VALUE OF PHASE CONTRAST MAGNETIC RESONANCE IMAGING FOR INVESTIGATION OF CEREBRAL HYDRODYNAMICS

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SUMMARY

Objective: Phase Contrast Magnetic Resonance Imaging (PCMRI) is a noninvasive technique that can be used to quantify variations of flow during the cardiac cycle. PCMRI allows investigations of blood flow dynamics in the main arteries and veins of the brain but also the dynamics of cerebrospinal fluid. These cerebral flow investigations provide a description of the regulation mechanisms of intracranial pressure during the cardiac cycle. The objective of this article is to describe the contribution of this technique in diseases related to disorders of cerebral hydrodynamics in the light of 5 clinical cases.

Method: Flow measurements were performed using PCMRI sequences on a 1.5 Tesla MR imager in 4 patients with symptomatic ventricular dilation and 1 patient with a syringomyelic cavity.

Results: Flow quantification in these 5 patients, representative of the diseases mainly concerned by cerebral hydrodynamics, is useful to guide the indication for ventricular shunting in patients with hydrocephalus, to demonstrate obstruction of the cerebral aqueduct, to demonstrate recirculation of ventricular CSF after ventriculostomy and to characterize the dynamic features of CSF inside a spinal cavity.

Conclusion: PCMRI, now available to neurosurgeons, is complementary to morphological MR and provides quantitative information on cerebral hydrodynamics. This information is mainly used to confirm alteration of CSF flow in the cerebral and spinal compartments. PCMRI is also a functional tool to better understand the pathophysiology of hydrocephalus and syringomyelia.

Key words: Phase-contrast magnetic resonance imaging, Flow dynamics, Hydrocephalus, Cerebrospinal fluid.

INTRODUCTION

Magnetic resonance (MR) imaging is a technique sensitive to moving fluids, especially blood flow and cerebrospinal fluid (CSF) flow. On T2-weighted morphological MR images, this is reflected by a loss of intensity of pixels representing moving spins, called “flow-void”. In the case of active hydrocephalus, the presence of this flow-void in the cerebral aqueduct is characteristic of hyperdynamic ventricular CSF, in favor of CSF shunting [9].

The development of Phase Contrast Magnetic Resonance Imaging (PCMRI) [26], during the eighties, allowed qualitative demonstration and, for the first time, quantification of movements of the various fluids of the brain [15, 17, 20, 27]. This sequence can be used to measure velocities in an encoding direction selected by the operator.

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Gating of the PCMRI to the subject’s heart rate allows measurement of velocity changes during several phases of the cardiac cycle (figure 1). This temporal approach of hydrodynamics can be used to study the mechanisms responsible for regulation of intracranial pressure [2].

Interpretation of these functional images is based on analysis of flow waveforms. These waveforms are characterized by temporal and quantitative parameters [5, 20]. The stroke volume, or oscillatory flow volume, is the volume of CSF which is initially driven out of the brain by the arterial systolic pressure and which subsequently returns to its initial site during diastole. More generally, PCMRI is a recognized complement to the diagnosis of CSF and blood dynamic disorders [14].

Based on previous studies [4, 5] of cerebral hydrodynamics in young and normal aging population of control subjects, we were able to temporally and quantitatively define the succession of vascular and CSF mechanisms that regulate arrival of the systolic blood volume in the skull (figure 2 and table I). Despite the large ventricular CSF volume, our study showed that ventricular CSF only plays a minor role in expulsion of CSF from intracranial subarachnoid spaces towards the expansion of the spinal canal which ends in the dural sac.

PCMRI can be used to investigate the hydrodynamic aspects of the pathophysiology of hydrocephalus [6, 16, 29]. These cerebral dynamic studies now provide a body of knowledge on cerebral volume exchanges. In more practical terms, this article describes the contribution of quantitative flow measurement to the diagnosis of CSF dynamics disorders, as performed routinely at Amiens’ hospital. The clinical cases presented here illustrate the importance of functional data as a complement to morphological data.

**MATERIAL – METHODS**

**Image acquisition**

PCMRI examinations were performed on a 1.5 Tesla imager (GE healthcare) with the head coil. Data were acquired with a cine phase-contrast sequence, allowing measurement of velocities located within a sensitivity range defined at the time of pro-
gramming of the sequence by ± Venc. The Venc parameter was formatted according to the disease and anatomical level studied.

