Foramen magnum cerebrospinal fluid flow characteristics in children with Chiari I malformation before and after craniocervical decompression

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Object. The Chiari I malformation presents significant challenges to clinicians because its pathophysiology is not well understood. In conducting cerebrospinal fluid (CSF) flow studies, investigators have attempted to correlate the clinical severity of these lesions with general flow velocity or bulk flow at the foramen magnum; however, these techniques have not allowed consistent prediction of symptomatology, explanation of the presence of syringomyelia, or the assessment of the hydrodynamic characteristics of the decompression. The authors used temporally and spatially resolved flow analyses to assess the characteristics of CSF flow in children with Chiari I malformation and the changes in these flow characteristics that occur after suboccipital decompression.

Methods. The authors studied eight children with symptomatic Chiari I malformation with or without syringomyelia and two children without Chiari I malformation. All patients underwent phase-contrast magnetic resonance imaging before and after posterior fossa decompression. Velocity plots were displayed for each voxel. Several indices of CSF flow were developed to characterize the flow patterns associated with Chiari I malformation.

In children with symptomatic Chiari I malformation, even though bulk flow or velocity is often normal, there was marked heterogeneity of flow at the foramen magnum. This was evident for several reasons: 1) an increase in cephalad and caudal peak velocities; 2) spatial inhomogeneity in velocities; 3) simultaneous bidirectional flow; and 4) substantial net cranial or caudal flows within particular voxels and subregions during the cardiac cycle. After posterior fossa decompression, the severity of these flow abnormalities decreased.

Conclusions. Foramen magnum CSF flow in children with symptomatic Chiari I malformations is spatially and temporally heterogeneous, and this heterogeneity improves postoperatively. The authors propose that relying on mean flow parameters in patients with Chiari I malformation is no longer sufficient; instead, more elaborate techniques to analyze foramen magnum CSF flow have become necessary.

KEY WORDS • syringomyelia • posterior fossa • cerebrospinal fluid • pediatric neurosurgery

The Chiari I malformation, or tonsillar herniation through the foramen magnum, presents significant diagnostic and therapeutic dilemmas to clinicians. First, the imaging-depicted severity of the Chiari I malformation—that is, extent of tonsillar herniation—correlates poorly with the type and severity of clinical manifestations. In fact, the notion of a Chiari “0” malformation disputes the concept that tonsillar herniation is even necessary for a Chiari malformation—like pathophysiology to exist. Second, the criteria for surgical intervention and the choice of the procedure in the treatment of the Chiari I malformation are controversial. The diversity of the surgical procedures used to treat Chiari I lesions reflects its uncertain pathogenesis. Recommended surgeries for symptomatic Chiari I malformation range from simple bone decompression, to bone resection and subsequent duraplasty, to reducing the size of the cerebellar tonsils, as well as plugging the obex. Even the extent of osseous decompression has recently been debated. Commonly, symptoms and signs may resolve incompletely following surgery, which is another fact that raises questions about the adequacy of surgical treatment.

These controversies regarding the pathophysiology of the Chiari I malformation and syringomyelia have not been resolved by experimental studies. Williams has shown experimentally that, in patients with a Chiari I malformation, a pressure differential existed between the cranial and spinal compartments, indicating a relative obstruction of CSF flow at the foramen magnum. Although such experimental designs were considered revolutionary when Williams published his results, there is now technology with which to evaluate the relative obstruction of CSF flow noninvasively and more accurately. The advent of phase-contrast MR imaging techniques has broadened our capacity to analyze the disease’s pathophysiology. In previous reports on the Chiari I malformation, investiga-
tors have described abnormalities in the movement of the tonsils and brainstem. In addition, CSF flow velocities have been measured within syringomyelic cavities.

