Velocity and pressure gradients of cerebrospinal fluid assessed with magnetic resonance imaging

Clinical article

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Object. New approaches for understanding CSF motion in healthy individuals and patients with hydrocephalus and Chiari malformation are presented. The velocity and the pressure gradient of CSF motion were determined using phase contrast (PC) MRI.

Methods. The authors examined 11 healthy control subjects and 2 patients (1 with hydrocephalus and 1 with Chiari malformation), using 4-dimensional PC (4D-PC) MRI and a newly developed computer analysis method that includes calculation of the pressure gradient from the velocity field. Sagittal slices including the center of the skull and coronal slices of the foramen of Monro and the third ventricle were used.

Results. In the ventricular system, mixing and swirling of the CSF was observed in the third ventricle. The velocity images showed that the CSF was pushed up and back down to the adjacent ventricle and then returned again to the third ventricle. The CSF traveled bidirectionally in the foramen of Monro and sylvian aqueduct. Around the choroid plexus in the lateral ventricle, the CSF motion was stagnant and the CSF pressure gradient was lower than at the other locations. An elevated pressure gradient was observed in the basal cistern of the subarachnoid space. Sagittal imaging showed that the more prominent pressure gradients originated around the cisterna magna and were transmitted in an upward direction. The coronal image showed a pressure gradient traveling from the central to the peripheral subarachnoid spaces that diminished markedly in the convexity of the cerebrum. The 2 patients, 1 with secondary hydrocephalus and 1 with Chiari malformation, were also examined.

Conclusions. The observed velocity and pressure gradient fields delineated the characteristics of the CSF motion and its similarities and differences among the healthy individuals and between them and the 2 patients. Although the present results did not provide general knowledge of CSF motion, the authors’ method more comprehensively described the physiological properties of the CSF in the skull than conventional approaches that do not include measurements of pressure gradient fields.

(key Words) cerebrospinal fluid • hydrodynamics • hydrocephalus • magnetic resonance imaging • image analysis • Chiari malformation • diagnostic and operative techniques

N ormal CSF movement is important for the health of the brain, and disturbances in CSF movements can be directly linked to a variety of abnormalities, including hydrocephalus. Typically, assessment of the health of the CSF space involves invasive techniques such as CSF pressure monitoring with a ventricular catheter or through lumbar drainage, by using either metrizamide 19 as a contrast agent or radioisotopes, 11 both of which require injection into the CSF. These conventional examination methods change the physical and physiological characteristics of the CSF space. Therefore, the condition of the CSF space can be better evaluated using noninvasive methods such as MRI 8,9 For example, the PC MRI method 13 has a long history of use for observing the dynamics of the CSF. 13,16,24 However, a noninvasive method for assessing the CSF space in the cranial cavity is still lacking. In the field of hydromechanics, the pressure gradient is an alternative parameter for describing the CSF flow field. The localized pressure gradient is related to the motion of the CSF and is indicative of the velocity of the CSF, compliance and elastance within the cavity, CSF viscosity, and distribution and pulsation of the CSF in the skull. Once these physiological factors of the CSF are measured, what information do they provide to the neurosurgeon? Medical imaging techniques and computer analysis methods provide the neurosurgeon with information that can be easily understood and interpreted. For example, data presented in a vector format, as a color scale, or as a movie are easy to comprehend and familiar to neurosurgeons.

In this study, we observed the flow velocities of the
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CSF in 4 dimensions (anteroposterior, mediolateral, caudal cephalic, and over time) by using the PC-MRI technique. Time series of the velocity vector fields and pressure gradient fields were assessed to examine whether these CSF flow characteristics are useful for neurosurgeons to identify and classify the CSF dynamics in healthy individuals and in patients with abnormal CSF flows.

**Methods**

This research was approved by our institution’s internal review board. All subjects were examined after obtaining appropriate informed consent, consistent with the terms of the approval from the internal review board of Tokai University Hospital.

Quantitative CSF motion analysis was performed in 11 healthy individuals (aged 26–56 years) and 2 patients with abnormal CSF flows (aged 13 and 22 years). One of the patients had hydrocephalus due to subarachnoid hemorrhage, and another had a Chiari Type I malformation. The CSF motion was examined in a thick sagittal slab covering the entire lateral ventricle or in a coronal slab covering parts of the lateral and third ventricles. A 1.5-T scanner (Gyroscan, Philips) equipped with an 8-channel phased array head/neck coil was used with the following conditions: flow encode directions, foot-head, right-left, and anterior-posterior; number of cardiac phases 32; TR 9.8–16.4 msec; TE 6.6–6.7 msec; flip angle 20°; FOV 22 × 22 cm² or 32 × 32 cm²; velocity encoding 5 cm/sec; and spatial resolution 1.96 mm (isotropic). The 4D-velocity field of the CSF was separated from blood flow by a previously described technique. The in-plane velocities were then delineated by vectors, whereas the through-plane velocities were visualized by colors. The vector color-coded CSF velocity field was then superimposed on the T2-weighted images with the stationary tissues.