In the spinal cord, Venc was set to 5 cm/s for CSF studies and 80 cm/s for vascular studies.

In the cerebral aqueduct, Venc was set to 5 cm/s for demonstration of stenosis and 15 cm/s in cases of communicating hydrocephalus.

At the floor of the third ventricle, in the presence of a ventriculostomy, Venc was set to 5 cm/s.

Gating of PCMRI sequence acquisition to heart rate was performed using a peripheral pulse transducer applied to the subject’s finger. The acquisition parameters used for flow measurements were: TR between 29 and 43 ms, TE between 11 and 17 ms, a 160×120 mm² rectangular field of view and a 256×128 matrix, a slice thickness of 5 mm, a flip angle of 20°-30° with one excitation. The Phase encoding direction was set to right/left. The field of view selected is a compromise between the acquisition time and sufficient spatial resolution to study a flow area consisting of a small number of voxels as in the aqueduct. It must also be sufficiently large to avoid overlap artefacts in the center of the image. The choice of retrospective gating provides up to 32 time-points equally distributed throughout the cardiac cycle. The duration of this type of acquisition, depending on the subject’s heart rate, is nearly 2 minutes. The flow direction acquisition parameter was selected as "slice". Section planes for flow acquisitions were inclined perpendicularly to the direction of CSF or blood flows. These sections were positioned directly from previously acquired series during the systematic morphological assessments.

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**TABLE I.** The table presents the main values of Cerebrospinal Fluid and blood flows. The reference values of blood and CSF flows were established from a control population in a previous work [5]. These values are used as references to study the CSF and blood dynamics of the patients.

**TABLEAU I.** Ce tableau présente les valeurs des flux sanguin et du LCR. Les valeurs de référence ont été établies par l'évaluation d'une population témoin, telle que décrite précédemment [5]. Ces valeurs de référence ont été utilisées pour l'étude des flux sanguins et du LCR chez nos patients.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Healthy population</th>
<th>Patient 1</th>
<th>Patient 2</th>
<th>Patient 2 after shunt</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aqueductal stroke volume (μl/cardiac cycle)</strong></td>
<td>51±25</td>
<td>184</td>
<td>134</td>
<td>32</td>
</tr>
<tr>
<td><strong>Aqueductal Peak outflow velocity (cm/sec)</strong></td>
<td>6.3±2.2</td>
<td>9.6</td>
<td>8.6</td>
<td>3.8</td>
</tr>
<tr>
<td><strong>Aqueductal Time to arterial systolic peak flow as a percentage of cardiac cycle</strong></td>
<td>21±7</td>
<td>13</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td><strong>Cervical stroke volume (μl/cardiac cycle)</strong></td>
<td>467±147</td>
<td>571</td>
<td>381</td>
<td>265</td>
</tr>
<tr>
<td><strong>Cervical Peak outflow velocity (cm/sec)</strong></td>
<td>4.5±0.9</td>
<td>4.1</td>
<td>3.5</td>
<td>4.2</td>
</tr>
<tr>
<td><strong>Cervical Time to arterial systolic peak flow as a percentage of cardiac cycle</strong></td>
<td>5±3</td>
<td>2</td>
<td>–10</td>
<td>–5</td>
</tr>
<tr>
<td><strong>Cerebral blood flow (ml/min)</strong></td>
<td>687±187</td>
<td>334</td>
<td>385</td>
<td>460</td>
</tr>
<tr>
<td><strong>Vein TAPF: Time to arterial systolic peak flow as a percentage of cardiac cycle</strong></td>
<td>20±12</td>
<td>3</td>
<td>3</td>
<td>11</td>
</tr>
</tbody>
</table>

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**FIG. 2.** Intracranial Pressure (ICP) is not constant during the cardiac cycle, but depends on arterial and venous blood flow. CerebroSpinal fluid (CSF) flow and brain compliance. Arterial flow suddenly increases during systole. The variation in brain blood volume increases the ICP. According to Pascal’s law, ICP is then regulated by expelling CSF and venous blood out of the cranium. This outflow is not instantaneous, but depends on blood and CSF viscosities, pressure, and resistance to flow. Arterial peak flow (1) is first transmitted to cervical CSF flow (2), then to venous blood flow (3) and finally to supratentorial ventricular CSF flow (4). These successive stages involve changes in brain compliance.