Although measurements of intracranial pressure and elastance have been obtained, they have not been used to study Chiari malformations. More relevant for our study, phase-contrast MR imaging was successfully conducted to assess CSF flow qualitatively (cine-MR imaging) as well as calculate bulk flow and/or mean CSF velocities at the foramen magnum. These studies have provided data regarding the relative general obstruction of flow within the foramen magnum and have certainly been helpful in allowing more informed follow up in patients with severe flow obstruction; however, these same studies, in which investigators assumed a spatially homogeneous flow in the foramen magnum, failed to identify a simple measure of CSF flow that consistently differentiated between symptomatic patients with Chiari I lesions and healthy individuals. This was especially true in the patients who were either asymptomatic or exhibited mild to moderate symptoms.

The first demonstrations of spatial heterogeneity in CSF flow at the foramen magnum in patients with Chiari I malformation were reported by Armonda, et al., in 1994 and Bhadelia, et al., in 1995, who described differences in flow in four different regions of the posterior fossa and foramen magnum. These authors showed that the differences in flow patterns in the four compartments were correlated with the anatomical anomalies, such as tonsillar herniation and crowding of the posterior aspect of the foramen magnum. Nonetheless, the velocity measurements were averaged across large areas comprising hundreds or even thousands of voxels.

We hypothesized that CSF flow abnormalities at the foramen magnum in Chiari I malformation are complex both temporally and spatially and that specific foramen magnum flow hallmarks may be associated not only with particular anatomical variations (the extent and symmetry of tonsillar herniation, posterior fossa and foramen magnum size, arachnoid adhesions, and syringomyelia), but also with certain symptomatic states. In other words, we propose that what determines the symptomatic state of the patient is not the general flow velocity or volume over the entire foramen magnum or even large regions of the foramen magnum. Instead, clinical states are closely associated with a complex spatial and temporal heterogeneity of flow in very small regions or even individual voxels within the foramen magnum. In this preliminary report, we present a set of CSF flow indices that attempt to characterize some of these complex flow patterns in children with symptomatic Chiari I malformation, and we describe how these patterns change postoperatively. The four indices calculated for this purpose are as follows: 1) spatially resolved peak cephalad and caudal velocities; 2) spatial inhomogeneities in velocity and flow volume; 3) bidirectionality of flow; and 4) positive or negative net CSF flow within certain voxels.

Clinical Material and Methods

Patient Population

We studied the CSF flow patterns in eight consecutive symptomatic pediatric patients with Chiari I malformation before and after decompressive surgery. A Chiari I malformation was diagnosed if the cerebellar tonsils herniated greater than 3 mm through the foramen magnum. The extent of tonsillar herniation was classified as mild (3–5 mm), moderate (5–9 mm), and severe (> 1 cm). The decision to perform surgery was based on the presence of typical symptoms such as valsalva-induced headache or the presence of syringomyelia (Table 1). All patients underwent neurological examination preoperatively and at 1 week, 3 months, and 1 year postoperatively. The surgery involved a suboccipital craniectomy, C-1 laminectomy, and duraplasty. Arachnoid opening, fourth ventricle exploration, and tonsillar reduction were not performed in any case; however, in the patient in Case 3, a second operative procedure was undertaken when symptoms and syringoid did not resolve. This second operation consisted of reopening the wound (without further osseous resection) and using bipolar coagulation to reduce the size of one cerebellar tonsil, creating a more capacious foramen magnum. Magnetic resonance imaging flow studies were conducted before and 3 months after surgery. Exclusion criteria included a contraindication to MR imaging, age greater than 17 years, and the presence of hydrocephalus, hypertension, or previous surgical treatment for a spinal abnormality.

Control Population

A 3-year-old girl without Chiari I malformation underwent phase-contrast MR imaging as part of an imaging protocol for new-onset headaches. There was no history of other medical or neurological problems, and MR imaging demonstrating no abnormalities. This individual was considered to be a healthy control patient. The second healthy individual, a 6-year-old child, presented with diabetes insipidus and a cystic lesion within the sella turcica. There was no suprasellar extension or other abnormalities. This child also underwent a CSF flow study, and the results were considered normal.

Magnetic Resonance Imaging

The healthy control children and all patients underwent imaging in a 1.5-tesla imager; conventional T1- and T2-weighted sequences of the cervical spine were obtained to assess the extent of tonsillar herniation and syringomyelia. Each individual underwent phase-contrast MR imaging of CSF flow in the foramen magnum, and the images were reviewed and reported as part of each patient’s imaging studies.

