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An innovative approach to investigate the dynamics of the cerebrospinal fluid in the prepontine cistern: A feasibility study using spatial saturation-prepared cine PC-MRI

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Abstract

Purposes: Accurate measurements of the cerebrospinal fluid that flows through the prepontine cistern (PPC) are challenging due to artefacts originating from basilar artery blood flow. We aim to accurately quantify cerebrospinal fluid (CSF) flow and stroke volume in the PPC, which is essential before endoscopic third ventriculostomy.

Materials and methods: We developed a new PC-MRI sequence prepared with Hadamard saturation bands to accurately quantify CSF flow in the PPC by suppressing the blood signal in the surrounding vessels. In total, 28 adult hydrocephalic patients (age 59 ± 20 years) were scanned using conventional PC-MRI and our developed sequence. CSF was separately extracted from the PPC and the foramen of Magendie, and flow (min and max) and stroke volume were quantified.

Results: Our modifications result in a complete deletion of signal from flowing blood, resulting in significantly reduced CSF stroke volume ($Conv = 446 \pm 113\ mm^3$, $Dev = 390 \pm 119\ mm^3$, $p = 0.006$) and flow, both minimum ($Conv = -1630 \pm 486\ mm^3/s$, $Dev = -1430 \pm 406\ mm^3/s$, $p = 0.005$) and maximum ($Conv = 2384 \pm 657\ mm^3/s$, $Dev = 1971 \pm 62\ mm^3/s$, $p = 0.002$) compared with the conventional sequence, whereas no change in the area of interest was noted ($Conv = 236 \pm 65\ mm^2$, $Dev = 249 \pm 75\ mm^2$, $p = 0.21$).

Conclusions: Accurate and reproducible CSF flow and stroke volume measurements in the PPC can be achieved with sat-band prepared cine PC-MRI.

Keywords: Prepontine cistern; Foramen of Magendie; CSF; PC-MRI; Spatial saturation; Aliasing

1. Introduction

Cine phase-contrast MRI (PC-MRI) is a flow-sensitive imaging method that has been increasingly used in clinical practice for quantifying blood [1] and cerebrospinal fluid (CSF) flow [2]. CSF oscillations are altered in disorders, including hydrocephalus [3], intracranial hypo- or hypertension [4], subarachnoid haemorrhage [5], and posterior fossa cystic malformations [6]. CSF flow parameters are positively correlated with CSF opening pressure, headache scores [7], response to shunt insertion in hydrocephalic patients [3], and the success of endoscopic third ventriculostomy (ETV) in cases of aqueductal stenosis [8]. In most of these disorders, CSF dynamics are measured in the aqueduct of Sylvius and rarely in the subarachnoid spaces (SAS), although CSF flow through the SAS around the basilar artery is particularly important for brain compliance

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[4,9]. Cardiac cycle (CC)-induced brain vascular expansion flushes the CSF through the spinal canal. This CSF, which oscillates during the CC, mainly originates from the intracranial SAS (90%) and to a lesser degree from the ventricular CSF (10%) [9]. This action subsequently results in an increased oscillating CSF volume in cases with decreased SAS, as noted in hydrocephalic patients or patients with subarachnoid haemorrhage [5].

Accurate CSF flow measurement with PC-MRI in general and through the PPC in particular is technically challenging. First, the CSF flows encountered are very low and therefore difficult to calculate. The error of this technique is approximately ±10% when measuring flow rates through the aqueduct [10]. Background correction is required to remove the effect of phase offset errors and movement occurring during the CC [11]. Second, inappropriate selection of the maximum velocity encoding gradient (*Venc*) leads to reduced sensitivity by reducing the signal-to-noise ratio, whereas selection of lower values results in aliasing. Third, for the narrow aqueduct and PPC, the effects of limited spatial resolution cause diameter-dependent systematic overestimations in pulsatile volume changes. This problem can be resolved by increased spatial resolution at the expense of longer acquisition times and increased signal averaging [12]. Similarly, McCormac et al. noted that contrary to the laminar flows through the narrow cerebral aqueduct, CSF flow in larger regions, such as the SAS, is often turbulent. This phenomenon causes phase dispersion and signal loss in the PC-MRI, resulting in underestimation of flow in the SAS [13]. Fourth and most important, the PPC is infiltrated with the basilar artery, which generates blood flow artefacts. Surrounding vessels additionally corrupt the signal and make it difficult to segment the CSF flow area of the PPC using PC-MRI. Applying a Hanning window filter reliably reduces such artefacts but also results in a large net reduction in spatial resolution [14]. The objective of this investigation was to develop a novel 2D cine PC-MRI sequence to assess CSF dynamics that (1) is automatically filtered from blood flow artefacts at the acquisition level, (2) is highly sensitive to slow velocities typical of altered CSF dynamics and (3) does not compromise spatio-temporal resolution. We hypothesised that the saturation of the blood signal from basilar artery flow makes it possible to accurately assess CSF dynamics in the PPC. Such a CSF quantification method might be useful to better diagnose and understand various types of CSF flow alterations.

