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CFD ANALYSIS OF CEREBROSPINAL FLUID FLOW IN THE CRANIO-CERVICAL REGION

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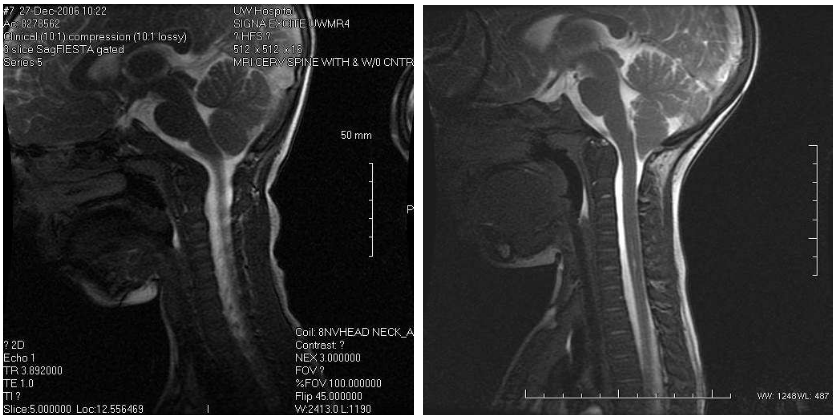
Summary. Cerebrospinal fluid (CSF) surrounds the brain and the spinal cord, and during each heart-cycle CSF flows in a pulsatile manner in the so called subarachnoid space. Through MR images the magnitude and distribution of the flow can be seen at a given time in a given cross-section, but visualizing hydrodynamics for the entire subarachnoid space has not been achieved. Furthermore, pressure fluctuations in the CSF are not demonstrated by MR. By using computational fluid dynamics (CFD) on an idealized model of the subarachnoid space, we study the detailed spatio-temporal effects of anatomic variations on CSF pressures and velocities.

1 INTRODUCTION

The cerebrospinal fluid (CSF) is present in the ventricular system within the brain, and around the brain and the spinal cord, occupying what is called the subarachnoid space; see Figure 1(a). The fluid has similar viscous properties as water.[1] In the subarachnoid space and the ventricular system within the brain there is approximately $150cm^3$ of CSF in an adult human. It functions as a mechanism to minimize the pressure changes in the cranial vault due to brain expansion during systole. As the arteries in the brain expand with each heart-beat, the CSF is forced out of the cranium and down along the spine with velocity $2-3cm/s$. When the arteries contract again, the CSF flows back into the cranium. This CSF flow may be impeded by malformations of the brain.

The Chiari I malformation is a state where the cerebellar tonsils are abnormally positioned in the upper cervical spinal canal; see Figure 1(b). It occurs in 0.8% of individuals. The



(a) Normal subject. (b) Chiari I patient.

Figure 1: A sagittal cross-section of the cranio-cervical region of a normal subject, and a patient with the Chiari I malformation. We see the spinal cord as a grey string surrounded by the brighter cerebrospinal fluid. In the Chiari I patient, we see that the cerebellar tonsils are positioned in the junction between the neck and the cranium.

location of the tonsils does not predict specific symptoms. Some patients with the Chiari I malformation have no symptoms, others have neurological symptoms such as headache, weakness and sensory disturbances, and some have fluid-filled cavities (cysts) in the spinal cord. The treatment is surgery (cranio-occipital decompression), where part of the skull surrounding the tonsils is removed.

The Chiari I malformation causes a partial blocking of the subarachnoid space, and since the amount of CSF forced out of the cranium due to the expanding arteries is the same for normal subjects and patients, the peak CSF velocities increase from $2-3cm/s$ to $10cm/s$ and pressure gradients are increased. It is believed that this change in CSF flow characteristics causes the symptoms and cysts related to the Chiari I malformation. It is not known, however, how much of the skull surrounding the tonsils needs to be removed during surgery, in order for the symptoms to remit. Sometimes additional surgery is needed.

The aim of this study is to develop an idealized anatomic model of the subarachnoid space and use computational fluid dynamics (CFD) to demonstrate CSF flow characteristics, as the anatomy of the subarachnoid space changes. CFD has previously been applied with patient-specific 3D anatomical models of the subarachnoid space.[2] It has also been used to study flow characteristics in simpler models of the spinal canal.[3,4] By using an idealized model, we effectively study the relationship between subarachnoid space parameters and CSF flow.