Phase-Contrast MR Imaging

Cardiac-gated phase-contrast images of the foramen magnum were acquired when a steady heart rate was achieved. A commercially available phase-contrast flow sequence was used (flip angle 20°, TR 20 msec, TE 5 msec, slice thickness 5 mm, field of view 180 mm, matrix 256 x 256, encoding velocity 10 cm/second). Slice orientation was axial and perpendicular to the spinal canal, and the slice location was chosen at the narrowest portion of the foramen magnum in the control individuals. In patients in whom tonsillar herniation obscured the CSF in the foramen magnum, the chosen slice was located at the point below the tonsils in which sufficient CSF was pres-
Heterogeneity of CSF flow in Chiari I malformation

Quantitative of Inhomogeneity and Flow Velocity in the Subarachnoid Space

Analytical techniques were created to measure temporal and spatial variations in CSF flow in the foramen magnum throughout the cardiac cycle. Algorithms applicable to the phase-contrast MR imaging–documented CSF flow measurements were developed in IDL (Research Systems, Inc., Boulder, CO), which is widely used for analysis of MR imaging or astronomical data. With IDL, data assigned to a spatial or temporal point are extracted for analysis or display. In our IDL program, the entire subarachnoid space is mapped to a grid of voxels. Each voxel is assigned an identification number based on its location, enabling analysis of individual voxels or collections of voxels (for example, the anterior or posterior portion of the subarachnoid space or any particular region exhibiting unusual flow). For each voxel, one of the following spatially or temporally oriented flow indices can be displayed graphically: peak caudad velocity, peak cephalad velocity, cumulative flow, and net CSF flow volume. Of particular utility in this analysis was the ability to generate color plots of velocities within each voxel during the cardiac cycle as well as each voxel’s cumulative flow. Cumulative CSF flow volume (defined as the integral of the flow velocity over a constant fraction of the cardiac cycle) and net CSF flow volume (defined as the integral of CSF flow in any voxel at the end of the cardiac cycle) were also displayed graphically. A large nonzero (positive or negative) net flow volume in a given voxel indicated that voxel’s preferential flow direction. The maximum positive and negative cumulative net flow values and the spread of these values from the least negative to the most positive were also tabulated. Using color plots, it is possible to see spatial variations in CSF flow volume and velocity that would be nearly impossible to detect using a gray scale. The algorithms were written for analysis of two- or three-dimensional data. Based on these data, a general assessment of spatial homogeneity was performed, mainly considering the presence of flow jets and the extent to which there is limitation of flow posteriorly compared with anteriorly in the foramen magnum. In addition, the presence and degree of bidirectional CSF flow were assessed. Bidirectional flow was defined as the simultaneous occurrence of cephalad and caudad flow in adjacent voxels or small regions in the foramen magnum, which does not occur in normal individuals. A point system was developed by scoring independently the number of quadrants in which bidirectionality occurs at any one time point (0, none; 1, one quadrant; 2, two quadrants; and 3, three or four quadrants), and the number of time points within the cardiac cycle in which bidirectional flow occurs (0, none; 1, one–five time points; 2, six–10 time points; and 3, 11–14 time points). This system yields a total score of 0 to 6 points.

The signal intensity within the subarachnoid space was assessed visually for uniformity or inhomogeneity on color plots with a linear violet-blue-green-orange-yellow-red color scale. The images were inspected for a focus of an abrupt temporal change in signal intensity that indicated so-called aliasing. As previously defined, aliasing occurs when CSF velocities exceed the velocity encoding parameter chosen for this study (10 cm/second), thus resulting in underestimation of the velocities. When aliasing was detected in a voxel (< 5% of the total number of voxels in the subarachnoid space in any case), it was corrected using the algorithms described by Lee, et al. A cursor was placed to include the entire subarachnoid space (including the spinal cord) and to exclude the vertebral arteries, even if a portion of the subarachnoid space was thereby excluded. The cursor placement was intended to include all portions of the subarachnoid space with the

