Physical Models of Cerebrospinal Fluid Flow in Patients with Chiari I Malformation

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INTRODUCTION

The Chiari I malformation is characterized by the protrusion of the cerebellar tonsils into the foramen magnum. In theory, this abnormality creates disturbances in cerebrospinal fluid (CSF) flow dynamics and pressure differentials in the spinal canal. Oftentimes, patients with a Chiari I malformation experience Valsalva-induced headaches. However, there exist asymptomatic Chiari I patients with the malformation but with no marked symptoms. Furthermore, Chiari 0 patients experience the related symptoms but have no such malformation. A challenging aspect of treatment planning with Chiari patients is identifying those who will benefit from intracranial decompression surgery.

A more thorough understanding of the velocity and pressure distributions in patients with Chiari malformations is needed for appropriate treatment planning. In this study, a 3D volume data set was obtained of the foramen magnum in a normal human subject. Using the 3D volume data set, a 3D geometric model was created using commercial software. From the geometric model, a patient-specific 3D physical model of the foramen magnum was created. In the future, physical models may be used as flow phantoms to validate computational fluid dynamics (CFD) models.

MATERIALS AND METHODS

A multi-echo 3D radial acquisition (VIPR) was acquired in a single normal subject with isotropic spatial resolution and fat/water separation [1] in a 1.5 T MR scanner (Signa Excite, GE Healthcare, Milwaukee, WI, USA). Using the VIPR acquisition, a 20x20x20 cm^3 image volume of 256x256x256 $voxels^3$ was acquired in a five-minute scan time. A 3D geometry was built with commercial software (Mimics 9.0, Materialise, Ann Arbor, MI, USA). The 3D volume image data was inverted (to generate a negative) and segmented in MATLAB (MATLAB version 7.0, The MathWorks Inc., Cambridge, MA, USA) using a simple threshold algorithm and exported as a solid model in the VRML2 format. The VRML2 file was imported into printer software (Zprint, Z Corporation, Burlington, MA, USA) and merged. The model was "printed" using a 3D printer (Z406 3D printer, Z Corporation, Burlington, MA, USA), which uses a constructive process to generate layers, with layer thickness = 100 µm and in-plane resolution = 500 pixel/inch. The model was waterproofed with a cyanoacrylate adhesive (Cynergy 6211 Fast Setting, Ellsworth Adhesives, Germantown, WI, USA).

RESULTS AND DISCUSSION

A patient-specific 3D physical plaster model of cerebrospinal fluid in the foramen magnum was created from a VIPR 3D MR data set (Figure 1). ZPrint allowed for rapid automated segmentation. Minimal manual segmentation was required. The plaster model printed in 1.5 hours; minimal model cleanup was required (Figure 2). The 3D printer can model dimensions as large as 20 x 25 x 30 cm at a cost of \$1/cm^3 of filled volume.

CONCLUSIONS AND FUTURE WORK

In this study, a VIPR 3D data set was acquired in the foramen magnum. From this data set, a 3D computer-generated geometry could be created and subsequently a 3D physical model could be manufactured. This technique allows us to generate flow phantoms from patient-specific anatomical images with minimal lead time. The fat-suppressed VIPR images provide an excellent basis for automated segmentation with high contrast and high isotropic spatial resolution. In the future, we will simulate CFD models using the Mimics software. We will then use the 3D-printed models to validate CFD models with flow measurements acquired from the MR scanner. The 3D-printed models will be connected to tubing and a pulsatile flow pump. Subsequently, additional models from different patients can be created for phantoms with varying degrees of malformation. In future work, pressure may also be simulated. These models may potentially be used to differentiate the fluid and pressure dynamics of symptomatic Chiari I patients, asymptomatic Chiari I patients, and Chiari 0 patients.

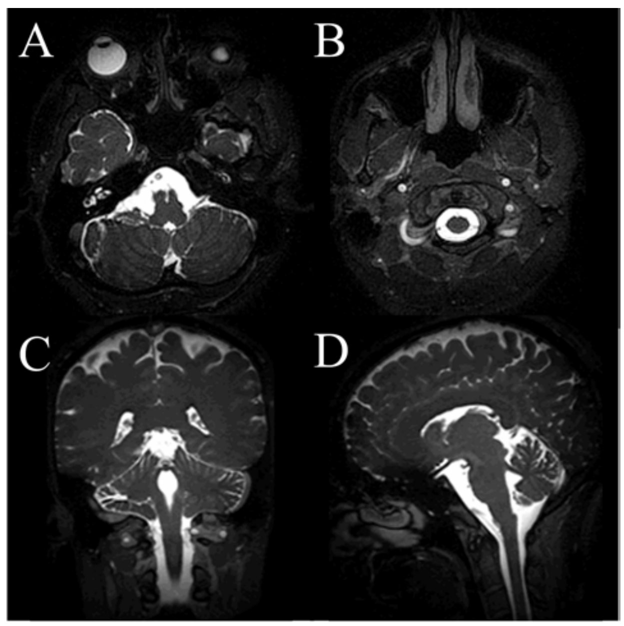

Figure 1. Axial (A,B), coronal (C), and sagittal (D) maximum intensity projection images demonstrating high SNR as obtained using a multi-echo 3D VIPR acquisition.

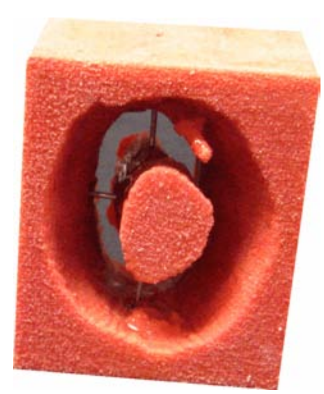

Figure 2. A 3D physical model derived from the 3D geometry using a multi-echo 3D VIPR acquisition.

REFERENCES

1. Lu A, Brodsky E, Grist TM, Block WF. Rapid fat-suppressed isotropic steady-state free precession imaging using true 3D multiple-half-echo projection reconstruction. Magn Reson Med 2005;53(3):692-699.