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CEREBROSPINAL FLUID FLOW SIMULATIONS IN BRAIN VENTRICLES WITH ELASTIC WALL RESPONSES

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SUMMARY

The cerebrospinal fluid surrounds the brain and the spinal cord, and is believed to be a potential risk factor to many CNS diseases. The biomechanics of the CSF flow in the brain ventricles is poorly understood due partly to the difficulty in obtaining the flow data *in vivo*. This paper describes the outcomes of a computational study to examine the elastic response of the walls of the ventricles and its effects on the flow. Comparisons of the simulated results are guided by clinical data obtained with the Time-SLIP MRI, which captures ventricular CSF flows in real time *in vivo.*

Key words: *cerebrospinal fluid flow, elastic wall, simulation*

1 INTRODUCTION

In the cranial vault, the cerebrospinal fluid (CSF) fills the cerebral ventricle and the subarachnoid space. Clinical evidence continues to indicate CSF as a potential risk factor to many diseases of the central nervous system. Significant advances in the visualization of the transient CSF flow in the ventricles inside the brain were made recently by the development of the Time-SLIP MRI (Time-Spatial Labeling Inversion Magnetic Resonance Imaging) medical imaging technology [1-6]. The Time-SLIP MRI captures views of the ventricular CSF flow in real time *in vivo*, which has not been possible with cardiac-gated brain MRI.

CSF is reported to have a specific gravity of about 1.007, close to that of water. Deep inside the brain, the ventricles, including the paired lateral ventricles, the third ventricle, and the fourth ventricle are interconnected, allowing the CSF to move freely in the brain ventricles and to the subarachnoid space. The flow of the CSF in the ventricles is believed to present throughout the ventricles. The ventricular CSF flow performs many irreplaceable tasks that are critical to the functioning of the brain. For instance, the ventricular CSF flow transports nutrients, hormones, and brain metabolites from where they are produced to target nucleuses, such as the circumventricular organs. The pressure-volume relationship between the intracranial pressure, the volume of CSF, blood, and brain tissue, is known as the Monro-Kellie doctrine. The cranium's constituents maintain a homeostasis, such that any increase in the volume of one of the cranial constituents must be compensated by a decrease in the volume of the others. CSF flow dynamics is a result of the interaction between brain tissues, the vascular systems, and other factors, such as respiration.

Computational models are being applied at increasing rate toward a better understanding and assessment of the circulation of biofluids, and prediction of deleterious human physiological effects. Computational modeling provides detailed spatial and temporal descriptions of biofluid flow, which are not readily achievable via physical measurement. Patient-specific computational fluid dynamics (CFD) simulations, using commercial software, of the CSF flow in the spinal or cranial compartments [7-9] have been reported, where measured flow volume and velocity at the computational boundaries are applied to generate pulsating CSF flow. Through the use of

mathematical models of different levels of resolutions, e.g. system vs. local, computer simulation makes available realistic flow quantities for a wider range of patient cases. For instance, lumped-parameter based models [10] that provides beat-by-beat and long-duration information of the cardiac system has been used to provide the boundary conditions in CFD calculations of the modeled compartments.

This paper describes a work that develops a physiologically accurate computer simulation platform that models different biophysics for the purpose of the simulation of the ventricular CSF flow. In particular, the effects of the response of the soft brain tissue to the CSF flow are examined and the results are presented in this paper. The computations of the fluid/structure interactions study are performed using clinically obtained anatomy of the brain and of the ventricles. The results of the multiphysics study are compared with those of fluid-only simulations using two CFD approaches. The comparison of the simulated CSF flow is guided by the clinical observations made by using the new Time-SLIP MRI technology.

2 METHODOLOGY

To digitally define anatomically-accurate ventricular spatial regions in the head, the T1-weighted MRI of a subject of interest is used. The spatial resolution of the MRI is 0.67 mm isotropic. The MRI images are segmented to identify the brain tissues and the ventricular space where the CSF flows and exported into CAD geometries. These are performed by using the ScanIP [11] software.