**TABLE 1**

<table>
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<tr>
<th>Case No.</th>
<th>Age (yrs)</th>
<th>Tonsillar Herniation (mm)</th>
<th>Preop Symptoms &amp; Signs</th>
<th>Postop Outcome</th>
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<td>14</td>
<td>11</td>
<td>severe sudden valsalva headaches</td>
<td>occasional mild headaches</td>
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<td>2</td>
<td>12</td>
<td>15</td>
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<td>all resolved; Babinski sign &amp; scoliosis stable</td>
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<tr>
<td>3†</td>
<td>12</td>
<td>15</td>
<td>Lt hand weakness, headache, syringomyelia</td>
<td>failed 1st op; all symptoms resolved after 2nd decompression; transient pseudomeningocele</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>8</td>
<td>headache, scoliosis, syringomyelia, clonus, enuresis, neurogenic bladder</td>
<td>headaches resolved; scoliosis stabilized; syrinx much smaller; bladder improved</td>
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<tr>
<td>5</td>
<td>8</td>
<td>7</td>
<td>headache, B/B dysfunction, holocord syringomyelia</td>
<td>syrinx smaller but not resolved; all symptoms resolved</td>
</tr>
<tr>
<td>6</td>
<td>16</td>
<td>3</td>
<td>headache, mild hand numbness/paresthesias, tremor</td>
<td>hand numbness resolved; headaches &amp; tremor unchanged</td>
</tr>
<tr>
<td>7</td>
<td>12</td>
<td>3</td>
<td>headache, fatigue, hand numbness</td>
<td>all resolved</td>
</tr>
</tbody>
</table>

*B/B = bowel and bladder; LE = lower-extremity; UE = upper-extremity.
† Clinical improvement and reduced syrinx size occurred only after the second decompressive procedure.
greatest CSF velocities. The program then displayed the flow velocity for each time point in each voxel in the region of interest. It calculated maximal, minimal, and mean velocities as a function of location or throughout the cardiac cycle. The time course of the velocity was inspected and compared with the expected shape of the curve. If the time courses failed to show the expected biphasic diastolic-systolic-diastolic flow curve, the cursor was repositioned to eliminate a region in which flow velocities may have been confounded by arterial flow. Typically, velocity measurements were verified by the placement of small regions of interest at multiple locations in the subarachnoid space. The greatest velocity measured in any voxel during caudad and cephalad phases of CSF flow was recorded.

Results

Clinical Findings

Preoperative symptoms and signs ranged from valsalva-induced headaches to neurological deficits (Table 1). All eight patients experienced symptomatic improvement or resolution after suboccipital craniectomy and duraplasty. The major complaint in Case 8 was head hitting. Because in young and nonverbal older children head hitting is often a sign of headache or discomfort, the patient in Case 8 was assumed to be suffering headaches. In fact, the unusual behavior did resolve postoperatively as well. The patient in Case 6 exhibited mild symptoms and experienced the least clinical improvement postoperatively. Preoperative evidence of syringes was observed in four patients, in all of whom size decreased postoperatively. In Case 3, a failed first operation was followed by a repeated craniectomy and subsequent reduction in the size of one tonsil. The syrinx and symptoms resolved only after the second procedure. The mean follow-up period was 27 months (range 12–48 months). Intraoperative findings included tonsillar herniation and/or crowding of foramen magnum structures in all patients. There were no other identifiable causes of CSF obstruction, such as arachnoid veils or adhesions.

Spatial Inhomogeneity

Velocity measurements in individual voxels of the foramen magnum varied highly in the patients preoperatively. Most of the abnormally high-velocity voxels were concentrated anteriorly in the foramen magnum and more specifically in small subregions (or nodes) of the anterior quadrants uni- or bilaterally. When these nodes reached extreme velocities (~10- to 20-fold higher than mean velocity) they were termed jets. These regions of concentrated increased velocities in the anterior subarachnoid space were associated with slightly decreased velocities in the posterior subarachnoid space. Postoperatively, there was a relative decrease in this heterogeneity in six of the patients (Figs. 1–3). Visual inspection of the contour plots of the peak cephalad flow and of the peak caudad flow revealed a decrease in the jets in these six cases. This decrease was more conspicuous in the cephalad than caudad flow. In two cases, the jets did not appear to decrease.

