Phase-contrast magnetic resonance imaging of cerebrospinal fluid flow in the evaluation of patients with Chiari I malformation

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The author describes the methods used for obtaining and interpreting qualitative and quantitative data regarding cerebrospinal fluid flow (CSF) and cerebellar tonsillar motion at the craniocervical junction during the cardiac cycle in patients with Chiari I malformations.

KEY WORDS • magnetic resonance imaging, cine phase-contrast • cerebrospinal flow • Chiari malformation

The observation of cerebellar tonsillar ectopia on a sagittal MR image of the brain or cervical spine in the absence of syringomyelia or hydrocephalus is of uncertain clinical significance. When symptoms such as cough- or strain-related headache, ataxic gait, or sensory deficit are elicited, a causal relationship is sought between these symptoms and anatomical observations.

The symptoms associated with Chiari I malformation are believed to be related to crowding of structures at the foramen magnum. The development of syringomyelia has been attributed to alteration of normal CSF flow. In phase-contrast MR imaging a flow-sensitive pulse sequence is used that can assign amplitude and direction to flowing blood, CSF, and brain structures. The quantitative accuracy of the phase-contrast sequence has been validated against Doppler ultrasonography for determining blood flow in vessels.

A body of literature exists in which the bidirectional craniocaudal displacement of CSF during cardiac systole and the subsequent caudocranial displacement during diastole are documented. The cerebellar tonsils and spinal cord experience characteristic displacements as well. These observations are attributed to the Monro–Kellie doctrine in which it is stated that the calvarium is rigid and that the volume of the intracranial space is constant. When blood volume related to the systolic arterial pulse wave enters the calvarium, there must be compensatory displacement of CSF from the intracranial space. Following the net outflow of blood from the venous system and because of the elastic recoil of the spinal dura, CSF reenters the intracranial space during cardiac diastole.

Phase-contrast MR imaging sequences can be acquired in the sagittal and transverse planes. These images can be displayed in static or cine modes. Cerebrospinal fluid flow waveforms and tables are generated to analyze CSF flow velocity, and temporal and volumetric parameters at specific locations around the craniocervical junction. Analysis of these parameters determines if alterations can be attributed to cerebellar tonsillar herniation.

DESCRIPTION OF PHASE-CONTRAST IMAGING TECHNIQUE

Routine imaging sequences of the brain and cervical spine are obtained to determine the presence of hydrocephalus, syringomyelia, or other craniocervical junction lesions. Evaluation of the midline image is used to quantify cerebellar tonsillar ectopia in relation to a line connecting the basion and opisthion, thus defining the margins of the foramen magnum.

A phase-contrast sequence is obtained in the midline sagittal plane (TR 50 msec, TE 10 msec, a 15° flip angle, and two signal averages). Peripheral cardiac gating allows for collection of 12 to 24 phases during the repetition interval, depending on the heart rate. A matrix of 256 × 192, a field of view of 22 cm and a 3-mm slice thickness are used. Velocity encoding at 5 cm/second is initially selected and increased to 10 cm/sec if aliasing is encountered. The direction of flow encoding is superoinferior, which assigns bright signal to craniocaudal CSF displacement. Bhadelia and colleagues described the aforementioned...
tioned sequence in their analysis of patients with Chiari I malformation.

The magnitude and weighted-phase images derived from the sagittal acquisition are displayed in cine mode and are qualitatively evaluated for flow signal alteration around the foramen magnum (Fig. 1; Video Clip). The characteristics of displacement of the cerebellar tonsils and spinal cord observed during the cardiac cycle are studied as well.

Additional transverse phase-contrast sequences can be obtained perpendicular to the spinal canal below the foramen magnum. The axial phase-contrast sequence uses a TR of 60 msec, TE of 5 msec, a 30° flip angle, one signal average, 16 phases, a matrix of 256 × 256, a field of view of 18 cm, and a 5-mm slice thickness. Velocity encoding is set at 10 cm/second in the craniocaudal direction.

Cerebrospinal fluid flow waveforms are generated from the transverse sequences. Regions of interest are placed near the center of the CSF space being investigated. Larger ROIs are chosen for background subtraction. Specific areas of analysis are the anterior subarachnoid spaces immediately below the foramen magnum and at the level of the C2–3 interspace, the anterior subarachnoid space at the body of the axis and the posterior subarachnoid space below the cerebellar tonsils (Figs. 2 and 3).

