Normal and Abnormal Cerebrospinal Fluid Dynamics Evaluated by Optimized Cine Phase-contrast MR Imaging

LUNG-HUI GIANG1,3 CHENG-YU CHEN1 MING-YEN CHEN2 TENG-YI HUANG2 HSIAO-WEN CHUNG2

Department of Radiology1, Tri-Service General Hospital
Department of Electrical Engineering2, National Taiwan University; Yuanpei Technical College3, Taiwan

To evaluate the normal and abnormal cerebrospinal fluid (CSF) hydrodynamics by quantitatively measuring the peak velocity of CSF in the aqueduct using two-dimensional cine phase-contrast magnetic resonance (MR) imaging.

A prospective CSF flow study was performed with the use of an optimized two-dimensional cine phase-contrast MR technique. Ten normal age-matched volunteers (mean age 58.5 years) and 20 patients with abnormal CSF hydrodynamics were enrolled. The patient groups include 16 normal pressure hydrocephalus (NPH) cases (mean age 69.2 years) and four with communicating hydrocephalus (CH) (mean age 38.5 years). All images were acquired on both sagittal and axial planes using a bipolar gradient pulse sequence on a 1.5-tesla scanner (Siemens Vision+, Erlangen, Germany).

The mean maximum CSF flow velocities (Vmax) at the aqueduct were 4.93 ± 0.28 cm/s (mean ± SD) for the control group, and 6.22 ± 0.67 and 7.24 ± 1.08 cm/s for the NPH and CH groups, respectively.

The NPH group could be further divided into hyper- and hypodynamic groups when compared with the normal age-matched subjects. Vmax of the control group was significantly higher than that of the hypodynamic-NPH group (1.92 ± 1.11 cm/s, \( p < 0.001 \)) and lower than that of the CH group (\( p < 0.007 \)) and of the hyperdynamic-NPH group (10.52 ± 0.23 cm/s, \( p < 0.001 \)).

With optimized parametric setting, two-dimensional cine phase-contrast MR imaging appears to be practical for routine evaluation of patients with abnormal CSF flow dynamics. The peak velocity of the CSF flow was significantly higher in the hyperdynamic-NPH group but lower in the hypodynamic-NPH group as compared with the control group. Our results confirm that, in NPH patients, a pre-surgical MR imaging evaluation of CSF potentially can be very helpful in distinguishing the low-CSF-dynamic from high-CSF-dynamic groups before any CSF diversion procedure is contemplated.

Key words: Magnetic resonance imaging (MRI); Cerebrospinal fluid; Cine magnetic resonance imaging; Normal pressure hydrocephalus (NPH)

Recent improvements in magnetic resonance (MR) imaging hardware and techniques have enabled its clinical use for techniques previously considered too difficult such as evaluating the hydrodynamics of cerebrospinal fluid (CSF) [1]. A very recent CSF study using high-resolution two-dimensional (2D) cine phase-contrast has shown promising results in which a subgroup of patients with shunt-responsive normal pressure hydrocephalus (NPH) could be distinguished from shunt-nonresponsive NPH patients [2]. However, with the high-resolution imaging parameter setting that allows for accurate quantification of CSF motion in small channels such as the aqueduct of Sylvius, a scanning time of greater than 14 minutes was required [3]. This is certainly not practical as the expected CSF motion artifact becomes prominent after a long acquisition time, and a reasonable patient throughput can not be achieved, considering practical issues with this technique.

The normal physiological motion of CSF is pulsatile (to-and-fro) which synchronizes with the cardiac cycle. Quantitative analysis of CSF flow in pathways such as an aqueduct that is tubular and relatively regular in diameter is desirable because the resultant laminar flow can be measured accurately by the current sophisticated cine phase-contrast technique [4]. However, as has been described in hyperdynamic turbulent flow such as in patients with acute communicating hydrocephalus, the non-laminar characteristic may cause underestimation of the CSF motion if stroke volume is measured [5]. In this the study, we optimize the parameters in cine phase-contrast MR imaging for clinical use by shortening the scan time to within 8
minutes, while maintaining a similar in-plane spatial resolution by changing field of view (FOV)/matrix size from 16 cm/512 × 512 to 10 cm/256 × 256. We want to know whether the peak velocity of the CSF flow in normal and abnormal patients could be distinguished by this optimized method.

