Ventricle wall movements and cerebrospinal fluid flow in hydrocephalus

Clinical article

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Object. The dynamics of fluid flow in normal pressure hydrocephalus (NPH) are poorly understood. Normally, CSF flows out of the brain through the ventricles. However, ventricular enlargement during NPH may be caused by CSF backflow into the brain through the ventricles. A previous study showed this reversal of flow; in the present study, the authors provide additional clinical data obtained in patients with NPH and supplement these data with computer simulations to better understand the CSF flow and ventricular wall displacement and emphasize its clinical implications.

Methods. Three NPH patients and 1 patient with aqueductal stenosis underwent cine phase-contrast MR imaging (cine MR imaging) for measurement of CSF flow and ventricular wall movement during the cardiac cycle. These data were compared to data previously obtained in 8 healthy volunteers.

The CSF flow measurements were obtained at the outlet of the aqueduct of Sylvius. Calculation of the ventricular wall movement was determined from the complete set of cine MR images obtained axially at the middle of the lateral ventricle. The data were obtained before and after CSF removal with a ventriculoperitoneal shunt with an adjustable valve. To supplement the clinical data, a computational model was used to predict the transmural pressure and flow.

Results. In healthy volunteers, net CSF aqueductal flow was 1.2 ml/minute in the cranioaudal direction. In patients with NPH, the net CSF flow was in the opposite direction—the caudocranial direction—before shunt placement. After shunting, the magnitude of the abnormal fluid flow decreased or reversed, with the flow resembling the normal flow patterns observed in healthy volunteers.

Conclusions. The authors’ MR imaging-based measurements of the CSF flow direction and lateral ventricle volume size change and the results of computer modeling of fluid dynamics lead them to conclude that the directional pattern and magnitude of CSF flow in patients with NPH may be an indication of the disease state. This has practical implications for shunt design and understanding the mechanisms that produce hydrocephalus.

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Key Words: • hydrocephalus • normal pressure hydrocephalus • ventricular wall movement • CSF flow • mathematical model

In a large cine MR imaging study of 28 healthy volunteers and 11 patients with hydrocephalus, Kim et al.10 noted that patients with NPH had a net flow of CSF through the aqueduct from the fourth ventricle into the third, which they noted is opposite to that found in healthy volunteers. The “retrograde” net flow reversed to the normal “anterograde,” cranial-caudal flow pattern after VP shunt placement. This observation has important implications for an understanding of fluid dynamics of hydrocephalus and the effect of CSF shunting. It means that, in hydrocephalus, the brain parenchyma absorbs CSF via a transependymal route rather than producing it. Shunting is able to reverse this abnormality and allow flow again in the normal brain-to-ventricle route. We have confirmed the findings of Kim et al. in healthy volunteers and in a small group of patients with NPH and provide a computational model based on fluid dynamics to explain their findings and our own. To see whether the hyperdynamic flow patterns that they found in hydrocephalus cause abnormal ventricle wall movements, we also measured lateral ventricular wall displacement in our healthy volunteers and in the patients with NPH. We found that wall movements were slightly larger in the NPH patients but did not change significantly with shunting, a result predicted by our fluid dynamic modeling. This finding has clinical implications for shunt design. If the pulsating CSF flow were the root cause of ventricular

Abbreviations used in this paper: cine MR imaging = cine phase-contrast MR imaging; NPH = normal pressure hydrocephalus; VP = ventriculoperitoneal.
dilation, then reducing such flow could be easily achieved by constructing a mechanical system that dampens CSF oscillations. Our findings suggest such a solution would not work and that the fundamental problem to be treated is the accumulation of CSF in the ventricles and the abnormal flow into brain tissue.

Methods

The details of the cine MR imaging techniques used in the study are described in full in our previous article. The scans were performed using the 3T GE Sigma system (GE Medical Systems) equipped with a standard quadrature birdcage head coil. Measurements previously obtained in 8 healthy volunteers (4 men and 4 women, mean age 35 years, range 23–52 years) were used as control data.

Three patients diagnosed with NPH and one with congenital aqueductal stenosis were studied before and after treatment with VP shunt placement (adjustable-valve Strata Shunt; Medtronic Inc.). The diagnosis of NPH was made on the basis of clinical criteria, primarily gait disturbance and early mentation changes, and confirmed by a positive response to 3 or 4 days of continuous lumbar drainage. In retrospect, the third patient with the diagnosis of NPH did not have the syndrome. He did not improve clinically with shunting, his ventricular size did not decrease, and his dementia progressed without further gait problems. The patient with aqueductal stenosis underwent shunt placement because of headaches and memory problems 12 years after a previous shunt revision. This case is included because it provides an opportunity to study ventricle wall dynamics after shunt treatment of obstructive hydrocephalus and not because of issues related to aqueductal flow. The patients underwent cine MR imaging 1 week before shunt placement and 2–6 months postoperatively. They all signed consent forms for the additional MR imaging, and the study was approved by the institutional review board of the University of Chicago. Some of the data obtained in the healthy volunteers were previously published, but these data have been reanalyzed for this paper.

The cine MR images were collected at an axial slice across the middle of the lateral ventricles to investigate the lateral ventricle volumetric change and an axial slice across the junction between the aqueduct of Sylvius and the fourth ventricle to measure the CSF flow rate. For the slice across the lateral ventricles, velocities in 3 directions were measured; images obtained at 16 equidistant time frames were reconstructed per cardiac cycle. For the slice at the other location, only the velocity perpendicular to the slice plane was measured; images were acquired at 32 equidistant time frames per cardiac cycle. Flow compensation and peripheral gating were applied for the 2 cine MR imaging measurements. A low maximum measurable velocity of 5 cm/sec was chosen as the limit to achieve a reasonable velocity resolution. Other MR imaging parameters were as follows: TR 18 msec, TE 8.3 msec, flip angle 20°, FOV 240 mm, slice thickness 5 mm, matrix size 256 × 192, and 75% phase field of view to achieve an effective matrix resolution of 256 × 256. The pixel velocity in regions of CSF was corrected by subtraction of the time-average “velocity” of a nearby solid brain tissue within a 29 × 29 mm² region having this pixel at its center.

