MRI-based noninvasive measurement of intracranial compliance from the relationship between transcranial blood and CSF flows: Modeling vs direct approach

R-W. Tain[1], and N. Alperin[1]

[1]University of Illinois, Chicago, IL, United States

Purpose:

This work compares modeling based approach to a direct approach for noninvasive measurement of intracranial compliance (ICC) [1]. The work aims to assess whether measurements of phase shift between blood and CSF flows used by several groups are a reliable estimate of ICC [2]. A 2nd order lumped parameters model of craniospinal system (CSS) and in vivo MRI measurements of trasncranial blood and CSF flows were employed to characterize the affect of changes in ICC on the CSF flow dynamics. The sensitivity of the phase based approach was compared with that of the direct based approach.

Methods:

Velocity encoded MRI scans from five healthy volunteers provided volumetric flow rate measurements of total arterial inflow, venous outflow, and CSF oscillatory flow between the cranium and the spinal canal [1]. The compartmental and the analogous electrical circuit model used for simulating the output (CSF flow) from the measured input, i.e., the net transcranial blood flow (nTBF) are shown in Figure 1. The lumped parameters were then estimated by using autoregressive-moving average with least squares method. The simulated CSF that best matched the measured CSF flow is shown in Figure 2-(a). Simulated CSF flow for a 50% and 180% increase in ICC are shown in Figure 2-(b). Maximal intracranial (IC) and spinal canal (SC) volume changes, CSF pressure gradient, and intracranial compliance index (ICCI) for the initial and the increased ICC states were obtained. The time lag of the CSF peak flow with respect to blood flow was determined by the shift that maximizes the cross-correlation coefficient value. The derived time lags are then expressed in terms of phase shits.

Results:

The Bode plot, demonstrates almost no change in phase over the range of the frequencies of interest (i.e. the heart rate), while the amplitude response demonstrates reduced CSF pulsation amplitude. The reduced amplitude with relatively no phase shift is also seen in the simulated time domain CSF flow waveform shown is Figure 2-(b). The reduced CSF flow amplitude results with reduced CSF pressure gradient amplitude and increase in the maximal intracranial volume change (less CSF is leaving the cranium during the systolic phase), thereby overall reduced ICCI (ICCI=dV/dP). The combined effect on the ICCI is an average increase of 37% and 65%. On the other hand, there was no detectable phase shift for the 50% increase in ICC and less than 10 degrease for a 2.8 folds increase in ICC. The results are summarized in Table 1.

Conclusions:

Intracranial compliance modulates the coupling between the transcranial pulsatile blood and CSF flows. This study, demonstrate that ICC is not the dominate factor causing a time lag (or phase shift) between CSF and blood flow and therefore, estimation of ICC based on phase shift may be less accurate than approaches based on amplitude changes such as the direct approach proposed by Alperin et al [1].

References:

[1] Alperin N., Lee S.H., Loth R., Raksin P.B., and Lichtor T. MR-Intracranial Pressure (ICP): A Method to Measure Intracranial Elastance and Pressure Noninvasively by Means of MR Imaging: Baboon and Human Study. Radiology. 217 (3):877-885:2000.

[2] Wagshul ME, Chen JJ, Egnor MR et al. Amplitude and phase of cerebrospinal fluid pulsations: experimental studies and review of the literature. J. Neurosurg 104:810-819:2006.

Figures and Tables:

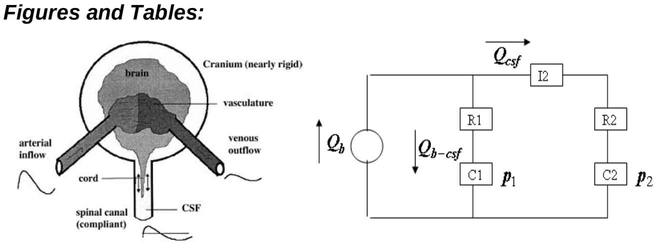

Figure 1: The craniospinal flow volume compartmental model (left) and it's electrical analogue (Right). Q_i, p_i, C_i, R_i, and I_i correspond to flow rate, pressure, compliance, resistance and fluid inertance, respectively.

Table 1: Relative difference in parameters used for derivation of ICC (direct approach) as well as estimation of ICC changes (phase shift) Note: 1. dec = decrease. 2. ptp PG= peak-to-peak pressure gradient

ICC	ptp PG	CI	ICVC	CSF stroke volume	Phase difference
1.5x	20%(dec)	37%	8%	19%(dec)	No diff.
2.8 x	29%(dec)	65%	15%	40%(dec)	10 degrees

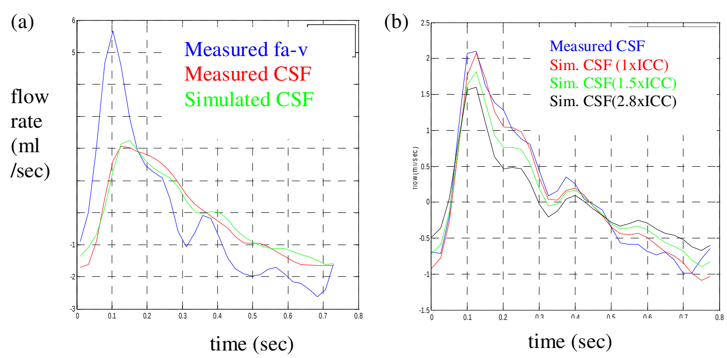

Figure 2: (a) The MRI-based measured volumetric flow waveforms for transcranial blood flow (arterial inflow-venous outflow) in blue and CSF flow in red. The model-derived CSF outflow is shown in green (82.4% fit). (b) Estimated CSF (Red) from measured CSF and simulated CSF flow (other colors). As ICC increased, no significant phase shift was observed. Blue: Measured CSF flow; Red: Estimated CSF flow; Green: Simulated CSF with 1.5xICC; Black: Simulated CSF with 2.8xICC.