**MATERIALS AND METHODS**

**Subjects**

Between February 1999 and January 2000, a total of 20 patients was enrolled into this study, including 16 cases of NPH (mean age 65.23 years) and four cases of high-pressure communicating hydrocephalus (mean age 38.5 years). Ten subjects (mean age 58.5 years) without neurological symptoms and with normal MR imaging findings were included as the control. The diagnoses of NPH were made according to the clinical symptoms (the presence of the triad of dementia, gait disturbance, and urinary incontinence) and MR imaging criteria (ventriculomegaly, out of proportion to cerebral sulcal widening and/or peri-ventricular white matter hyperintensity on T2-weighted images). Criteria used for high-pressure communicating hydrocephalus were: 1) imaging findings of ventriculomegaly together with cortical sulcal effacement and without recognizable cause of CSF obstruction; and 2) clinical manifestations of increased intracranial pressure.

**MR imaging techniques**

Fast-spin echo T2-weighted (TR/TE: 4000/99) axial imaging, axial FLAIR (fluid attenuated inversion recovery; TR/TE/TI: 9000/110/2500) and conventional spin-echo T1-weighted (TR/TE: 700/14) axial imaging were obtained in all patients and normal subjects before the application of the quantitative CSF MR imaging study. All MR scans were performed on a 1.5-tesla unit (Siemens Magnetom Vision plus, Erlangen, Germany).

Quantitative 2D cine phase-contrast MR images were acquired on axial planes that were perpendicular to the proximal third of the cerebral aqueduct. A 2D-FLASH (fast low-angle shot) gradient echo pulse sequence was used with flow-sensitive gradient encoding along the direction of the slice selection that allowed the through-plane evaluation of CSF phase changes in the aqueduct and calculation of the CSF velocity (velocity encoding [VENC]: 20 cm/s; matrix size 256 × 256; FOV 100 mm; in-plane resolution 0.39 mm) (Fig. 1). Because the diameter of the aqueduct is only 2 to 3 mm, the ROI (region of interest) was controlled to between 0.01 and 0.03 cm², which contains no stationary brain tissue and is slightly smaller than the diameter of the aqueduct. At this optimized setting, an average cross-sectional area of the aqueduct may contain about 10 to 24

![Figure 1.](image1.png) The region of interest (solid circle) is routinely placed within the aqueduct, and determined as an area of phase change with respect to the background. Background motion correction was performed by referencing to static tissues such as the brain parenchyma [11].

![Figure 2.](image2.png) Maximal velocity (Vmax) of cerebrospinal fluid acquired at the aqueduct. It is greatest in the Hyper-NPH group, followed by the CH, the normal, and the Hypo-NPH groups. Hyper-NPH = hyperdynamic normal pressure hydrocephalus; Hypo-NPH = hypodynamic normal pressure hydrocephalus; CH = communicating hydrocephalus.

![Figure 3.](image3.png) CSF velocity plotted as a function of one cardiac phase shows the peak velocity of a Hyper-NPH patient at 13.87 cm/s, which is much higher than the average of the normal group (4.93 cm/s).
pixels for the CSF flow study. In order to increase the signal-to-noise ratio, 6 mm slice thickness was used, and the bandwidth per pixel was changed from 130 to 78 Hz. Using a half-Fourier algorithm, the scanning time was limited to within 8 minutes to avoid motion artifacts.