Peak Velocity

Although mean velocities during the cardiac cycle were normal in most patients (range 0.1–2.8 cm/second, mean 1 cm/second) and did not change substantially after cranio cervical decompression, the peak cephalad and caudad velocities were markedly elevated in all patients and decreased in most, although not all, after surgery. The mean peak cephalad velocities (± standard deviation) were 9.7 ± 2.3 cm/second preoperatively and 6.6 ± 1.9 cm/second postoperatively, whereas peak caudad velocities similarly decreased from 5.2 ± 1.6 to 3.5 ± 0.6 cm/second (Table 2). In two patients (Cases 2 and 4), the peak cephalad velocity increased postoperatively. In one patient (Case 6), the peak velocities were low preoperatively (close to normal) and remained the same postoperatively. In this patient tonsillar herniation was mild, symptoms were minimal, and only mild improvement occurred after surgery.

Simultaneous Bidirectional Flow

In children with symptomatic Chiari I malformation, caudad flow in some regions of the subarachnoid space occurs concurrently with cephalad flow in other regions. The simultaneity of bidirectional flow was demonstrated in all eight patients preoperatively. Postoperatively the bidirectional flow decreased in seven patients (Table 2). The only exception occurred in Case 7, in which we observed mild bidirectionality that did not change postoperatively. As such, the severity of bidirectionality and symptoms tended to correlate. Because of the small sample size, however, no attempt was made to establish the statistical significance of this correlation.

Cumulative CSF Flow

The temporal plot of cumulative flow volumes in individual voxels showed larger dispersions in patients than in the controls (Fig. 3). In voxels associated with anterior subarachnoid space jets (keeping in mind that jets occur in patients with Chiari I malformation and not in controls), the cumulative flow volume increased substantially during diastole and decreased minimally if at all during systole. Some voxels had large positive cumulative flow volumes that diverged from the mean and from cumulative flow volumes in other voxels. This occurred particularly in the anterior subarachnoid space. In the healthy individuals, the cumulative flow volumes did not show large dispersions at any point in the cardiac cycle. In all the voxels of the healthy control patients, the mean cumulative flow showed a small deviation in the positive direction during diastole and subsequently in the negative direction during systole, resulting in a near-zero value (zero net flow volume) at the end of the cardiac cycle.

Net CSF Flow

In seven of eight patients, the net flow volume (that is, the cumulative flow at the end of the cardiac cycle) in some voxels exceeded ~3 and +4 mm³ preoperatively in the caudad and cephalad directions, respectively, indicating a marked degree of preferential flow direction. In the patient in Case 6, in whom we observed near-normal peak velocities and minimal symptoms, near-normal net flow volumes in all voxels (~1.5 to +1.4 mm³) were also demonstrated. The voxels with maximum net positive and
negative flow volumes in the other seven patients reached values of 15.2 and 9.8 mm$^3$, respectively. The range in net flow volumes decreased substantially after surgery in six of eight patients (Table 3). Conversely, minimal change in net flow postoperatively were demonstrated in Case 6. Additionally, in one patient (Case 4) with a paradoxical increase in peak velocities postoperatively, a rise in the net flow values also occurred after surgery. Despite large changes in net flow volume in specific voxels or subregions, no excess of negative or positive flow was evident when all voxels were considered collectively. Thus, within the accuracy of our measurements, the net flow volume over the foramen magnum was zero, as expected.

