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A COUPLED SIMULATION OF SPINAL CORD BLOOD FLOW AND CEREBROSPINAL FLUID MOTION IN THE SPINAL SUBARACHNOID SPACE BASED ON IN VIVO MEASUREMENTS

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ABSTRACT

A preliminary coupled 1-D model of the systemic arterial tree and cerebrospinal fluid (CSF) system was constructed. The systemic tree model includes arteries greater than 2 mm in diameter and a simplified spinal cord vasculature. Coupling of the arterial tree and CSF system is accomplished by a transfer function based on *in vivo* cerebral blood flow (CBF) and CSF pulsation measurements in 17 young healthy adults. A 1-D tube model of the CSF in the spinal subarachnoid space (SSS) is formed based on *in vivo* measurements and used to determine flow and pressure along the SSS. The pressure and flow results in the CSF and systemic arterial tree are qualitatively and quantitatively similar to *in vivo* measurements in healthy subjects. The relative arrival time of blood pulsations in the spinal cord and CSF in the SSS is impacted by CSF system compliance and geometry. With low CSF system compliance the CSF pulsations arrive around the spinal cord before arterial pulsations and vice versa. Overall, the preliminary results support that geometric and mechanical properties of the CSF and cardiovascular system have an important impact on the flow and pressure environment and accent the importance to obtain *in vivo* measurements to improve modeling capabilities.

INTRODUCTION

Coupling between the cardiovascular and CSF system is thought to play a role in cerebrovascular disease, craniospinal disorders, and intrathecal drug delivery. In particular, the phase relation between spinal cord blood and CSF pulsations has been hypothesized to influence movement of perivascular fluid in the neural tissue [1]. Disruption of perivascular fluid movement may help explain tissue edema that often precedes craniospinal disorders such as hydrocephalus and syringomyelia.

In previous work, we developed and validated a comprehensive blood flow model for primary systemic arteries [2]. The goal of the present work is to 1) expand the systemic model to encompass the spinal cord arteries and 2) couple the systemic model with a simplified hydrodynamic CSF system model.

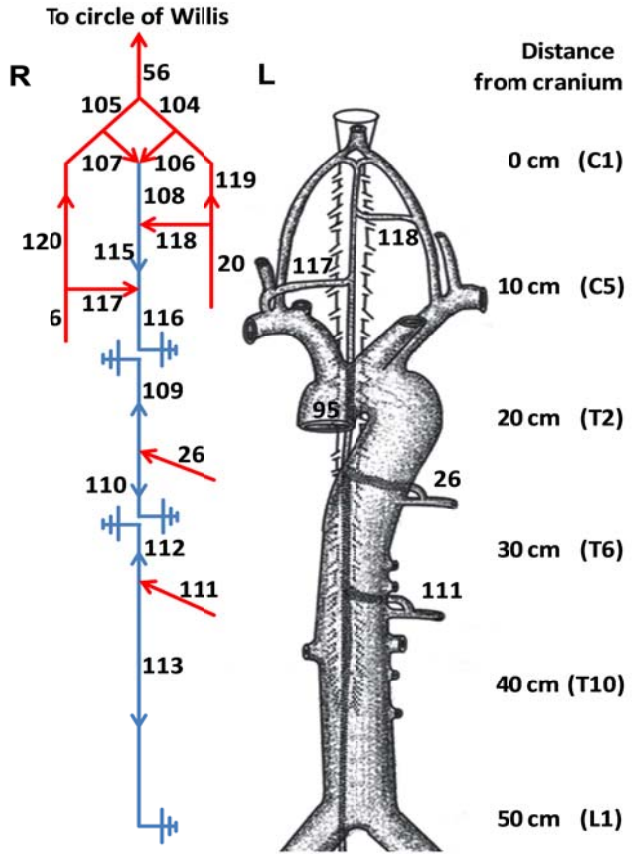

Figure 1. Schematic diagram for blood flow to the spinal cord (left) and anatomical sketch (right) reprinted from Novy et al. [3] (electrical grounding denotes segment termination).

METHODS

The model consists of four components: 1) simulation of systemic blood flow 2) calculation of the total CBF, 3) utilization of an *in vivo* based CBF to CSF pulse transfer function to obtain CSF pulsation at the craniospinal junction, and 4) simulation of the CSF pulsation in the SSS.

The 1-D cardiovascular model used to solve blood flow and pressure is identical to Reymond et al. [2] with the exception that 17 vascular segments are added to simulate spinal cord blood flow (Figure 1). The model takes into account the influence of intracranial pressure acting on the cerebrovascular and spinal cord vessels. Blood flow to the spinal cord is assumed to be supplied from a) the left and right posterior inferior cerebellar arteries (106 & 107), b) the radicular artery (26), and c) the artery of Adamkiewicz (111). The spinal cord is considered to have three primary non-communicating segments with terminal resistance set to result in a flow distribution similar to *in vivo*. The total arterial CBF, $Q_{CBFa}(t)$, through the L and R internal carotid (ICA) and L and R vertebral arteries at the craniospinal junction (C2-C3) is calculated. A transfer function to relate $Q_{CBFa}(t)$ and the CSF pulsation, $Q_{CSF}(t)$, is determined based on *in vivo* phase contrast MRI measurements conducted on 17 young healthy volunteers obtained at the C2-C3 cervical level in the SSS and at the L & R vertebral and internal carotid artery.