In general, a vector field is fully characterized by divergence and curl of the velocity field based on Helmholtz’s theorem. Curl denotes the rotation of the vector field and thus characterizes the intensity of the vortex in the vector field of the CSF. This quantity was visualized as a measure for turbulence in CSF flow. The other quantity we used to characterize the flow dynamics was the pressure gradient, which is directly obtained based on the Navier-Stokes equations. Since a flow is generated in part by a spatiotemporal difference in the fluid pressure, this quantity was expected to allow the visualization of the motive-force distribution of the CSF flows.

**Results**

*Velocity Analysis Using the 4D-PC Method*

The results of velocity analysis by the 4D-PC method in various CSF spaces are summarized in Table 1. The whole-skull sagittal and limited-lateral and third-ventricle coronal velocity images are shown in Figs. 1 and 2 and in Videos 1 and 2.

**Video 1.** Sagittal imaging of CSF velocity. In the sylvian aqueduct, well-ordered, bidirectional CSF motion is seen in these sagittal images. The velocity imaging also shows significant CSF motion in the third ventricle, sylvian aqueduct, fourth ventricle, and cisterna magna and in the premedullary, prepontine, and anterior parts of the interpeduncular, suprasellar cisterns. Compared with the anterior horn, the CSF velocity was diminished in the posterior part of the lateral ventricle. Click here to view with Quicktime.

**Video 2.** Coronal imaging of CSF velocity. In the coronal view of the ventricular system, CSF motion is observed surging up from the third ventricle through the foramen of Monro and running to the ventricular wall where it changes direction and travels upward and to the wall again. This circular motion is not turbulent. The regulated swirl of the CSF motion seems to form a compartmentalized motion in the anterior horn of the lateral ventricle. A prominent CSF velocity is visible in the third ventricle, and the CSF moves in a bidirectional fashion in the foramen of Monro. Click here to view with Quicktime.

In the sagittal view of the ventricular system (Fig. 1 and Video 1), a well-regulated lamination was observed in the sylvian aqueduct, and a high-velocity downward motion was noted after a slow upward motion. The slow upward motion was mainly observed during the cardiac cycle and the fast, sharp, and downward motion occurred in the fourth ventricle. This bidirectional CSF motion in the sylvian aqueduct was seen in all healthy individuals. In the lateral ventricle, the CSF velocity tended to be decreased from the anterior horn to the posterior part of the lateral ventricle, except in 4 of the healthy subjects. Specifically, it appeared that stagnant fluid was prominent in the posterior part of the lateral ventricle. In the coronal view of the ventricular system (Fig. 2 and Video 2), a lengthy upward movement from the third to the lateral ventricle lasted for most of 1 cardiac cycle, ending with a downward motion at the foramen of Monro. This bidirectional CSF motion at the foramen of Monro was observed in all healthy individuals. There was well-ordered motion in the ventricular system, except in the third ventricle, in which turbulence was prominent. Sometimes the turbulence in the third ventricle spread into the lateral ventricle, but this turbulence was limited around the foramen of Monro (Fig. 2 and Video 2). Observation of the movement of the CSF in the anterior part of the lateral ventricle revealed a circular CSF motion like a regulated swirl. This swirling motion formed a compartment in the anterior horn of the lateral ventricle (Fig. 2 and Video 2). In the anterior horn, the CSF motion was turbulent, in contrast to the mostly motionless CSF in the posterior part of the lateral ventricle observed in the sagittal images (Fig. 1 and Video 1).