We chose to analyze the peak CSF velocity instead of stroke volume per cardiac cycle because cine phase-contrast MR imaging has been proved accurate for laminar flow, but it underestimates turbulent flow in patients with hyperdynamic CSF flow [4]. Therefore, a quantification study of the CSF stroke volume in the aqueduct was not undertaken. The definition of “Vmax” is a spatially averaged peak velocity in CSF flow. This parameter was observed to indicate the to-and-fro motion for differentiating clinical cases.

\[ V_{\text{max}} = \frac{\sum_{i=1}^{N} V_i}{N}, \]  

where \( f(v,t) \) is absolute velocity (v) function at the aqueduct during cardiac cycle (t), and N is the number of pixels in the ROI.

RESULTS

The mean maximum CSF flow velocity (Vmax) at the aqueduct for the patient groups and control group are summarized in Figure 2. Vmax values were 4.93 ± 0.28 cm/s (mean ± SD) for the control group, and 6.22 ± 0.67 and 7.24 ± 1.08 cm/s for the NPH and CH groups, respectively. By using the normal subjects’ Vmax as the normal value, the NPH group could be further divided into hyper- and hypodynamic CSF-motion groups. NPH patients with Vmax values higher than the normal value were statistically separated from NPH patients with values lower than the control. Therefore, a hyperdynamic NPH groups (n = 10) with a Vmax value of 10.52 ± 0.23 cm/s (Fig. 3) could be distinguished from the hypodynamic NPH group (Vmax = 1.92 ± 1.11 cm/s) (Fig. 4). The Vmax of the control group was significantly higher than that of the hypodynamic-NPH group (p < 0.001) and lower than that of both the CH group (p < 0.007) and the hyperdynamic-NPH group (p < 0.001).

DISCUSSION

A relatively wide range of normal aqueductal CSF Vmax values measured by the cine phase-contrast MR technique has been reported by several investigators [1, 6]. This may be because different gradient strengths and parameters used by the different groups. For example, in Bhadelia’s study on 17 healthy volunteers using cine phase-contrast MR images with the axial aqueduct technique [7], the field of view was 18 cm, matrix size was 256 × 192, and scan thickness was 3 mm (in-plane resolution of 0.65 mm). The region of interest included in the aqueduct consisted of only 2 to 4 pixels. As a result, the calculated aqueductal CSF velocities in his study were 1.9, 0.3, and 0.93 cm/s for the maximal, minimal, and mean velocities, respectively, which were much lower than those of our study. Another study by Barkhof et al. Used an even lower spatial resolution (1.0 mm) resulting in a mean peak velocity of 4.2 ± 1.5 cm/s in the rostral aqueduct and 7.8 ± 4.9 cm/s in the caudal aqueduct [8]. The wide range of normal Vmax values in previous reports is apparently a result of the partial volume effect caused by the low spatial resolution in data acquisition. Moreover, a large ROI that contains the boundary brain tissue may further underestimate the calculated CSF velocity. By using high-resolution imaging, it is much easier to precisely define the aqueduct and ROI, and therefore avoid most of the partial volume effect [9]. On the other hand, while high-resolution imaging is important for the quantitative measurement of CSF dynamics, it is hampered by a longer acquisition time. In our study, we used a much smaller field of view (from the reported 16 cm to 10 cm) and reduced the matrix size in half (from 512 to 256). These changes resulted in a 1/3 reduction in scanning time while maintaining the same small in-plane resolution (0.39 mm). The need for a higher demand of gradient strength for a small field of view is not a problem for our newly equipped MR scanner. Thus, it appears that our cine phase-contrast MR imaging parameter setting is practical for both routine examinations and for CSF dynamics research.

To further reduce the scanning time for cine phase-contrast MR imaging studies, we used the retrospective ECG-gating method to trigger the R wave. Because prospective ECG gating may significantly increase the scanning time when the trigger is ineffective in patients with arrhythmia due to the R-R interval change possibly leading to a 200-ms dead-time interval.