To date PC-MRI is the unique technique to assess in vivo CSF flow and dynamics despite the inheriting errors from eddy-currents, phase-shift and blood flow artefacts. Other modalities like cranial Doppler fail to achieve better results in the physiologic state because normal CSF lacks sufficient interfaces to generate signal and require presence of scattering particles or cells, thus cannot be used as a control modality. As a proof of concept, a phantom with properties optimised to resemble the properties of human SAS, PPC and FOM would be desirable. The artificial phantom used for such a validation approach would disturb the extremely sensitive and technically challenging acquisition of the PC-MRI signal and would not provide reproducible and meaningful results. Therefore, to validate our hypothesis, the foramen of Magendie (FOM) was chosen as our control structure. The FOM is not infiltrated by blood vessels; thus, CSF flow and stroke volume measurements are unaffected by sat-pulses.

2. Materials and methods

2.1. Subjects

Twenty-eight consenting adult patients (age = 59 ± 20 years, 15 females) with suspected hydrocephalus (normal pressure, idiopathic, communicating, occlusive, and secondary) were prospectively enrolled in this study. The inclusion criteria were ventricular dilation with either one of the following: gait disturbance, urinary disturbance or cognitive alterations. The patients were scanned using conventional cine PC-MRI, which is part of our routine clinical protocol for this pathology, followed by our developed sequence through the same slice position and with the same imaging parameters. The main advantage of the addition of our developed sequence to the hydrocephalus protocol is that we will perform both sequences on patients with no bias of eddy-current and/or phase-error shift. The regional ethical review board approved the study, and all participants provided written consent.

2.2. Image acquisition

The study was performed using a 3 T scanner (GE Healthcare) with retrospectively and peripherally gated cine PC-MRI to record 32 cardiac phases. The following imaging parameters were used: slice thickness = 5 mm, FOV = 140 mm × 140 mm, BW = 62.5 kHz, flip angle = 20°, minimum TE and TR, matrix 256 × 160, and 2 views per segment. In addition, the slice position was at the level of the PPC and was obliquely oriented to be perpendicular to the direction of the CSF flow (Fig. 1). The velocity encoding (*Venc*) of the conventional sequence was set to the minimal possible value of 50 mm/s. The commercial available sequence was first modified to achieve a lower *Venc* of 20 mm/s to increase the sensitivity of the acquisition of reduced flow. In addition to removing the signal from blood flowing into the selected slice and avoiding aliases with the CSF flow signal, spatial selective pre-saturation pulses were incorporated. These pulses consisted of Hadamard pulses, or double-sided bands (20 mm thick), to achieve a perfect parallelism with the selected slice and reproduce the same sat-band (thickness, gap and orientation) in the other side. To validate our hypothesis, we oriented the slice position and the sat-bands to include both structures. On one hand, the PPC is typically infiltrated by the basilar artery and consequently suffers from blood flow artefacts. On the other hand, the FOM lacks blood flow artefact and was used as our control structure.

2.3. Image processing

Image processing was performed using homemade software with a dedicated CSF algorithm segmentation to differentiate tissue with reduced pulsatility compared with CSF as characterised by large amplitude oscillations and synchronised with the CC [9]. The software uses a "spectral segmentation" algorithm that