**FIG. 2.** La pression intracrânienne (PIC) n’est pas constante durant le cycle cardiaque, mais dépend des écoulements du sang artériel et veineux, de l’écoulement du liquide cérébrospinal (LCS) et de la compliance du cerveau. Le débit artériel augmente soudainement pendant la systole. La variation du volume de sang cérébral augmente la PIC qui, suivant la loi de Pascal, se transmet à l’ensemble des compartiments et entraîne l’expulsion du LCS et du sang veineux hors du crâne. Cette expulsion n’est pas instantanée, mais dépend des viscosités du sang et du LCS ainsi que de la résistance à l’écoulement. Le pic de débit artériel (1) est d’abord transmis à la chasse du LCS cervical (2), puis au drainage du sang veineux (3) et finalement à la chasse du LCS ventriculaire (4).
Image processing

PCMRI series were analyzed using home made software developed at Amiens’ hospital. Image processing consisted of extracting, from the whole images of the series, the Regions Of Interest (ROI) representing CSF or blood velocities. The flow waveform was calculated from these extracted ROI, by multiplying the mean velocity of the ROI by its area for each cardiac phase. To correct for offsets in baseline velocity, a standard background was manually delineated in static tissues near each segmented region. The mean velocity of this noise area was calculated and subtracted to the ROI so as to correct eddy currents effects.

The final waveform represents the time-course of CSF or blood flows during all the phases of one cardiac cycle (figure 1). The result of integration of the positive part of this waveform is equal to the CSF or blood volume flushed during the cardiac cycle, and the result of integration of the negative part is equal to the CSF or blood volume displaced during filling. The CSF stroke volume corresponds to the smaller part of these two volumes. Cerebral blood flow corresponds to the sum of internal carotid and vertebral artery mean flows measured at neck level.

RESULTS: CLINICAL APPLICATIONS

Case 1

This 73-year-old man, with a history of hypertension, was referred for assessment of disorders of higher functions associated with gait disorders (ataxia) and sphincter disorders. Morphological MR demonstrated: dilation of the ventricular system, deep cortical sulci and nonspecific abnormalities of the periventricular white matter. The clinical and morphological assessment was unable to formally demonstrate the active nature of the ventricular dilation and the indication for ventricular shunting.

PCMRI was performed in the cerebral aqueduct with an encoding velocity of 15 cm/s and in the C2-C3 cervical spine with an encoding velocity of 5 cm/s for CSF and 80 cm/s for blood.

The results are presented in table I and figure 3. The oscillatory flow volume measured in the cerebral aqueduct was very high, the peak velocity measured was 9.6 cm/s and occurred early at 13% of the cardiac cycle after the arterial systolic peak. Normal CSF fluctuations were observed in the cerebral subarachnoid spaces where the stroke volume was 571 μl/min. The blood flow was small (334 ml/min) and the peak jugular vein outflow velocity was observed early at 3% of the cardiac cycle after the arterial systolic peak.

Ventriculoperitoneal shunting induced a marked clinical improvement with resolution of the gait disorders and sphincter disorders. Radiological follow-up demonstrated a reduction of ventricular volume.

In this first clinical case, demonstration of a markedly hyperdynamic ventricular system supported the indication for ventricular shunting in this patient, as for many authors, increased ventricular activity is predictive of a favourable outcome of shunting. In a population of 18 patients with normal-pressure hydrocephalus, Bradley et al. showed that the 12 patients with the highest oscillatory flow volume in the aqueduct were all improved by shunting. They also showed that the flow void (signal loss on proton density-weighted morphological images) in the aqueduct did not constitute a significant prognostic factor [8]. In fact, flow void is sensitive to CSF velocity and the increase in diameter of the aqueduct observed in some patients decreases CSF velocity despite a markedly increased CSF flow. Mase et al. [25] showed that the amplitude of flow in the aqueduct of patients with normal-pressure hydrocephalus was significantly greater than the amplitude measured in subjects with asymptomatic ventricular dilation or cerebral atrophy. They also mentioned a correlation between CSF velocity in the aqueduct and intracranial pressure variations after injection of a physiological saline solution into the lateral ventricles. They concluded that CSF flow could be used as a cerebral compliance marker. Later (2002), a large-scale study based on 236 patients, including 43 with normal-pressure hydrocephalus, confirmed the results of previous studies concerning the correlation between normal-pressure hydrocephalus and increased ventricular CSF dynamics [14, 24].

