Visualization of pulsatile CSF motion separated by membrane-like structure based on four-dimensional phase-contrast (4D-PC) velocity mapping

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Introduction

Principal driving forces of pulsatile Cerebrospinal fluid (CSF) has not been understood completely [1]. Pressure transmission from the blood vessels and/or brain parenchyma can be regarded as driving forces in intracranial and spinal CSF. Cardiac gated two-dimensional phase contrast (2D-PC) MR has been used to evaluate the regional CSF pulsatile motion in an attempt to understand normal CSF dynamics and to diagnose disorders such as hydrocephalus [2][3]. On the other hand, Yamada et al. have reported that bulk flow and turbulent flow of CSF can be visualized by means of time-spatial labeling inversion pulse (Time-SLIP) technique [4]. However, it is difficult to get a comprehensive view of CSF movement by 2D-PC and time-SLIP technique. We have been developing a method for visualization of time-varying velocity of intracranial pulsatile CSF motion by four-dimensional phase contrast (4D-PC) technique to analyze spatial and temporal CSF hydrodynamics in an extensive field. In this study, 4D-PC is performed in a pulsatile flow phantom and a volunteer with arachnoid cyst to indicate usefulness of 4D-PC technique in assessing pulsatile CSF motion in comparison with the Time-SLIP.

Material and Methods

Phantom experiments and a clinical application to a 22-years-old man with asymptomatic arachnoid cyst were performed to verify difference of characteristic of pulsatile fluid flow obtained by 4D-PC and time-SLIP technique. The phantom design is shown in Fig.1. The inflow side was derived into two acryl tubes through a Y-shaped branch; the one tube was equipped in the center with a thin rubber membrane mimicking the membrane-like structures such as thin wall of arachnoid cyst to observe pulsatile propagation, while the other tube was equipped with no membrane so as to allow a side flow coming from the membrane-equipped tube. The phantom was connected to a roller pump (HAD 101; Mera, Tokyo, Japan) by expansion-free rubber tubes and plastic tubes. The physiological saline water was oscillated to simulate CSF pulsation by the periodic pressure of the roller pump. The roller pump was synchronized by a waveform generator (HP 33120a, Agilent Technologies, Santa Clara, CA) to have 1Hz cycle. The same synchronization signal was sent to a 1.5-T scanner (Gyroscan, Philips; Best, The Netherlands) via ECG cables. The 4D-PC images were obtained the following conditions; flow encode directions, IS, RL and AP; TR, 8.1 ms; TE, 5.6 ms; Flip angle (FA), 20°; Field of view (FOV), 30 × 30 cm^2; Velocity encoding (VENC), 5-10 cm/s; slice direction, coronal; and spatial resolution, 1.96 mm (isotropic). Images were acquired at 32 temporal points per a cardiac cycle and were retrospectively reconstructed. In the case of the volunteer experiments, the imaging slab was at sagittal or coronal, and the retrospective image reconstruction was synchronized by the pulse from a finger plethysmograph. After obtaining the velocity information in three directions, the in-plane velocities were delineated by vectors, while the through-plane velocities were visualized by colors with a custom-made software programmed with Matlab (R2010a or later, Mathworks, Natick, MA, USA). The vector-color coded CSF velocity field was then superimposed on the T_2 weighted images. Time-SLIP image were taken immediately before the 4D-PC image acquisitions in each subject with the following conditions: TR, 6,000 ms; TE, 73.8-78.7 ms, FA, 90°; slice thickness, 5 mm; FOV, 26 × 26 cm^2; acquisition matrix, 256 × 256; and inversion time (TI), 1,700-5,900 ms. Labeling was given in a region covering within orange-color square in the phantom (Fig.2b) and the mid portion within arachnoid cyst in volunteer (Fig.4c)

Results

Results of the phantom measurement on pulsatile flow with 4D-PC and time-SLIP image are shown in Fig. 2. In the Time-SLIP image, labeled fluid exhibited laminar flows with a maximum displacement at the center of the inflow tube without membrane and the outflow tube. The 4D-PC velocity image presented similar flow pattern in the vector field. In the inflow tube with membrane, labeled fluid showed only a slight displacement in the Time-SLIP image. In contrast, oscillating fluid propagating beyond the point of the membrane was observed in the 4D-PC velocity image. Temporal changes of the mean velocity within the region-of-interest (ROI) at the anterior/posterior position of membrane (the blue square in Fig. 1(b)) are shown in Fig. 3. The waveform anterior to the membrane bore striking resemblance with that posterior to the membrane although with a slightly lowered peak-to-peak amplitude.