Failure of Surgery to Relieve Symptoms and Syringomyelia

One of the eight children (Case 3) failed to experience improvement after suboccipital craniectomy, C-1 laminectomy, and duraplasty. At follow-up examination, her symptoms persisted and the syrinx had not changed in size. Phase-contrast MR imaging revealed minimal change in peak velocities, the amount of flow bidirectionality, flow heterogeneity, and net flow volume. A second surgical procedure was considered to reduce crowding in the foramen magnum due to persistently impacted tonsils. Approximately 1 year after the first surgery, the patient underwent a second posterior fossa decompression in which bipolar cautery was used to reduce the size of one tonsil. By 3 months after this second procedure, the patient’s symptoms had resolved. At this time, spinal MR imaging demonstrated that the syrinx had significantly decreased in size. After the second surgery, phase-contrast MR imaging revealed a marked change in flow dynamics at the foramen magnum, with reduction in heterogeneity, peak velocity, simultaneous bidirectional flow, and net flow volume in some voxels (Fig. 2). The peak systolic velocity was 10.1 cm/second preoperatively, 6.6 cm/second after the first operation, and 3.3 cm/second after the second operation; similarly, the bidirectionality scores were 5, 4, and 2, respectively. The differences between the largest positive and largest negative net flow volumes were 8.25, 10.98, and 4.89 mm$^3$ preoperatively and after the first and second surgeries, respectively, which was essentially the same as the range in net flow volume seen in the children without Chiari I malformation (5.1 mm$^3$).

Control Individuals Without Chiari Malformation

In the children without Chiari I malformation there was little evidence of inhomogeneity in CSF flow in the foramen magnum. No high velocity jets were noted. Peak cephalad and caudad velocities (4.1 and $\sim$4.2 cm/second, respectively) in the younger child were close to mean velocity throughout the foramen magnum (range 0.4–2.1 cm/second, mean 1.5 cm/second). In the older child, the peak velocities were more elevated; however, the overall velocities were elevated homogeneously, with no obvious jets. Additionally, in neither patient was there any bidirectional flow, and no large negative or positive net flow was observed in any particular voxels or small regions in the foramen magnum (Fig. 3).

Discussion

A more accurate diagnosis and treatment of the Chiari I malformation would be achieved if the underlying pathophysiology of the symptoms and the development of syri-
ringomyelia were better understood. Assessment of changes in flow volume or mean velocity has not led to a comprehensive understanding of this pathophysiology. We hypothesize that examining distinct spatiotemporal flow patterns within the foramen magnum would provide a more physiologically based explanation of this pathogenesis than examining results of global flow patterns. In particular, we suggest that specific symptomatic states may correlate with specific flow characteristics, and we propose that using MR imaging to analyze spatially and temporally resolved indices of CSF flow at the foramen magnum, we can better characterize the flow patterns in the healthy individual and the patient with the Chiari I disease. As these temporal and spatial flow analyses become more sophisticated, there is a potential that one or more of the indices could be used to predict symptomatology and to guide the timing and choice of surgical interventions.

In this study, we used four indices to define the effects of decompressive surgery on such flow patterns. These are not optimized for the purpose of detecting clinically significant abnormalities of CSF flow. Instead, they are based on calculations that are conveniently derived from the acquired flow data. Marked qualitative and quantitative changes in these indices were noted to occur after cranio-cervical decompression, implying that surgery that tends to yield symptomatic improvement also alters the CSF flow pattern in a complex manner. This was best exemplified by the velocity and flow plots observed in the patient (Case 3) who did not experience symptomatic improvement after the initial operative intervention but in whom symptoms resolved after the second operation. In that situation, significant changes in the heterogeneity index, jet velocities, simultaneous bidirectionality of flow, and net flow volume were only seen after the second surgery.

**Foramen Magnum CSF Flow Heterogeneity**

With each arterial pressure wave, a certain quantity of CSF exits through the foramen magnum. When the fora-
men magnum volume decreases secondary to a mass lesion such as the cerebellar tonsils, or when adhesions or anatomical abnormalities restrict CSF flow in certain parts of the foramen magnum, the same amount of CSF is theoretically compelled to traverse a narrower region of the foramen magnum with greater speed. A measurement of mean CSF velocity, which includes regions with increased velocity and those with decreased or normal velocity (or counterdirectional flow), may or may not reflect these local increases in velocity. Our measure of peak velocity reflects the maximal velocity at the foramen magnum within a particular voxel or small region irrespective of the mean velocity throughout the foramen magnum. This measurement reflects the presence of velocity jets, whereas measuring mean velocity does not. In symptomatic patients with Chiari I malformation, the mean velocity is often normal across the foramen magnum, but high velocity jets are very common.