Another advantage of using the retrospective ECG-gating method is that, with a fixed TR interval, up to...
22 of 48 cardiac phases can be utilized to describe each cardiac cycle. Therefore, the phase shift due to the eddy currents under the time-related gradient can be avoided. The selection of an optimal VENC value is based on the velocity of the CSF flow. Generally, the value is slightly higher than the expected maximal flow velocity of the measured CSF flow. However, it should be adjusted according to different pathological conditions to avoid aliasing and false low velocity readings. The normal peak velocity of CSF flow in adults is about 5.1 ± 2.7 cm/s [1]. Therefore, a range from 10 to 20 cm/s of VENC was selected in our study so that both normal and fast CSF flow would be covered.

Measurement of CSF stroke volume as a guide for the treatment of NPH has been proposed by Bradley et al [10]. In their study, 12 NPH patients with a CSF stroke volume over 42 µL had positive response to shunt surgery. In our study, although two groups of NPH patients with high and low CSF Vmax values could be separated by the cine phase-contrast technique, we did not calculate stroke volume because we considered that non-laminar effects which inherently exist in the aqueduct in a hyperdynamic state might have hampered the measurement. Whether CSF Vmax can be used as a guide for hyperdynamic NPH treatment need further correlation of Vmax and surgical responses.

The CSF Vmax value in high-pressure CH patients was, as expected, statistically higher than that of the normal control group. Surprisingly, although statistically insignificant, the Vmax value of the CH group was lower than that of patients with hyperdynamic NPH. It has been implied that in the early stages of NPH, the hyperdynamic CSF motion within a fixed intracranial space produces radiating shear forces that can injure the peri-ventricular white matter, thus, resulting in gait apraxia. Our result indirectly suggests that the shearing force produced by the to-and-fro CSF pulsation may be larger in hyperdynamic NPH patients than in high-pressure CH patients. Moreover, although our four CH patients had high Vmax values, they did not present prominent gait disturbance.

In conclusion, cine phase-contrast MR imaging with optimized parametric settings appears to be practical for routine use in patients with abnormal CSF motion. Hyperdynamic NPH patients can be clearly separated from the hypodynamic NPH group by this technique.

REFERENCES
正常與不正常大腦脊髓液運動
使用高解析二維相位對比磁振造影技術與評估

江鎮輝 陳震宇 陳明彥 黃穀毅 鍾孝文

本研究之目的在使用高解析度二維相位對比磁振造影定量正常與不正常大腦脊髓液運動，以提供臨床醫師診療不正常大腦脊髓液運動病人做參考。

我們使用1.5 tesla scanner分別取得矢狀及軸位切面的高解析度二維相位對比磁振造影影像，針對30位成年人，包括10位正常受試者（平均約58.5歲）和20位不正常大腦脊髓液運動病人做參考。其中16位高常壓性水腦（平均約62.2歲），4位交通性水腦（平均約38.5歲），進行大腦脊髓液流速的定量研究。研究方法乃使用高解析影像在大腦導水管的截面積獲得18至22個含相角変化的相素，運用大腦導水管內大腦脊髓液的相角變化，測量大腦脊髓液的最大搏出速度。

四組受試者中，以高常壓性水腦病患的最大流速（10.52 ± 0.23 cm/s, p < 0.001）比其它三組高，而交通性水腦病患次之（7.24 ± 1.08 cm/s, p < 0.007），其次為正常受試者（4.93 ± 0.28 cm/s; mean ± SD），最低的是低常壓性水腦的病患（1.92 ± 1.11, p < 0.001）。

使用高解析度二維相位對比磁振造影技術定量正常與不正常大腦脊髓液運動，可獲得比較穩定且信賴度高的測量值。高常壓性水腦病患有最高的大腦脊髓液搏出速度，遠高於正常受試者及低常壓性水腦的病患的大腦脊髓液搏出速度，顯示大腦對腦室內脊髓液的推力比正常人高，所以，從本報告吾人建議使用高解析度二維相位對比磁振造影影像，來鑑別高流速及低流速常壓性水腦病患，並且對於高常壓性水腦患者術前評估很有幫助，進一步使用脊髓液引流術治療效果可能比較明顯。

關鍵詞：磁振造影；大腦脊髓液；相位對比影像；常壓性水腦