Case 2

This 63-year-old woman was regularly followed for sphenoidal meningioma treated exclusively by radiotherapy due to the site and extent of the tumor. Six months after radiotherapy completion, the patient presented with memory disorders and sphincter disorders. Although morphological MR demonstrated a stable tumor volume, the ventricular system appeared to be dilated with early signs of transependymal resorption.

PCMRI was performed in the cerebral aqueduct with an encoding velocity of 15 cm/s and in the C2-C3 cervical spine with an encoding velocity of 5 cm/s for CSF and 80 cm/s for blood.

The results are presented in table I and figure 4. The flow measured in the cerebral aqueduct was hyperdynamic with a very high oscillatory flow volume of 134 μl/cc, while the peak velocity measured, observed early at 11% of the cardiac cycle after the arterial systolic peak, was only 8.6 cm/s. In the cervical subarachnoid space, the oscillatory flow volume of 381 μl/cc was located at the lower end of normal range. Blood flow was 385 ml/min and the peak jugular vein outflow velocity was observed early at 5% of the cardiac cycle after the arterial systolic peak.

Ventriculoperitoneal shunting induced complete clinical recovery of this patient. The flow measured in the cerebral aqueduct markedly decreased, the oscillatory flow volume was normal and the peak velocity decreased to 3.8 cm/s. The oscillatory flow volume in the cervical subarachnoid space slightly decreased, while blood flow increased to 460 ml/min and the peak jugular vein outflow velocity was observed at 13% of the cardiac cycle after the arterial systolic peak.

Complications of radiotherapy can be characterized by inflammatory brain disease. Perrini et al. [28] reported the case of two patients who developed hydrocephalus with high ICP after radiotherapy,
therefore requiring CSF shunting. Our second case is similar since this patient presented with ventricular dilation 6 months after radiotherapy completion. This dilation was associated with a transependymal resorption which reflected a high ventricular CSF pressure.

Flow imaging supports the hypothesis of an alteration of subarachnoid spaces after radiotherapy by showing decreased flow in subarachnoid spaces counterbalanced by abnormally raised ventricular flow. The increased blood flow observed after shunting also supports the hypothesis of a link between normal-pressure hydrocephalus and a reduction of cerebral blood flow [13].

Case 3

This 39-year-old man presented with an intracranial hypertension syndrome. He had a history of meningitis in childhood. Morphological MRI demonstrated triventricular dilation, but no apparent stenosis of the aqueduct. Two PCMRI sequences were performed in the cerebral aqueduct, the first with an encoding velocity of 15 cm/s to detect hyperdynamic flow and the second at 5 cm/s (minimum possible) to detect stenosis of the aqueduct.

As shown in figure 5, no flow was demonstrated in the aqueduct whatever $V_{enc}$ was used. The oscillatory flow volume in the cervical subarachnoid space was 744 μl/cc and the peak velocity, observed at 4% of the cardiac cycle before the arterial systolic peak, was 4.1 cm/s. The blood flow was 588 ml/min and the peak jugular vein outflow velocity was observed early at 3% of cardiac cycle after the arterial systolic peak.

Hydrocephalus can be classified into two categories. The first one, called communicating hydrocephalus, is characterized by a free circulation of CSF between the ventricular system, main source of CSF secretion, and the subarachnoid spaces which are related to CSF resorption pathways. The second, called non-communicating hydrocephalus, is characterized by a ventricular dilation induced by CSF retention due to clogging. This obstruction is mainly located in the cerebral aqueduct, but the foramina of Monro, Magendie and Luschka can also be alterna-
Fig. 4. – a, d) Gadolinium-enhanced T1-weighted spin echo axial sections of the sellar region. b, c) Gadolinium-enhanced T1-weighted spin echo coronal sections of the sellar region. c, f) T2-weighted Fast Spin Echo supratentorial axial sections.

The stable volume and extension of the meningioma cannot account for dilation of the ventricular system and transependymal resorption (arrow) visible on the MR examination performed 6 months after completion of radiotherapy (e, f).

g) Graph representing CerebroSpinal fluid (CSF) flow in the aqueduct before and after shunting compared to CSF flow in a control population.

MR imaging in this 63-year-old patient demonstrates the presence of a meningioma. 6 months after radiotherapy, she presented with dilation of the ventricular system associated with hyperdynamic CSF flow in the aqueduct.