Both anatomical and cine-flow MR imaging studies have shown that in children with Chiari I malformation, posterior CSF flow in the foramen magnum is often markedly reduced compared with that anterior to the spinal cord and brainstem. We have recently studied the distribution of peak velocities in the foramen magnum of adults with this disorder and compared findings with those obtained in control individuals; we found, similarly to this study, that there were abnormal velocity jets in particular regions (mainly anteriorly) of the foramen magnum. The existence of these jets implies that flow in the foramen magnum is abnormal, with no large increases in mean velocities. Measurements of bulk flow and mean velocity throughout the foramen magnum may be more revealing in circumstances of relatively severe obstruction of CSF flow. Such measurements may not be helpful in distinguishing less severely compromised patients with Chiari I malformation from healthy individuals. In the majority of patients in this study, peak velocities were elevated preoperatively and decreased postoperatively. Additionally, we went further to show that in patients with Chiari I malformation, there is significant flow heterogeneity throughout the foramen magnum and that this heterogeneity decreases after decompressive surgery.

Temporal and Spatial Flow Indices

Using current technology, we developed various flow indices that describe flow behavior voxel by voxel within...
the foramen magnum. In the present study, we have described the four indices, mainly qualitative, that seemed to be most relevant to our patient population. We expect that more sophisticated quantitative parameters will become available once the neuroimaging and analytical techniques evolve.

Peak Velocity. Peak velocity measurement is an example of a quantitative measure. We have observed that most of the high velocity jets occur anteriorly in the foramen magnum. In patients with Chiari I malformation, in whom by definition there is a posterior limitation of flow secondary to the tonsillar ectopia, it is reasonable to assume that the anterior jets may represent fluid forced to travel anteriorly, rather than posteriorly, at higher velocities; however, we have yet to determine the real association between posterior restriction of flow and the severity of anterior jets. In a previous study involving adult patients with Chiari I malformation, we proposed that peak velocity is an important measure of spatial inhomogeneity because it indicates that there are abnormal jets of very high flow velocities in certain portions of the foramen magnum, whereas mean velocity across the foramen magnum remains within normal limits.6 The preoperative peak velocities reported here are on average more elevated than those we have previously observed in adults.6 The reason for this is twofold. First, in the present study, we used an updated methodology that allowed us to correct for aliasing. Second, it has been our observation that in children with Chiari I malformation peak velocities are higher than in adults with this disease, even when aliasing is removed from both groups. These observations were fortified when we observed the flow patterns in one child in whom the first posterior fossa decompression was inadequate, and in whom improvement in syrinx size and symptoms occurred only after a second decompressive procedure. In this case, the heterogeneity and peak velocities improved markedly only after the second surgery.

Synchronous Bidirectional Flow

Synchronous bidirectional flow, evaluated by means of a qualitative measure in this study, may be analyzed more effectively when analytical techniques are improved. In healthy controls without Chiari I malformation, the general flow in the foramen magnum was homogeneous, and at any one time point, it was either caudal or cephalad, not both. In patients with Chiari I malformation, CSF flow in a caudal direction in one area of the foramen magnum occurs simultaneously with CSF flow in a cephalad direction in adjacent voxels. Bidirectional flow implies disturbance in the general flow patterns within the foramen magnum and more specifically indicates a counter–current effect due to the presence of large jets. The flow running counter to the general direction typically occurs in proximity to the high-flow jets occurring in the anterior quadrants of the foramen magnum.

Cumulative and Net CSF Flow Volumes. In healthy individuals without Chiari I malformation, the flow traveling caudal through any voxel during systole is balanced by a similar flow traveling cephalad during diastole, with no preferential flow directionality. In contrast, significant flow directionality occurs in foramen magnum voxels in patients with Chiari I malformation, resulting in a non-zero net flow volume in these voxels at the end of the cardiac cycle. This flow directionality decreases after posterior fossa decompression. Although net flow volume in any particular voxel may be non-zero in children with Chiari I malformation, the net flow for the sum of all voxels approximates zero (that is, it does not have a large positive or negative value), similarly to that in healthy individuals. Thus, the difference between healthy and Chiari I malformation–afflicted children is that in the former, caudal and cephalad flow volumes are more nearly equal even within subregions or individual voxels, producing near-zero net flow volumes in most voxels.