In the clinical application, morphological MR images of the volunteer demonstrated the arachnoid cyst located around the falx cerebelli. The 4D-PC velocity image at the infratentorial was shown in Fig. 4(a) and (b) with a corresponding Time-SLIP image with labeling horizontally in the center of the arachnoid cyst is shown in (c). In the 4D-PC image, a relatively small but clear oscillating motion was observed within the arachnoid cyst. In contrast, no displacement of the labeled CSF in the arachnoid cyst was seen in the Time-SLIP image. This result suggest that the 4D-PC technique can reveal the propagations of pulsatile CSF motion partitioned by the thin wall of cyst despite that there is no communications between arachnoid cyst and neighboring CSF space.

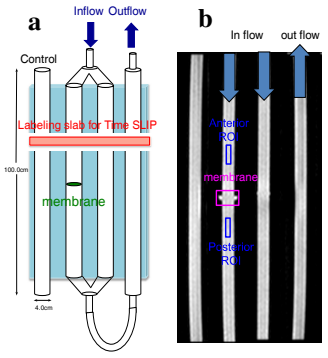

Fig.1 (a) The pulsatile phantom design (b) T2 weighted coronal image of the phantom

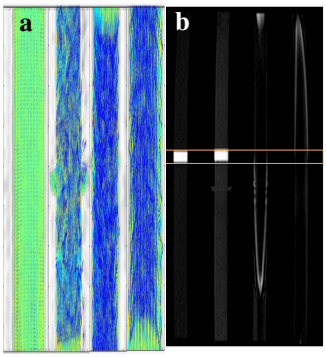

Fig.2 The phantom image of 4D-PC (a) and Time-SLIP (b)

Discussion and conclusion

In vitro, the pulsatile fluid motion generated by the cardiac pump was observed similar flow pattern obtained by the 4D-PC image in the anterior and posterior of the position equipped the membrane in the duct. In contrast, fluid labeled by the Time-SLIP image showed little displacement due to flow blocked by the membrane. Similar phenomenon was observed in the arachnoid cyst in vivo. These results confirmed that pulsatile CSF flow disrupted by the thin wall of the arachnoid cyst indicated clearly to be transmitted pressure and waveform of velocity to cephalic or caudal directions beyond the point of the membrane tissue. The 4D-PC visualization of the CSF motion separated by the membrane is based on the propagation of the fluid pressure. In conclusion, this technique could indicate propagation of CSF pulsation through the intracranial membranous structures, which suggest that to seek origins of CSF pulsation due to the brain expansion and propagation of major cerebral arteries or choroid plexus pulsation may be possible by evaluating delay time at the voxel of CSF space with similar velocity waveform to any reference points.

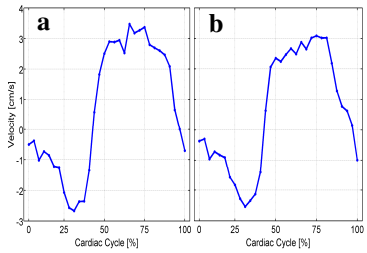

Fig.3 (a) Temporal changes of the mean velocity in anterior ROI of the membrane (b) Temporal changes of the mean velocity in posterior ROI of the membrane

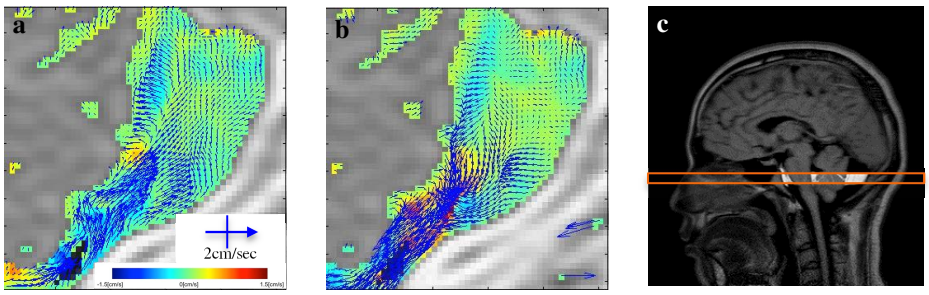

Fig.4 Flow visualization within arachnoid cyst. Velocity image by 4D-PC of intra arachnoid cyst; 9.3% of peripheral one cardiac cycle (a), 81.3% of peripheral cardiac cycle (b). (c) Time SLIP image labeled (orange-colored square) in the mid portion within the arachnoid cyst

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