Fig. 4. – a, d) Coupes longitudinales et b, e) coupes coronales, de la région sellaire en écho de spin pondérées T1 avec injection de Gadolinium. c, f) Coupes axiales supratentorielles en écho de spin rapide pondérées T2.

La stabilité du volume du méningiome, ne peut pas expliquer la dilatation du système ventriculaire et la résorption trans-épendymaire (flèche) évidente sur l’examen IRM réalisé 6 mois après la fin de la radiothérapie (e, f).

G) Ce graphique représente le débit de Liquide Cérébro-Spinal (LCS) dans l’aqueduc avant et après la mise en place de la dérivation. Ce débit est comparé à celui d’une population témoin.

L’examen IRM de cette patiente de 63 ans montre la présence d’un méningiome. 6 mois après radiothérapie, une dilatation du système ventriculaire associée à un écoulement hyperdynamique du LCS dans l’aqueduc est mise en évidence.
tive sites of obstruction [12]. However, this type of obstruction is not always demonstrated by morphological imaging, as illustrated by this patient. Then, PCMRI, that clearly demonstrated the lack of flow in the aqueduct, can be useful to guide neurosurgical management.

Case 4

This examination corresponded with the checking of the efficiency of the third ventricle floor aperture after ventriculostomy in a 40-year-old man treated for ventricular dilation secondary to aqueduct stenosis. PCMRI was performed near the floor of the third ventricle using an encoding velocity of 5 cm/s. Native phase contrast MR images showed a zone of low and high intensity signal reflecting the presence of pulsatile flow (figure 6). Quantification of this zone of interest confirmed the efficiency of aperture creation on the floor of the third ventricle. The oscillatory flow volume measured was 146 µl/cc and the CSF oscillatory flow volume in the cervical spine was 510 µl/cc. A second examination performed one year after the operation confirmed the efficiency of the ventriculostomy with an oscillatory flow volume of 220 µl/cc at the third ventricle floor aperture.

Case 5

This 25-year-old woman presented with an Arnold-Chiari type I malformation associated with a very large syringomyelic cavity extending from the foramen magnum to the lumbar enlargement of the subarachnoid space. PCMRI was performed at 5 levels of the spinal cord: (C2-C3, C5-C6, T4-T5, T9-T10, T11-T12) with an encoding velocity of 5 cm/s. The first qualitative analysis of the cine series images demonstrated the presence of CSF flow in the subarachnoid space at C2-C3 level. This flow was characterized (figure 7) by the existence of a low-intensity crown depicting the cranial CSF filling motion. At C5-C6 level, the CSF crown area was markedly decreased with a complete obliteration of the posterior subarachnoid spaces and the presence of a high flow pattern at the center of the CSF crown. At T4-T5 level, the subarachnoid spaces were no longer visible and the central area was increasingly large. At T9-T10 level, the subarachnoid space was visible again, while the central zone was smaller. At T11-T12 level, the crown of CSF flow was present and the central flux area had completely disappeared. Quantitative analysis of these functional flow images showed that CSF flow in the cervical subarachnoid spaces was normal and strongly correlated with the flow in the central zone at T4-T5 level (figure 7).

DISCUSSION

Velocities can be measured by MR imaging since the end of the 80’s, but this technique has not been widely used, mainly because of the limited degree of
the reliability and accuracy of cine phase-contrast sequences has now been clearly established [23]. However, the compromises between acquisition time, signal-to-noise ratio and precision of the measurement can account for the discrepancies between flow measurements reported by various authors. Optimization of the velocity measurements accuracy is often achieved to the detriment of acquisition time. Our study protocol is the result of a compromise between an acceptable level of precision of measurement and an acquisition time compatible with routine clinical practice.

Before applying this protocol to disease states, we first performed this imaging protocol on a control population in order to determine our own flow values [5, 19] and reduce the effects related to sequence parameters to a minimum. As our control population was young in comparison with the mean age of hydrocephalus patients, we have studied the effects of normal aging upon cerebrospinal fluid and cerebral blood flows. In this unpublished work, we have demonstrated that CSF flow variations induced by normal aging were negligible in front of the hydrodynamic alterations measured in hydrocephalus patients [4].

The encoding velocity (Venc) is one of the parameters which defines the sensitivity of the sequence
and, depending on its value, can be used to weight the image in relation to rapid or slow flows. A $V_{enc}$ lower than the velocities involved would induce a velocity overlap effect and would be characterized by the presence of pixels of opposite intensities in the center of the vessel. However, a $V_{enc}$ much higher than the measured velocities would decrease the sensitivity of the technique. So $V_{enc}$ must be fitted to the fluid velocity or the structure examined, taking into account the suspected disease.

