Contributions of in-plane CSF flow to the derivation of intracranial compliance: a three-direction cine phase-contrast flow study.

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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 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].

$$ICVC(t) \;=\; \left[\,Q_A(t) - Q_V(t) - Q_{CSF}(t)\,\right] \times \Delta t \qquad (1)$$

$$\nabla P \;=\; -\rho\,\left(\frac{\partial \vec{V}}{\partial t} + \vec{V}\cdot\nabla V\right) + \mu\cdot\nabla^2 V \qquad (2)$$

$ICVC$: intracranial volume change during cardiac cycle
Q_A: arterial inflow, Q_V: venous outflow, Q_{CSF}: CSF oscillating flow
ρ : CSF fluid density, μ : CSF fluid viscosity, V: velocity vector, P: pressure

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 MR images with peripheral pulse gating at C2-3 disc level. The volumetric blood flow rate at the neck was calculated from the following six vessels: vertebral arteries, bilateral internal carotid arteries, and internal jugular veins from the phase-contrast images, with their locations identified from the coronally reformateed 3D TOF MRA images. The velocity encoding values (Venc) for blood flow measurements ranged from 80-95 cm/sec. The CSF flow was measured at the same slice level with three-direction velocity encodings, with Venc set at 10/3/4 cm/sec for craniocaudal, right-left (RL), and anterioposterior (AP) directions, respectively. For all cases, a single slice section 5mm thick was acquired with a 16-18cm field of view, a 256*232 matrix, TR=102-163ms, TE=5-10.7ms, and flip angle of 20^o. 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 craniocaudal 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 through-plane direction during a cardiac cycle was also shown in Fig.2. The five normal volunteers' ICC values were 8.66±0.36 cm*mL/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 craniocaudal 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

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Fig. 1a pressure gradient in 3-direction

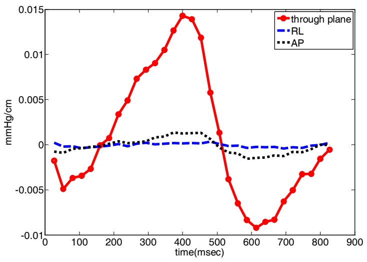

Fig. 1b viscous-term contribution in Navier-Stokes equation in 3-direction

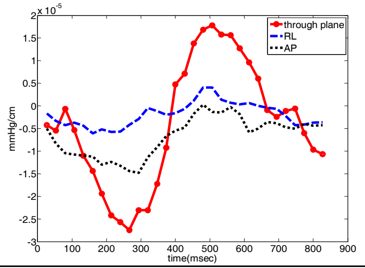

Fig.2 pressure gradient maps during a cardiac cycle