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PREDICTION OF THE IMPACT OF CRANIOSPINAL COMPLIANCE ON THE RELATIVE TIMING OF ARTERIAL AND CEREBROSPINAL FLUID PULSATIONS AND PERIVASCULAR FLUID FLOW INTO THE SPINAL CORD

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ABSTRACT

Craniospinal compliance (CC) has been hypothesized to have importance in craniospinal disorders such as hydrocephalus and syringomyelia in which tissue edema occurs. In this study we assess the impact of CC on 1) the relative timing of spinal cord blood flow (SCBF) and cerebrospinal fluid (CSF) pulsations and 2) perivascular flow (PVS) into the spinal cord (SC). A previously developed coupled model of the cardiovascular and CSF system is utilized to obtain the results. The results predict that CC can significantly alter the relative timing of arterial and CSF pulsations in the spine and total perivascular flow to the SC. CC was found to have the greatest impact on relative timing and PVF in the lumbar spine and to a lesser extent in the cervical and thoracic spine. A reduction in CC resulted in increased PVF to the SC that might help to explain tissue edema present in craniospinal disorders with reduced CC.

INTRODUCTION

Standard medical textbooks state that the perivascular spaces of the SC and brain are a specialized lymphatic system [1] to transport nutrients and waste from the central nervous system. However, the mechanics of PVF movement are not yet fully understood.

The importance of PVF movement in craniospinal disorders that coincide or are preceded by tissue edema is of interest [2]. These disorders include syringomyelia and hydrocephalus which to date do not have a clear pathophysiological explanation for tissue edema. Among many theories, researchers have conjectured that tissue edema could occur due to altered timing between arterial and CSF pulsations in syringomyelia [3] and/or altered CSF system damping characteristics in hydrocephalus [4, 5]. One of the factors hypothesized to play a role in both syringomyelia and hydrocephalus is CC [6, 7].

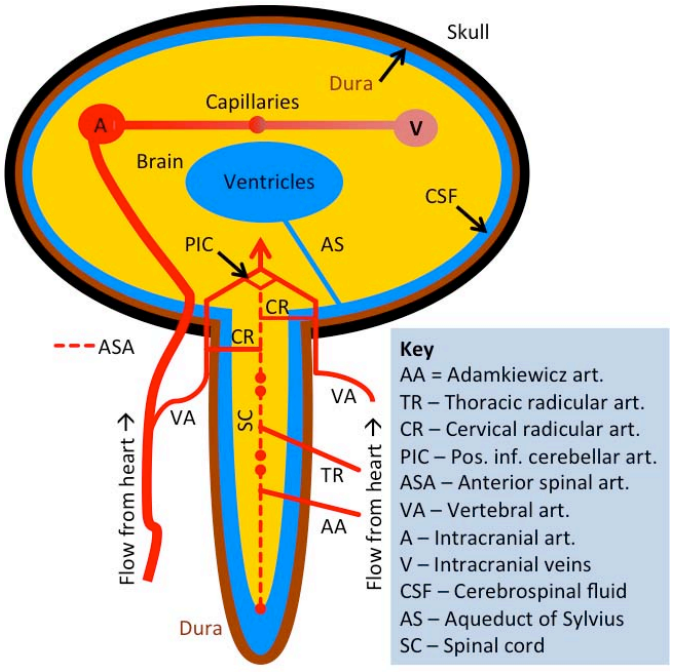

Figure 1. Schematic diagram for SCBF and related CSF and arterial anatomy modeled by the coupled cardiovascular / CSF system [8].

The objective of this study was to predict the impact CC might have on 1) the relative timing of SCBF and CSF pulsations along the spinal axis and 2) perivascular flow into the SC.