For the SSS, a 1D model is constructed and solved similar to the cardiovascular model except with properties and geometry corresponding to the spine. The SSS volumetric compliance, C, is considered to be $C = 1/(k_e P_{ic})$, with k_e an elastance coefficient, and P_{ic} the intracranial pressure. The influence of the elastance coefficient is examined by conducting simulations with K_e = 0.10, 0.26, and 1.00. The arrival time of the peak systolic, diastolic, and maximum pressure gradient of the arterial pressure and CSF pressure is calculated. The CSF to arterial pressure delay at each axial location along the spinal cord is calculated by subtracting the spinal cord arterial from CSF pulse arrival time.

RESULTS

The simulated spatial-temporal distribution of blood and CSF pressure along the spinal cord is shown in Figure 2. The CSF to arterial pressure delay along the spinal cord is shown in Figure 3. Overall, the pressure and flow at primary locations in the systemic tree (i.e. aorta, carotid, and vertebral arteries) is quantitatively and qualitatively similar to *in vivo*. Total CBF agrees with the *in vivo* MRI flow measurements, and the blood flow distribution to the spinal cord (cervical / thoracic / lumbar) is similar to *in vivo*. The transfer function results in a CSF waveform at the craniospinal junction similar to *in vivo* measurements in terms of shape and stroke volume. The calculated CSF to arterial phase delay along the spinal cord is smallest near the craniospinal junction and increases along the spine. In a healthy SSS ($K_e \sim 0.26$), arterial pulsation to the spinal cord arrives before CSF pulsations (Figure 3 – left). With a decrease in CSF system compliance, CSF pulsations arrive at the spinal cord before arterial (Figure 3 - right).

DISCUSSION

These preliminary results provide an approximation of what the blood and CSF flow and pressure distribution might be along the spinal cord. Additional *in vivo* measurements are needed to determine model parameters for healthy and disease states. The coupled model could be studied under healthy physiological conditions, in vascular pathologies such as hypertension and ageing, and craniospinal pathologies such as SSS stenosis, hydrocephalus, and syringomyelia.

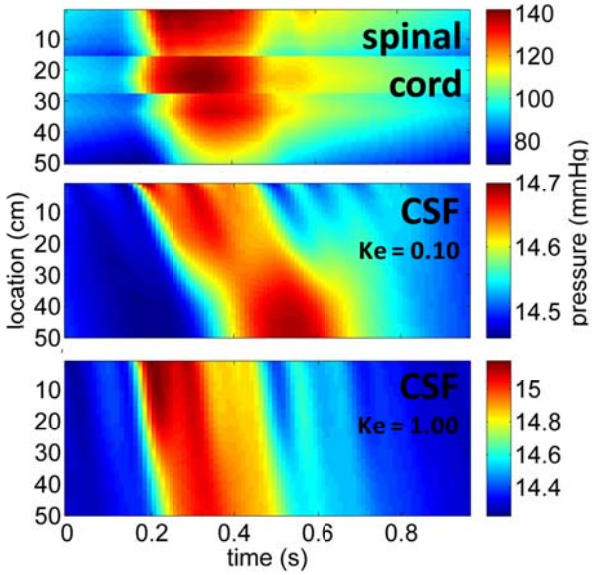

Figure 2. Spatial-temporal distribution of the spinal cord blood pressure (top) and CSF pressure in the SSS.

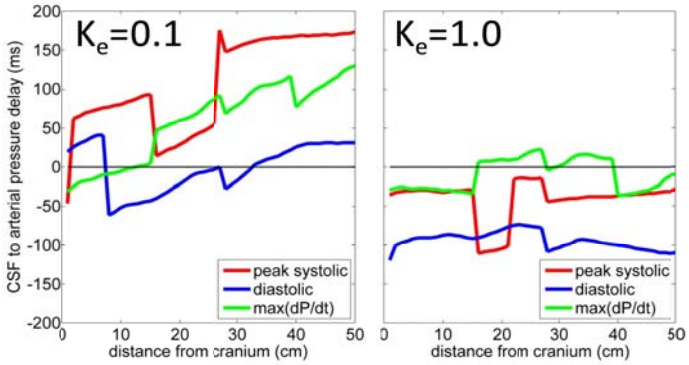

Figure 3. Axial distribution of CSF to arterial pressure delay based on peak systolic, diastolic, and maximum gradient (positive value indicates arterial arrives before CSF pressure).

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