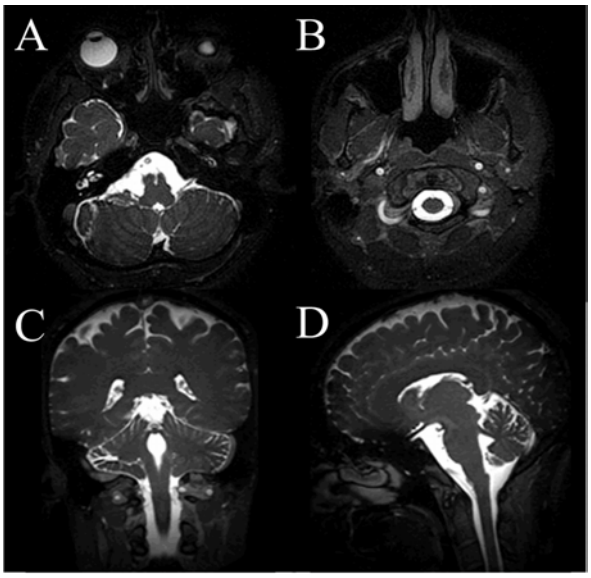

Figure 1. Axial (A,B), coronal (C), and sagittal (D) images demonstrating the excellent definition of CSF obtained with the submillimeter isotropic spatial resolution of the multi-echo 3D VIPR acquisition.

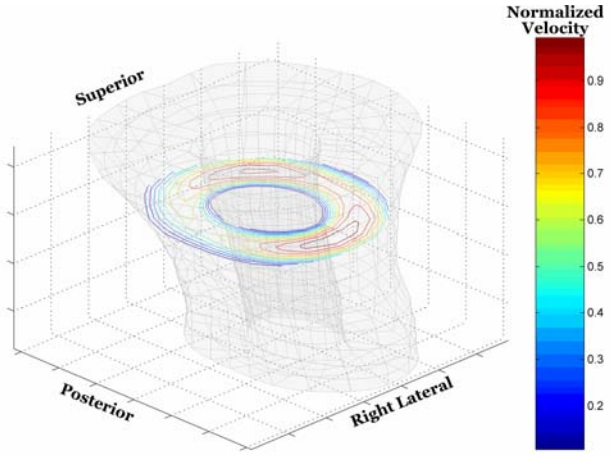

Figure 2. Velocity contour map calculated using the boundary element method model derived from a 3D VIPR MR data set.

RESULTS AND DISCUSSION

The CSF-containing space in a normal subject appears in the MR images as a region of high signal intensity (white on the gray scale) in which the brain is identified and around which the skull and spine are located (Figure 1). Models of CSF flow in a normal posterior fossa and spinal canal (Figure 2) show inhomogeneity of the CSF velocities in the subarachnoid space with greater velocities anterior and lateral to the spinal cord, as has been demonstrated in clinical studies [5]. In patients with a Chiari I malformation, greater inhomogeneity of CSF flow is demonstrated by our modeling methods. Pressure fields can also be calculated for the anatomical models.

CONCLUSIONS

We demonstrated the feasibility of CFD simulations from high resolution, patient-specific, anatomical MR scans. With boundary element modeling, regional fluctuations in CSF velocities and pressures of the CSF spaces could be derived. Further application of the method to patients with the Chiari I malformation will improve our understanding of the abnormalities in flow that affect neurologic function. We plan to collect more data from symptomatic and asymptomatic patients and also to acquire velocity measurements with phase contrast MR to compare with the predicted CSF velocities. In addition, pressure maps can be derived by the use of the Navier-Stokes relationship.

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