METHODS

Our approach was to use a previously developed coupled model of the cardiovascular and CSF system [8], based on the work of Reymond et al. [9], to predict relative timing of SCBF and CSF pulsations along the spinal axis under varying CC values. The arterial model included 120 viscoelastic arterial segments including a complete circle of Willis, coronary tree and ventricular elastance model of the heart. It also included included a simplified SCBF arterial anatomy (**Figure 1**). The anterior spinal artery (ASA) was modeled in three non-communicating segments: the cervical, thoracic and lumbar. These ASA segments were supplied from the greater arterial tree by different vessels (see figure). The spinal CSF was modeled as a 1D flexible tube with nonlinear viscoelastic compliance and varying cross section according to *in vivo* measurements.

Pressure and flow were solved throughout the entire system under each elastance coefficient value. Local delay along the SC axis was determined between the ASA and CSF pulsations based on detection of the foot of the pressure waveforms.

Perivascular flow into the SC was estimated by the following methodology. The local delay values were input into the previously published numerical simulation results of Bilsten et al. [3] that quantified perivascular flow based on a given delay between arterial and CSF flow waveforms. The flow around a single arteriole entering the SC was solved and then multiplied by the total number of arterioles entering each section of the SC. It was assumed that 10 arterioles enter the SC for every 1 mm^2 of surface area, with the surface area determined based on the hydraulic diameter of the SC at each axial location.

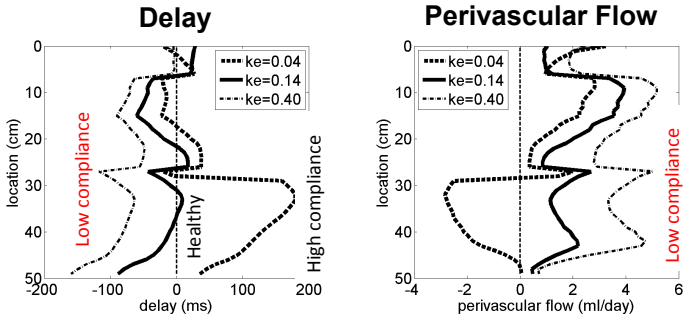

Figure 2. Axial distribution of CSF to arterial pressure delay and perivascular flow under varying elastance coefficient values.

RESULTS

Figure 2 indicates the results for delay and perivascular flow under varying elastance coefficient values (Ke = 0.04, 0.14 and 0.40) along the SC, with y-axis zero located at the craniospinal junction. The result corresponding to a low, healthy and high CC value is indicated. A summary of results in terms of elastance coefficient values and the corresponding CSF pulse wave velocity and average perivascular flow, over the entire SC, are shown in Table 1.

DISCUSSION

These results represent predictions about how CC might have an impact on the relative timing and perivascular flow along the SC axis. Many simplifications were taken in order to obtain the results and thus they are presented as a first estimation.

Alterations in CC were found to have an important impact on delay in the lumbar spine and to a lesser extent in the cervical spine (Figure 2). Arterial anatomy was an important factor in that the delay in each ASA section was different, since each section connected differently to the greater vascular tree.

CC was predicted to have a significant impact on total PVF into the SC (up to 229 ml/day) in comparison to the total CSF content produced daily (500 ml/day). This finding supports that decrease in CC could result in greater fluid movement into the SC and thus tissue edema if the increased fluid is not removed. In addition, the CSF pressure wave velocity was found to be an indicator of CC compliance. This parameter can be assessed noninvasively [10] and might be used to help assess disease states, as the absolute value of CC is not directly measureable without invasive means. This study has many limitations since the modeling required numerous assumptions that need to be improved by obtaining more accurate in vivo measurements about SCBF and CSF hydrodynamics.

Table 1. Summary of simulation results for average PVF and CSF pressure wave velocity for different elastance coefficients.

K_e (ml^{-1})	CSF pressure wave velocity (m/s)	Average perivascular flow (ml/day)
0.04	2.32	9
0.14	4.46	94
0.4	7.89	172
0.7	10.53	207
1.1	12.39	229

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