**DISCUSSION**

A causal relationship between the finding of cerebellar tonsillar ectopia and nonspecific symptoms can be difficult to establish. Analysis of CSF flow at the craniocervical junction and assessment of motion of intraspinal structures can provide additional physiological data. The association between Chiari I malformation and cervical syringomyelia is well established although, there is not universal agreement on the mechanism. The observation of stenosis at the foramen magnum created by the downward displacement of the cerebellar tonsils and the tenets of the Monro–Kellie doctrine are central to all theories. Using a mechanical model, investigators have postulated that shearing forces on the spinal cord are caused by enhanced caudal excursion during systole. In theory on bulk flow it has been suggested that arterial-driven flow in response to increased pressure in the subarachnoid spaces around the spinal cord drives fluid from dilated perivascular spaces into the cord along parenchymal interstitial spaces and eventually into the central canal. Egress of CSF from the central canal is blocked by compression at the foramen magnum. Others believe that the spinal cord itself produces the extracellular fluid and that net flow of this fluid either passes through the perivascular spaces and into the subarachnoid spaces or into the central canal. This net flow is dependent on the pressure gradient between these two spaces. The egress of CSF from the central canal or the obex at the craniocervical junction is blocked in the same fashion as previously described. The old concept that the water hammer effect of CSF pulsations drives fluid through the obex of the...
Evaluation of CSF in Chiari I malformation

Volumetric data are obtained by calculating the area under the systolic and diastolic portions of the velocity curves. These two volumes are expressed as a ratio called the systolic to diastolic CSF displacement ratio. This ratio is diminished in both the anterior and posterior subarachnoid spaces immediately below the foramen magnum in patients with obstructive Chiari I malformations. This ratio is increased in the anterior subarachnoid spaces at the C2–3 interspace.

The authors propose a ball-valve mechanism in which the brainstem and cerebellar tonsils obstruct CSF flow through the foramen magnum during cardiac systole. This mechanism may explain why symptoms are accentuated when a patient coughs and strains. The arrival of blood driven by the systolic arterial pressure wave requires displacement of the brainstem, cerebellar tonsils, and cervical spinal cord to maintain constant intracranial volume. Systolic CSF flow velocity is diminished immediately below the foramen magnum, the volume of systolic flow relative to diastolic flow is diminished, and the duration of systolic flow is shortened. Immediately above the foramen magnum, systolic CSF flow is prolonged. This same prolongation of systolic flow occurs at the C2–3 level as well.

The cine display of the sagittal sequence demonstrates in real time the caudal displacement of the cerebellar tonsils and spinal cord. The onset of caudal motion coincides with the end of cranial CSF flow and peaks by 25% of the cardiac cycle. This movement is subtle relative to CSF flow in healthy patients. In patients with obstructive Chiari I malformations, there is increased downward movement of the cerebellar tonsils and spinal cord with impaired passive recoil. The mechanism of impaired recoil is postulated to be either the weak retracting force of the brainstem or diminished diastolic return of CSF.

Based on phase-contrast MR imaging parameters, normalization of CSF flow dynamics has been documented following decompressive surgery in which suboccipital craniectomy, C-1 laminectomy, and duroplasty were performed. Immediately below the craniocervical junction and anteriorly there is increased amplitude of systolic CSF flow, prolongation of systolic CSF flow duration, and increase in the systolic to diastolic CSF displacement ratio compared with preoperative levels. At the level of the C2–3 interspace, the duration of craniocaudal CSF flow is shortened and there is increase in the volume of craniocaudal CSF flow volume during early diastole following surgery.

Armonda, et al., have reported a widening of the anterior CSF space caused by collapse of a cervical spinal cord syrinx. Although no change was noted in CSF flow parameters below the cerebellar tonsils following decompressive surgery, widening of the CSF space in this region was noted. They also documented increased flow velocity and prolongation of systolic craniocaudal CSF flow immediately below the foramen magnum following decompressive surgery. They described widening of CSF spaces surrounding the upper cervical spinal cord as well. Brugieres, et al., have directly applied CSF flow analysis to syringomyelic cavities and pericycstic subarachnoid spaces. They described pulsatile flow in syrinx cavities with identifiable systolic and diastolic flow peaks. They also detected pulsatile flow in pericycstic subarachnoid spaces. Following foramen magnum decompressive sur-
surgery and duroplasty, the authors noticed a decrease in peak systolic and diastolic flow velocities within syrinx cavities as well as a compensatory increase in pericystic CSF flow. High diastolic intracystic flow velocities following surgery were thought to correlate with a poor operative result.4

CONCLUSIONS

The use of phase-contrast MR imaging for quantitative and qualitative CSF flow analysis can provide useful information regarding alterations in normal CSF flow dynamics in patients with Chiari I malformations. These same techniques can be used to document normalization of flow parameters postoperatively. In patients with syringomyelia, quantitative CSF flow analysis can be applied to the cyst cavity directly and to pericystic subarachnoid spaces to document alterations of normal flow, response to therapy, and perhaps even provide clues to postsurgical outcome.

References
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