Upward motion occupied most of 1 cardiac cycle, followed by downward motion in the basal cistern (Fig. 1 and Video 1). A continuous backward motion was observed in the crural, ambient, and quadrigeminal cisterns. Continuous upward and backward motion was noted in the pericallosal cistern, with the upward motion being the dominant one. In the sylvian fissure, the CSF motion showed a trend of moving in the lateral direction. A slow, continuous, up, and somewhat backward motion was observed in the convexity of the cerebrum. Finally, moderate CSF motion was observed in the medial aspect of the cerebrum (for example, in the medial convexity in Table 1), which is adjacent to the superior sagittal sinus.
Fig. 1. Sagittal images of the CSF space. a–h: In the sylvian aqueduct, well-ordered and bidirectional CSF motion is seen in the sagittal images. The velocity images show significant CSF motion in the third ventricle, sylvian aqueduct, fourth ventricle, and cisterna magna and in the premedullary, prepontine, and anterior parts of the interpeduncular, suprasellar cisterns. In contrast, the CSF velocity was diminished in the posterior part of the lateral ventricle compared with that in the anterior horn.

TABLE 1: Summary of CSF velocity in healthy subjects rated by an experienced neurosurgeon*

<table>
<thead>
<tr>
<th>Subject No.</th>
<th>Lateral Ventricle</th>
<th>3rd Ventricle</th>
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<th>4th Ventricle</th>
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* Scores for CSF velocity were the following: + = low; ++ = moderate; +++ = high. Ant = anterior; NA = not assessed; Pst = posterior.
Pressure Gradient Analysis Using the 4D-PC Method

The results of the analysis of the CSF pressure gradient with the 4D-PC method are summarized in Table 2. In the ventricular system, a conspicuous pressure gradient was observed at the anterior part of the third ventricle and the inlet and outlet of the sylvian aqueduct (Fig. 3 and Video 3).

**Video 3.** Sagittal CSF pressure gradient distribution. The pressure gradient imaging shows a significant gradient in the anterior part of the third ventricle, around the sylvian aqueduct, suprasellar cistern, anterior part of the interpeduncular cistern, premedullary cistern, and cisterna magna. The pressure gradient in the subarachnoid space extended from the cisterna magna in an upward direction. Click here to view with Media Player. Click here to view with Quicktime.

In the basal cistern, a prominent pressure gradient was first seen in the cisterna magna and was transmitted upward toward the prepontine, interpeduncular, and suprasellar cisterns (Fig. 3 and Video 3). There was a reduction in the pressure gradient phase from the basal cistern to the convexity of the cerebrum. The pressure gradient was decreased in the sylvian fissure, but a high-pressure gradient was noted around the middle cerebral artery. Pressure gradients typically extended from caudal to rostral and from central to peripheral directions in the skull.

**Illustrative Cases**

**Case 1**

Figure 4 shows sagittal slices of hydrodynamic images in a 57-year-old woman with a ruptured right internal carotid artery aneurysm. Her MRI showed enlarged lateral and third ventricles due to secondary hydrocephalus. A marked pressure gradient originated in the prepontine and ventricular systems, and this high-pressure gradient was prominently visible around the brainstem (Fig. 4). The patient received a ventriculoperitoneal shunt to treat her hydrocephalus and a deterioration in her gait and orientation. After the shunting procedure, her symptoms dramatically improved. Figure 5 clearly shows the diminished pressure gradient in the ventricular system of this patient. In sum-

![Image of hydrodynamic parameters of CSF motion]
TABLE 2: Summary of CSF pressure gradients in healthy subjects rated by an experienced neurosurgeon

<table>
<thead>
<tr>
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* Scores for CSF pressure were the following: + = low; ++ = moderate; +++ = high.

**Fig. 3.** Images of the CSF pressure gradient. a–h: A significant pressure gradient is visible in the anterior part of the third ventricle, around the sylvian aqueduct, suprasellar cistern, anterior part of the interpeduncular cistern, premedullary cistern, and the cisterna magna. The pressure gradient in the subarachnoid space is transmitted from the cisterna magna in an upward direction.
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mary, the pressure gradient at the sylvian aqueduct shows a marked decrease after the shunting procedure (Fig. 6).

Case 2

A 13-year-old girl suffered from chronic headache. Preoperative MRI indicated Chiari Type I malformation with basilar impression (Fig. 7). We performed foramen magnum decompression and her headaches completely resolved after the surgical procedure. This favorable surgical outcome was confirmed by postoperative MRI (Fig. 8). The results of the pressure gradient analysis indicated a diminished pressure gradient at the sylvian aqueduct after the surgical procedure (Fig. 9).

Discussion

The present study examined the motion of the CSF within 1 cardiac cycle, which may reflect the CSF circulation. The effect of respiration on the CSF flow dynamics was not considered in this study. Because of the long acquisition time in the 4D-PC method and to ensure the comfort of the subjects during the examination, extending the acquisition time for respiratory and cardiac gating was not possible. In general, the CSF pressure gradients extended from caudal to rostral and central to peripheral directions in the subarachnoid space. In the ventricular system, a strong pressure gradient was present in the third and fourth ventricles.

