IMPLEMENTING PHYSIOLOGICAL PROCESSES IN COMPUTATIONAL FLUID DYNAMICS MODELS OF THE CEREBROSPINAL FLUID

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Introduction

The brain and the spinal cord are surrounded by the cerebrospinal fluid (CSF). This clear, water-like liquid provides protection against impacts and shocks and plays a crucial role in the maintenance of homeostasis in the central nervous system [1]. Disturbances in its normal production, absorption and/or movement modifies the neuro-biomechanical environment through changes in CSF and brain tissue pressures. This can lead to severe neurological complications as observed in patients with Chiari malformation, hydrocephalus and dementia [2]. However, the mechanisms underlying these disorders are not well understood, neither are the CSF dynamics under normal physiological circumstances. The aim of this study is to investigate, through computational fluid dynamics (CFD) modeling, the physiological processes affecting the dynamical behavior of the CSF by incorporating them as boundary conditions. Adequate boundary values were retrieved from clinical literature (Sakka et al. [3]) and numerical and magnetic resonance imaging (MRI) studies performed by Sweetman et al. [4], Khani et al. [5] and Matsumae et al. [6].

Methods

A three-dimensional model of the ventricular CSF space was constructed (figure 1). The geometry was obtained via segmentation of clinical T2 MRI images from Ghent University hospital, taken from a middle-aged female, using Mimics (Materialise, Leuven, Belgium).

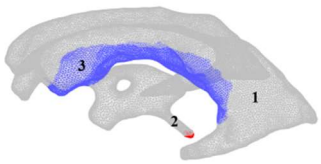

Figure 1: Geometry of (1) the lateral ventricles, (2) the cerebral aqueduct and (3) the choroid plexus.

An unstructured computational mesh was generated in ICEM (Ansys, Canonsburg, USA), with the final number of elements (650971) determined in a mesh sensitivity study. The CFD analysis was performed within the numerical software Fluent 2019 R3 (Ansys, Canonsburg, USA). The CSF was modeled as an incompressible Newtonian fluid with properties similar to water at body temperature (density 998.2 kg/m³ and dynamic viscosity of 0.8 mPa.s). Further, the flow was considered laminar because of low Reynolds numbers. Problem-specific boundary conditions are as follows. First, CSF production by the choroid plexuses, which are specialized cell structures in the cerebral ventricles, was implemented as a continuous bulk flow of 0.4 ml/min. Secondly, the arterial pulse causes the cerebral arteries to expand during systole, leading to periodic brain tissue displacement that induces pulsatility in the CSF flow. This effect was taken into account by inclusion of a pulsatile flow at the ventricular walls based on boundary conditions applied by Sweetman et al. [4]. Finally, the fluid leaves the ventricular space through the cerebral aqueduct, to normally flow via the fourth ventricle into the spinal and cranial subarachnoid space. At this outlet, the effects of pressure build-up and damping within the CSF space were implemented by imposing windkessel model boundary conditions to produce a realistic pressure distribution.

Results and discussion

The maximal velocities and flow rate through the center of the aqueduct were selected as a reference and compared to phase-contrast MRI measurements reported by Sweetman et al. [4] and Matsumae et al. [6]. Adequate finetuning of the boundary conditions allowed to simulate velocities and pressures within the physiological range (20 mm/s and 550 Pa above venous pressure respectively) as depicted in figure 2.

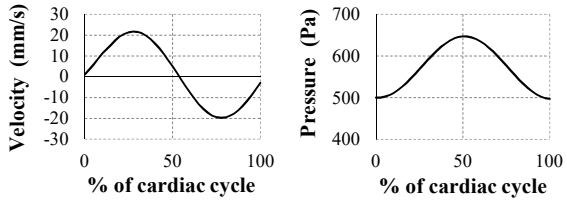

Figure 2: Velocity (left) and pressure (right) magnitude in the cerebral aqueduct simulated for one cardiac cycle.

These boundary conditions can be implemented into future models, hereby requiring appropriate validation, for investigation of the normal CSF circulation as well as for research of CSF-related neurological disorders.

References

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