Two numerical solvers for the fluid physics used, including the open source OpenLB [12], a lattice Boltzmann equation solver, and STAR CCM+ [13], a commercial computational platform widely adopted in academic research and industrial applications. The inflow/outflow boundaries are set at the apertures with a pulsatile flow at the median aperture, which varies sinusoidally in time at 1 Hz. The volume flow rate is based on clinically measured values. The lateral apertures that link the fourth ventricle to the cerebellopontine cistern are the free flow boundary. The ventricle wall is set as the interface between the fluid domain and the solid domain. The outer surfaces of the brain constituents next to the cranium are set as no-displacement boundary in the finite element solutions of the brain tissues mechanics. The reported experimental values of modulus of compression for a volumetric strain and the Poisson ratio of the brain tissues vary, but are in the range normally being regarded as soft solid. For example, 10 kPa and 0.49, respectively, for the Young's modulus and the Poisson ratio, are reported [14] and are used in the current simulation. The effects of the material properties adopted on the simulation results are examined. The ventricular CSF flow is solved in a time-accurate manner until a rhythmed periodic state is achieved. The multiphysics solution algorithms in STAR CCM+ are used for the simulation of the fluid/structure interactions (FSI) through the interface on the wall of the ventricles. The method performs two-way FSI co-simulation via an implicit coupling of the Navier-Stokes equations solver and the solid structure solver, with hydrodynamic mass effects [15]. For small ventricular wall displacement, the linear elastic solid stress solver is considered appropriate for the current study. In the coupling scheme, the fluid loads (e.g., pressure and viscous forces) and the structural deformation are allowed to be communicated iteratively per time step. The time step sizes are determined by the need to obtain accurate resolution of the turbulence physics, the stability requirement of the numerical algorithms, and the stability of the FSI numerical solution process.

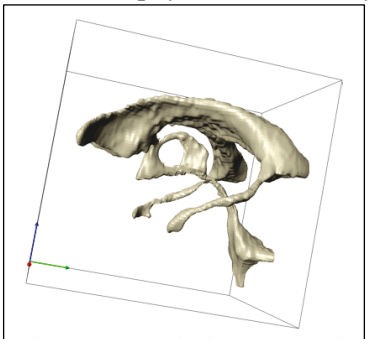
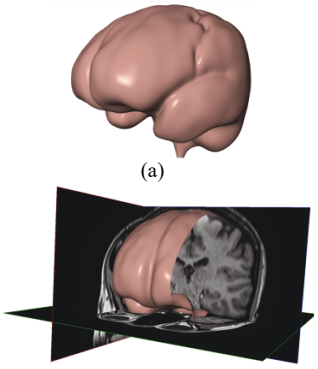


Figure 1. Ventricular system of the human brain.

3 RESULTS

Figure 1 shows the segmented CAD image of the ventricles. For the FSI study, digital representations of the brain geometry of the same patient, from the same MRI scan, is shown in Figure 2. Digital smoothing is applied and Figure 3 shows the errors of the smoothing superposed on the original MRI scan. Figure 4 shows variations of the maximum velocity at the aqueduct and the intraventricular foramina (or the foramina of Monro). The simulated flow becomes nearly void of the effects of the initial conditions and becomes periodic beyond 0.4 sec from the start of the computation. The results are obtained by modeling the brain tissue as elastic, nearly incompressible materials, while the CSF is modeled using a Newtonian fluid.

The velocities variations show that the CSF moves in a back-and-forth manner across the foramina, which connects the lateral ventricles to the third ventricle. The CSF flow is pulsatile in the aqueduct. Figure 5 shows a snapshot of the velocity vectors, colored by its magnitude, of the CSF on a cross sectional plane that cuts along channel of the right foramen of Monro. The figure shows that CSF moves from the third ventricle, through the channel, and forms a jet-like flow in the right lateral ventricle. Figure 6 shows a snapshot of the distribution of the displacement of the ventricle wall at the same instant of time as that for Figure 5. The von Mises stress of the brain on a sagittal plan is also shown in Figure 6. The lateral ventricles are seen to exhibit the most significant amount of deformation. The brain tissues exhibit the highest stress in the region surrounding the lateral ventricles.