The PCMRI sequence uses cardiac gating provided either by ECG electrodes or a plethysmograph. The waveform obtained with the pulse transducer is less accurate because it does not directly measure cardiac contraction but arrival of the systolic pulse wave at the finger. However, for reasons of simplicity, time gain and patient comfort, we use this pulse-based gating method. In any case, the difference in temporal precision between these two methods is negligible in view of the sequence sampling frequency. The pulse transducer must be carefully positioned and the shape of the cardiac profile visualized on the monitor must be checked before starting the measurements, as the quality of acquisition and acquisition time depend on this parameter.

In order to optimize flow image processing, we have developed a software exclusively devoted to the study of CSF and blood flows [5]. This software is now freely downloadable from the web. It uses

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**Fig. 7.** Functional flow imaging of a syringomyelic cavity.

a) Median sagittal T1-weighted spin echo sequence; b, c, d, e, f) Oblique sections perpendicular to the spinal cord on cine phase-contrast imaging at different levels of the syringomyelic cavity. g) This graph shows the CSF flow of the cavity at T4-T5 (image d) and its time-flow correlation with the flow in the C1 subarachnoid space (image b).

**Fig. 7.** Imagerie fonctionnelle d’écoulement dans une cavité syringomyélitique.

a) Coupe sagittale pondérée T1 en écho de spin. b, c, d, e, f) Images en contraste de phase sur des coupes perpendiculaires à la colonne vertébrale à différents niveaux d’une cavité syringomyélitique. g) Ce graphe montre le débit d’écoulement de LCS dans la cavité en T4-T5 (image d) et sa corrélation temporelle avec le débit mesuré au niveau des espaces sous arachnoidiens en C1 (image b).
the temporal information derived from the series of images to extract the pixels with a temporal velocity profile gated to the cardiac cycle. This software is independent of the acquisition consoles and provides all of the informations characterizing the flow rates of the segmented zone within a few seconds. The software output is a text file that can be directly read by a spreadsheet for comparative and statistical analysis of the flow waveforms measured. Rapid access to oscillatory flow volumes of ventricular and spinal CSF and cerebral blood flow provides a functional complement to morphological imaging for the investigation of disorders of cerebral hydrodynamics.

Pathophysiology of hydrocephalus

Pressure is defined by the intensity of the force exerted per elementary unit of area of the system considered. In the case of ventricular CSF, the force exerted on CSF at the entry to the aqueduct is the sum of all unit forces exerted on the entire surface of the lateral and third ventricles.

In the case of cerebral hydrodynamics, the force represents the reaction of the parenchyma to variations of the cerebral fluid volume (blood + CSF) during the cardiac cycle [18]. This systolic force applied to the surface of the ventricular compartment and the intracranial subarachnoid compartment is responsible for oscillatory CSF flow. These oscillatory CSF motions maintain volume equilibrium between ventricular, intracranial subarachnoid and spinal subarachnoid compartments as a function of cerebral blood volume variations and are therefore responsible for variations of ICP during the cardiac cycle [2].

In the case of communicating hydrocephalus, we have shown that patients presented a significant increase of CSF flow in the aqueduct whereas cerebral CSF flow was located in the normal range [3]. This result may be explained by a kind of brain adaptation characterized by an intracranial loss of compliance brought about by a decrease of the supratentorial venous compliance or an alteration of CSF flow in the intracranial subarachnoid space. Therefore, this compliance change could be balance by a significant increase of the ventricular CSF stroke volume flowing through the aqueduct. This long, narrow duct is the only channel connecting ventricular CSF to the subarachnoid spaces which communicates with the lumbar enlargement of the subarachnoid spaces. To raise the CSF volume oscillating between these two zones, the pressure gradient between the compartments must be increased and/or the huge resistance to flow of the aqueduct must be decreased. The enlarged ventricular surface in normal-pressure hydrocephalus corresponds to a need to increase the oscillatory CSF volume despite the normal pressure in the parenchyma. This raised CSF volume oscillating between the two levels of the cranium is designed to compensate for a reduction of supratentorial venous compliance and/or an alteration of CSF flow in cerebral subarachnoid spaces.