2 MODEL

In order to control the variations in the geometry, we construct an idealized model of part of the subarachnoid space. The cranio-cervical region modelled in a normal subject is shown in Figure 2, and contains the lower part of the cranium and the upper part of the spine. The dimensions in the model are chosen such that they approximate those in an anatomical model.[5] To assess the anatomic validity of the model, axial and sagittal sections of the model are also

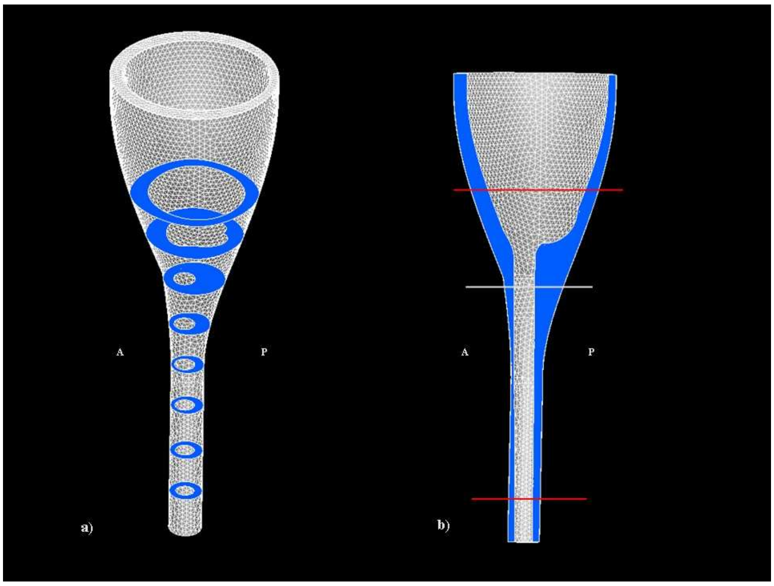


Figure 2: The computational model of a normal subject. The axial cross-sections in (a), indicate the size of the CSF space at different levels of the model. The red lines in (b) show the perimeter of the region of interest, the volumes above and below the red lines are added in order to deal with inflow/outflow boundary conditions in the computation.

compared to corresponding MR images from a normal subject.

We assume that the CSF is an incompressible Newtonian fluid, and the walls are chosen to be rigid with no-slip boundary conditions. We extend the model a few centimeters in both ends, and model the cyclic CSF flow by prescribing a plug-shaped velocity profile with sinusoidal variation at both the upper and lower end of the extended model. The period of the sine wave is 1 second, and the amplitude is chosen such that the maximum flow through the cranio-vertebral junction is in the range of that reported for normal subjects, i.e. $2 - 3cm/s$. The CSF velocities and pressures are found for the given boundary conditions by solving the Navier-Stokes equations in StarCD.[6] One sinusoidal period simulates one heart-beat and, since the initial flow is at rest, we simulate two cycles, and use the data from the second cycle.

3 RESULTS

The distribution of the computed velocities in the idealized anatomic model, agree with actual velocities in a normal subject.[7–9] When we next use the same boundary conditions on similar geometries where the cerebellar tonsils are enlarged and partially block the subarachnoid space at the cranio-vertebral junction, we clearly see an increase in CSF velocities. The pressure gradient past the cranio-vertebral junction is 50% larger than in the normal subject. The planar distribution of the computed velocity at the cranio-vertebral junction, compares well with phase-contrast MR velocity measurements.[8] In particular, high-velocity regions anterior on each side of the spinal cord are demonstrated. Also, there is simultaneous bi-directional flow in large parts of the model when the inflow/outflow changes direction. An interesting result is that the velocities are higher in the space below the cranio-vertebral junction than in it. The previously mentioned cysts often appear $2-3cm$ below the cranio-vertebral junction in patients with the Chiari I malformation, and if the CSF is involved in the formation of these it is of great interest to identify the features of the flow in this region.

4 DISCUSSION

We have shown that in an idealized anatomical model of the cranio-cervical region, CFD demonstrates variations in CSF velocities that correspond to characteristics of CSF flow measured in both normal subjects and patients with Chiari I malformation. We are able to study spatio-temporal changes in the CSF velocity and pressure as a result of changes in the anatomical model. This is important when trying to link CSF hydrodynamics to the formation of cysts in the spinal cord, and in future work we will further investigate this relationship.

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