(a) (b)

Figure 2. Segmentation of MRI images of the brain. (a) Reconstructed CAD geometry, (b) Composite view of MRI scans of the brain on the three anatomical planes and the segmented brain model transected along a sagittal plane.

4 DISCUSSIONS

Time-SLIP MRI imaging technology can resolve the transient evolution of the CSF flow in real time and has provided evidence that disrupts many current believes of CSF flow features [3-6]. One of the key observations made is there is a lack of unidirectional, bulk flow in the ventricular CSF flow system in the Time-SLIP studies of healthy subjects [5,6] and the CSF flow through the intraventricular foramina exhibit "back-and-fro" movement. The implication of the finding is significant as it suggests that flow mixing, either laminar or

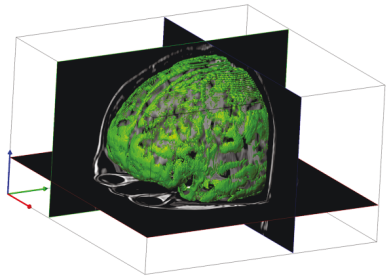


Figure 3. Errors of the smoothing of the brain surfaces.

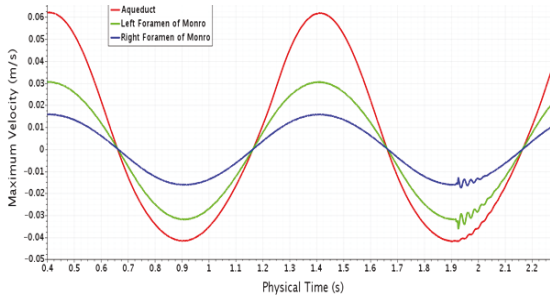


Figure 4. Evolution of the maximum CSF flow velocity.

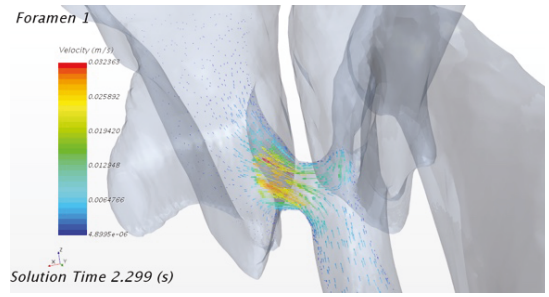


Figure 5. Velocity vectors of the CSF flow in the region around the right foramen of Monro.

turbulent, is responsible for the functioning of the CSF flow in the brain, instead of a bulk flow. In the simulations performed in this study (not shown here) where the wall of the ventricle is considered rigid, the CSF flow in the intraventricular foramina is insignificant. This is true using either of the two CFD solvers. In cases where the deformation of the brain tissue, as a result of its interactions with the simulated CSF flow, is considered, the behavior of the simulated CSF flow agrees with that based on the Time-SLIP MRI images. The results show that to capture physiologically plausible ventricular CSF flow in the brain, the responses of the brain tissues to the

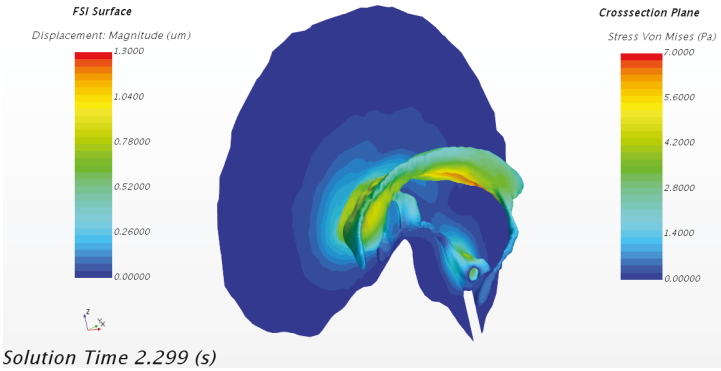


Figure 6. Contour of the von Mises stress of the brain tissues on a near midsagittal plane and the contour of the displacement of the ventricle wall that has been set as the FSI interface.

pulsating CSF flow should be modeled in the computer simulation platform, which is consistent with the Monro-Kellie doctrine.

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