Limitations of the Study

Several sources of confounding errors exist in these CSF flow studies. First, we have collected data in only one axial slice just below the cerebellar tonsils at 14 time points of the cardiac cycle. Analyzing the details of CSF flow in multiple slices obtained above, below, and at the level of the tonsils would yield a more accurate three-dimensional depiction of the flow patterns. The most severely elevated flow velocities, for instance, may not have been detected in our study. Additionally, although sampling 14 time points may seem sufficient for studying the obvious variation in flow direction through systole and diastole, one could envision sampling the data continuously through the cardiac cycle, potentially revealing more extreme alterations in flow patterns. Second, aliasing occurs when velocities in the CSF exceed the velocity-encoding parameter chosen for this study (10 cm/sec-

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<tr>
<th>Case No.</th>
<th>Peak Cephalad Velocity (cm/sec)</th>
<th>Peak Caudal Velocity (cm/sec)</th>
<th>Bidirectionality Score</th>
<th>Net Flow Spread (cm³)</th>
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<td>Preop</td>
<td>Postop</td>
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</table>

| Summary of pre- and postoperative peak cephalad and caudad velocities |

B. J. Iskandar, M. Quigley, and V. M. Haughton
Heterogeneity of CSF flow in Chiari I malformation

TABLE 3
Summary of pre- and postoperative cumulative CSF flow volumes

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Caudal Vol</th>
<th>Cephalad Vol</th>
<th>Vol Spread</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Preop</td>
<td>Control</td>
<td>Postop</td>
</tr>
<tr>
<td>1</td>
<td>4.3</td>
<td>8.3</td>
<td>9.7</td>
</tr>
<tr>
<td>2</td>
<td>3.3</td>
<td>3.3</td>
<td>2.4</td>
</tr>
<tr>
<td>3</td>
<td>4.5</td>
<td>1.4</td>
<td>3.7</td>
</tr>
<tr>
<td>4</td>
<td>10.9</td>
<td>8.2</td>
<td>7.9</td>
</tr>
<tr>
<td>5</td>
<td>3.2</td>
<td>1.8</td>
<td>2.4</td>
</tr>
<tr>
<td>6</td>
<td>1.4</td>
<td>0.97</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>5.6</td>
<td>3.1</td>
<td>9.4</td>
</tr>
<tr>
<td>8</td>
<td>15.2</td>
<td>9.2</td>
<td>9.8</td>
</tr>
</tbody>
</table>

control 1: -0.5 0.4 0.9
control 2: -1.1 0.95 2.05

* The spread of the volumes represents the difference between the most negative and most positive cumulative flow volumes.

Conclusions

For a better understanding of the pathophysiology of Chiari I malformation, spatial and temporal foramen magnum CSF flow patterns should be analyzed in more detail in symptomatic and asymptomatic patients with Chiari I malformation, those with or without syringomyelia, and those with syringomyelia but with or without tonsillar herniation. The determination of mean flow velocities by
using standard cine-MR imaging may be helpful in some of the more severe cases of foramen magnum crowding. The diagnostic and therapeutic challenges related to Chiari I malformation and syringomyelia, however, have become more sophisticated and cannot be adequately managed using techniques that assume homogeneous flow. We propose that relying on mean flow parameters is no longer sufficient; instead, more elaborate techniques to analyze foramen magnum flow are necessary. In the present study, we used predominantly qualitative flow parameters as a starting point for a thorough analysis of CSF flow within the foramen magnum of patients with Chiari I malformation, and have been able to remove confounding early problems such as aliasing and vascular contamination. As neuroimaging and data analysis technology improve, more quantitative methods should become available.

Disclaimer

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References


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