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Introduction

The intracranial compliance (ICC), defined as the ratio of the cranial volume change in response to a pressure change by injecting a certain amount of fluid into the cerebrospinal fluid (CSF) space, is a clinically relevant index that may reflect disease status in cases like hydrocephalus or traumatic injury [1]. The invasive placement of a pressure detector in the central nervous system such as lumbar spine or lateral ventricle for the measurements of pressure changes, however, is usually accompanied by risk including possible infections. Previous studies have proposed noninvasive phase-contrast flow mapping magnetic resonance imaging method to estimate ICC based on blood/CSF flow rates and CSF pressure gradient [2]. Assuming that the CSF flow direction is mainly caudocranial in the spinal canal at the measurement sites, the phase-contrast technique needs to be applied with only one velocity encoding direction, which greatly shortens the scan time. In this study, we attempted to verify this assumption by using three-direction measurements to examine the contributions of various terms that might cause estimation inaccuracies in MR imaging-based ICC measurements.

Theory

Assuming that intracranial volume is constant within the skull and that the CSF, blood, and brain parenchyma are all incompressible [3], the time-varying intracranial volume change (ICVC) could be computed from the net volumetric inflow of blood and CSF measured in the neck (Eqn.(1)) [2]. Furthermore, the Navier-Stokes relationship in Eqn.(2) [4] shows that the CSF pressure gradient could be derived from the spatial and temporal derivatives of CSF flow profile. ICC can then be derived from the change in volume for a unit change in pressure [1,2]:

\[
\text{ICVC}(t) = \left[ Q_c(t) - Q_v(t) - Q_{CSF}(t) \right] \times \Delta t
\]

\[
\nabla P = -\rho \left( \frac{\partial \bar{\phi}}{\partial t} + \bar{\phi} \cdot \nabla \bar{\phi} \right) + \rho \nu^2 V
\]

Materials and methods

Five healthy volunteers (four men and one woman) with no history of neurological diseases and a mean age of 26±2 years were studied using a 3-tesla MR imager (TIM TRIO, Siemens Medical solutions). Each volunteer’s imaging studies included a 3D TOF MRA as well as two sets of cine phase-contrast images. The velocity encoding values (Venc) for the internal carotid arteries, and internal jugular veins from the peripheral pulse gating at C2-3 disc level. A total of 32 time points equally spaced over the cardiac cycle were obtained for analysis.

Results

Fig.1a shows 3-direction CSF pressure gradient waveforms in one normal volunteer. The pressure gradient amplitude along the cranio-caudal direction was much larger than those found for the other two directions by about one order of magnitude. For the five subjects, relative contributions to the pressure gradient from the RL and AP were 4.46±1.47% and 16.71±5.24%, respectively. The viscous terms (2nd term in the Navier-Stokes equation Eqn.(2)) derived from the three-direction data were comparable in magnitude (Fig.1b), with relative contributions to the viscous term from the RL and AP directions being 12.85±0.18% and 23.80±7.95%, respectively. The CSF pressure gradient map in the phase-contrast flow mapping coronally reformated 3D TOF MRA images were comparable in magnitude (Fig.1b). For the five normal volunteers’ ICC values were 8.66±0.36 cmHg/mmHg, which fell in the normal range as reported in [2].

Discussion and conclusion

Results from this study show that, although the CSF flow in the spinal canal at C2-3 disk level has noticeable magnitudes along the RL and AP directions, likely reflecting the circling velocities, the resulting contributions to the pressure gradient calculation from these two components are negligible. The viscous terms from the three flow directions were found to be relatively comparable. Nevertheless, since the viscous term measured from the cranio-caudal direction was itself negligible for the derivation of pressure gradient and thus ICC, they seem to play minor roles in the quantification either. In conclusion, the estimation of ICC by means of cine phase-contrast MR imaging could be performed with single-direction velocity mapping, with errors from the other two directions well tolerated.

References


Fig.1a pressure gradient in 3-direction

Fig.1b viscous-term contribution in Navier-Stokes equation in 3-direction

Fig.2 pressure gradient maps during a cardiac cycle