The CSF was swirling at a ventricular chamber and transported to a connecting ventricular chamber in a bidirectional fashion. To our knowledge, this is the first report to provide a detailed description of CSF motion in the central nervous system using the 4D-PC method to determine the velocity and pressure gradient of the CSF.

The PC method has long been used to study CSF motion, and, for the last 20 years, it has focused mainly on determining CSF velocity. In addition, the study of CSF flow dynamics is routine in clinical settings and mainly uses 2D-PC analysis that includes only 1 spatial direction. This 2D-PC approach has some limitations, however, because the CSF moves in the chamber in 3 dimensions. Therefore, the 2D-PC analysis cannot fully detect pathological changes at other sites in the CSF space. Today, 3D- and 4D-PC analyses are the 2 primary methods for examining the CSF space. These methods have also been applied to the study of hemodynamics in major vessels in both the intracranial and cardiovascular regions. Using the PC method, many researchers have

![Fig. 4. Case 1. Pressure gradient in the patient with secondary hydrocephalus. a–h: The pressure gradient was markedly increased in both the ventricular system and the basal cistern in preoperative images.](image-url)
concluded that bidirectional fluid movement occurs in various parts of the CSF space, such as the sylvian aqueduct, foramen magnum, and spinal canal. It has long been believed that a downward stream of the CSF originates from the lateral ventricle and progresses to the convexity of the cerebrum in a unidirectional motion, and this assumed CSF flow represented the “bulk-flow theory.” Today, the development of the PC methods has dramatically improved our understanding of CSF flow dynamics and has changed the concepts of CSF dynamics including the bulk-flow theory.

Nevertheless, previously, the PC method was only useful for determining the direction of the CSF movement indicated by vector or signal intensity determined by visual recordings, or the CSF movement was calculated on the basis of the velocity of the CSF. Alperin et al. introduced new analytical methods based on MRI, and studies of intracranial pressure and elastance with the PC method provide additional perspectives on the physiology of the CSF. Because the PC method focuses only on the analysis of velocity, here we have described new methods to examine additional factors of hydrodynamics such as pressure gradients.

If the CSF space is rigid and stationary, the pressure and pressure gradient should be equal in any position in space. However, the slight viscosity of the CSF and the elasticity of the surrounding tissues generate spatial inhomogeneity and temporal changes of the CSF pressure. On the basis of fluid mechanics, a pressure gradient in a local segment of a moving fluid directly relates to the acceleration of the motion and to the shear forces as well as to external forces such as gravity or a pumping force acting on this segment. This visualizing the pressure gradients sheds light on these different factors. The other significant advantage of a pressure gradient map is that this parameter can be expressed as scalar by calculating its intensity. This map shows the flow status more clearly than a vector map of fluid velocity and thus makes the interpretation of the 4D-PC data somewhat easier.

This advanced and noninvasive study of CSF motion clearly delineated the different intracranial CSF dynamics. In the ventricular system, the CSF in the lateral ventricle was calm except in the region of the anterior horn. No significant pressure gradient was observed around the choroid plexus of the body of the ventricle. The choroid plexus of the body of the lateral ventricle seemed to contribute less to the oscillating CSF. In 1955, Bering suggested that the...
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![Graph](image)

**Fig. 6.** Case 1. Changes of the pressure gradient. Preoperative (solid line) and postoperative (broken line) observations of the patient with secondary hydrocephalus indicate a markedly diminished pressure gradient after the shunting procedure.

The choroid plexus of the lateral ventricles plays the role of a generator of the arterial pulsation of the CSF. Laitinen's findings in 1968 were in conflict with the theory of Beriing, showing that a ventricular CSF pressure wave occurred before the thalamic pressure and not in the choroid plexus.

![Image](image)

**Fig. 7.** Case 2. Preoperative MRI showing a Chiari Type I malformation with basilar impression in a 13-year-old girl.

Traditionally, the choroid plexus has been thought to act like a pump generated by the arterial pulse wave that drives the pulsatile CSF circulation and oscillation unidirectionally and rostrocaudally. The present results are not entirely consistent with this hypothesis. Our results indicated prominent pressure gradients in the third ventricle, and velocity imaging showed bidirectional flow mainly in the fourth and third ventricles. This CSF motion was classified as turbulent flow according to our velocity analysis. This observation is supported by those of du Boulay in 1966, who, using Myodil ventriculography, demonstrated to-and-fro movements similar to turbulent CSF motion. This relationship was typically observed in the anterior part of the third ventricle. In this area, the first prominent pressure gradients occurred, and transmitted pressure gradients introduced strong CSF motion in the third ventricle, and the CSF was finally pushed up by the pressure gradient. This result provided support for the use of velocity and pressure gradient analysis. Although the origin of this pressure gradient was not identified in the present study, there appeared to be a close relationship between the origin of the CSF pressure gradients and arterial pulsation from the circle of Willis.