In the case of cerebral atrophy, the process of ventricular dilation can be explained by degeneration of the cerebral parenchyma and the need to keep a normal intracranial pressure. This dilation is also associated with a decrease of the blood volume entering the cranium during a cardiac cycle resulting only in a slight increase of aqueductal CSF oscillatory flow compared to young subjects with no cerebral atrophy [6].

This increase appears to be non-significant compared to the marked increase of CSF oscillations observed in patients with normal-pressure hydrocephalus. Therefore, measurement of CSF flow in the cerebral aqueduct could be very useful in the differential diagnosis of atrophy and normal-pressure hydrocephalus.

Development of neuroendoscopic techniques now facilitates the treatment of aqueductal stenoses by opening the floor of the third ventricle (V3), thereby avoiding shunting (11). PCMRI in the fourth patient validates the surgical procedure by measuring the restored contribution of the ventricular system to supratentorial regulation of cerebral vascular expansion. Temporal and amplitude comparison of the flow waveform measured in the orifice of V3 with a flow waveform derived from the aqueduct in a normal population, shows that ventricular CSF can now flow through the aperture an be again in communication with the whole CSF system. The area of the hole made in the floor of V3 (45 mm²) in this patient is much larger than the area of a normal aqueduct (about 8 mm²) and the V3 floor thickness is also negligible compared to the length of an aqueduct which is about 2 to 3 cm. These two characteristics considerably decrease the resistance to ventricular CSF flow. Consequently, the ventricular CSF oscillatory flow volume is increased after ventriculostomy: 220 μl/cc versus 51±25 μl/cc for normal ventricular flow. To our knowledge, no study has demonstrated the impact of this difference on clinical recovery after ventriculostomy.

Several studies have investigated CSF pulsatility in the spinal canal [19] in patients with Chiari malformation [1], either isolated or associated with a syringomyelic cavity [7, 10, 21]. However, these studies were essentially based on modifications of CSF velocity in the cyst. We propose an extension of these investigations by studying the propagation of CSF flow along the spinal cord, inside and out of the cyst. Our report (figure 7) of the fifth case (syringomyelia) is not designed to explain this complex disease, but to illustrate the feasibility of functional assessment of this CSF dynamics disorder with a non invasive technique.

Although the origin of this disease is still unclear, CSF hydrodynamics appears to play an essential role in the development of these syringomyelic cavities [22]. Chiari malformation is often associated with this disorder. This congenital abnormality of the foramen magnum, located at the junction of intracranial dynamics, links intracranial CSF with the spinal subarachnoid space, which constitutes an expansion compartment for intracranial pressure regulation. Stenosis of this channel is characterized by a loss of the spinal subarachnoid channels functions, which increases the resistance to CSF flow, resulting in increased intracranial CSF pressure. This increased CSF pressure can then result in dilation of the central ependymal canal.
An analogy can be drawn with communicating hydrocephalus associated with an alteration of CSF flow in cranial subarachnoid spaces. In this case, the ventricular system enlarges to compensate for the decreased volume of subarachnoid CSF.

One of the surgical treatments for syringomyelia consists in enlarging the cisterna magna by a duroplasty to restore a larger communication between the cranial and spinal compartments. Another surgical solution consists in shunting the cyst in order to provide a supplementary drainage duct the same way a ventricular shunt acts.

Conventional MR imaging allows evaluation of syringomyelia in three dimensions as well as the demonstration of associated lesions, defining the congenital or secondary nature of this disease. PCMRI now provides functional information about CSF flow distribution inside the cyst. As demonstrated in this patient, cine phase-contrast sequences lasting about 2 minutes can now be used to rapidly demonstrate the pulsatile or stagnant appearance of the cyst. The quantitative analysis performed in this case demonstrated the active participation of the cyst in pressure regulation inside the spinal canal. This illustrates the influence of CSF flow inside the cyst on spinal dynamics. PCMRI provides complementary information about the functional aspects of this disease and provides a better description of CSF dynamics to guide surgical management.

CONCLUSION

Complementary to morphological imaging, PCMRI now provides supplementary information on intracranial dynamics and therefore provides a better understanding of the pathophysiology of disorders related to blood and CSF circulation. However, this type of imaging is not used to its full potential, as it requires knowledge of cerebral hydrodynamics and image post-processing that has not yet been integrated into commercially available consoles. This results in a limited use of this new approach to cerebral hydrodynamics.

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REFERENCES