Furthermore, the motion of the CSF in the subarachnoid space created a significant pressure gradient that extended from the spinal canal to the cisterna magna and rapidly traveled in an upward direction to the ventral surface of the brainstem. In particular, an intense pressure gradient was readily apparent around the vertebrobasilar artery, which is located on the ventral surface of the brainstem. This prominent pressure gradient introduced
After decompressive surgery, the pressure gradient is significantly decreased (solid line). After decompressive surgery, the pressure gradient is significantly decreased (broken line).

Fig. 9. Case 2. The result of pressure-gradient analysis. A markedly increased pressure gradient is noted preoperatively (solid line). After decompressive surgery, the pressure gradient is significantly decreased (broken line).

significant CSF motion in the subarachnoid space. This pressure gradient tended to decrease from high to low mediolaterally in the subarachnoid space. A prominent pressure gradient surge around the middle cerebral artery existed even at the distal end of the sylvian fissure. These findings suggest that an arterial pulsation may be closely related to the motion of the CSF; however, additional studies of the CSF hydrodynamics are necessary to provide conclusive evidence of the interaction between CSF motion and arterial pulsation.

In 1943, O’Connell suggested that the vascular system is important in maintaining the CSF circulation, which is supported by our findings. In the present study, slow, calm, upward, and dorsal-directional CSF motion was detected in the convexity area, which had a weak pressure gradient. The present method was efficient for identifying slow motion and a low-pressure gradient of the CSF. Thus, the pressure gradient results presented are useful for explaining the behavior of the CSF motion. For this reason, introducing the hydrodynamic factors of velocity and pressure gradient helps define the CSF environment.

As shown in the 2 illustrative cases of abnormal CSF flows, a markedly increased CSF pressure gradient was observed preoperatively in these 2 patients. This increased pressure gradient significantly decreased after the shunting procedure and foramen magnum decompression. Since the derivation of the pressure gradient for simplicity assumed that the CSF is Newtonian and incompressible and that the surrounding tissue wall is rigid, the effect of the compliance of the brain parenchyma was not evaluated accurately. Nevertheless, the behavior of the pressure gradient reflected the change in the case of the Chiari Type I malformation. We believe that this observation was due to an expansion of the narrow space around the foramen magnum by the surgical procedure and that the acceleration and the spatial difference of the flow velocity around this region were thus relieved. These dramatic changes in pressure gradients are explained by the favorable surgical outcome. The analysis of CSF pressure gradients is useful for determining the process of treatment, selecting candidates for specific treatments, and for classifying the disease states such as hydrocephalus, Chiari malformation, or other disorders associated with disruption of CSF movement. Future directions for this project include quantifying the CSF motion, tracing the source of the CSF pulsation with this new method, and examining various categories of disease to relate these abnormalities to the conditions in the CSF environment and to elucidate the course of these diseases.

The limitations of the present study are that this study examined subjects only in the supine position. It is well known that the dynamics of CSF change with the position of the head, Moreover, body movements such as rotation, squatting, jumping, and running can easily affect CSF behavior. However, it was not possible to examine the CSF behavior during the normal movements associated with daily life. The second limitation was that the acquisition time was longer (around 40 seconds) than that for the routine MRI method. The present 4D-PC method required acquisitions for 3 spatial directions, such as head and foot, right and left, and anterior to posterior, and over time. A refinement of the number of observations by specifying the particular region on which to focus the investigation is therefore necessary. The present study with healthy subjects is a starting point for such refinement.

Conclusions

The present technique for analyzing CSF motion, using observations of pressure gradients in addition to information about the velocity vector field, provides information for an improved understanding of CSF motion in healthy subjects and may help classify hydrocephalic patients on the basis of CSF hydrodynamic dysfunction.

Future studies examining the origin of CSF pulsation may provide additional valuable information. Collecting more data from patients with anomalous CSF flow will be useful for identifying abnormalities in the CSF space and for elucidating the course of diseases involving the CSF.

Disclosure

The authors have no financial conflicts or any interest with any commercial product used in this study or any substantial relationship with an entity that may impact or benefit from the conclusions of this research.

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