The CSF flow at the junction of the aqueduct of Sylvius and the fourth ventricle was estimated by the product of the average velocity through the region multiplied by the cross-sectional area. To estimate lateral ventricle wall movement, the edge between solid brain tissue and the lateral ventricle was first manually drawn on an image that showed the best cross-section from a T1-weighted image that was acquired at exactly the same scan plane. This drawing marks the initial pixel positions during a full cardiac cycle. The position shift of each pixel at the edge of the lateral ventricle was then estimated for each time frame of the cardiac cycle by integrating the velocity over time, including all 3 components of the velocity.

Results

Flow data previously obtained in 8 healthy volunteers were reanalyzed to calculate the net flow per cycle and then the net flow per minute. Every one of these individuals had net flow out through the aqueduct, cranial to caudal (Table 1). According to our standardized technique, the mean flow (± SD) was 1.14 ± 0.599 ml/minute (range 0.5–1.9 ml/minute). The mean value for ventricle wall movement in these same controls was 0.168 ± 0.038 mm (range 0.12–0.18 mm).

In contrast, 2 of the 3 patients who had the initial clinical diagnosis of NPH had a net flow into the third ventricle and lateral ventricles. The third patient, who by later clinical course proved not to have NPH, had flow in the normal direction. After VP shunting using an adjustable valve on a low pressure setting, the retrograde flow reversed in the first case and was markedly reduced in the second. In the patient who did not actually have NPH, the cranio-caudal flow increased. Table 1 also shows calculations of the displacement of the ventricle wall and lateral ventricle volume before and after shunting. The ventricle wall displacement was higher in hydrocephalic patients than in the controls, 0.21–0.30 mm compared with a mean value of 0.17 mm. Shunting had no significant effect on this movement. In the 2 patients who had excellent clinical responses to shunting, with major improvements in gait and mentation, the ventricle size decreased and the caudocranial flow pattern reversed to the normal direction. In the patient with minimal clinical improvement (the patient in Case 3), there was no change in ventricle size, and flow was initially cranio-caudal; with shunting, the cranio-caudal flow increased. The patient with congenital aqueductal stenosis responded to shunting with a complete remission of his symptoms of mental confusion and headaches. His ventricle size decreased, and the ventricle wall movement slightly increased after shunt placement.

Models of CSF Flow and Ventricle Wall Movement

In a recently published paper, we modeled the combined blood flow, CSF flow, and brain tissue dynamics of healthy individuals and patients with hydrocephalus. Figure 1 shows the model and areas of interest for the current...
Ventricle wall movements and CSF flow

### TABLE 1: Observations of net flow and wall displacement during cardiac cycle and calculation of ventricle volume in patients with NPH before and after treatment and in healthy volunteers

<table>
<thead>
<tr>
<th>Case or Group</th>
<th>Dx</th>
<th>Preop</th>
<th>Postop</th>
<th>Control</th>
<th>Net Flow (ml/min)</th>
<th>Wall Displacement (mm)</th>
<th>LV Vol (ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Preop</td>
<td>Postop</td>
<td>Control</td>
</tr>
<tr>
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<td>NP</td>
<td>NP</td>
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<td>0.27</td>
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<tr>
<td>Case 2</td>
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<td>-1.5</td>
<td></td>
<td>0.27</td>
<td>0.30</td>
<td>130</td>
</tr>
<tr>
<td>Case 3</td>
<td>NPH</td>
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<td>0.76</td>
<td></td>
<td>0.24</td>
<td>0.21</td>
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</tr>
<tr>
<td>Case 4</td>
<td>&quot;NPH&quot; *</td>
<td>1.17</td>
<td>3.07</td>
<td></td>
<td>0.25</td>
<td>0.26</td>
<td>123</td>
</tr>
<tr>
<td>8 healthy volunteers†</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.14 ± 0.599</td>
<td>0.168 ± 0.038</td>
<td>33 ± 9.4</td>
</tr>
</tbody>
</table>

* The patient in Case 4 did not have improvement with shunting and did not in retrospect have true NPH. Abbreviations: AS = congenital aqueductal stenosis; LV = lateral ventricle; NP = measurement not performed.
† Group mean values (± SD) are given for the 8 healthy volunteers.

Discussion

Our cine MR imaging studies show changes in the direction or magnitude of the net CSF flow in patients after shunting but no significant change in the ventricle wall movement. In our healthy volunteers, the net flow is outward through the aqueduct. This flow pattern was shown by Greitz et al. and confirmed by Huang et al. Kim et al. also found outward net flow in 28 healthy volunteers and what they call “retrograde” or reverse net flow, caudal to cranial, into the ventricles in 11 NPH patients. The flow normalized after shunting. Our findings in our NPH patients confirm this reversal of flow with shunting. The flow of CSF into the ventricular system in hydrocephalus should not be a surprise. Cisternography with In-EDTA was one of the early methods used to try to differentiate cerebral atrophy from clinically significant hydrocephalus. Distribution of the marker into the ventricular system from the basal cisterns and only later over the convexities was taken as an indication of communicating hydrocephalus. While the test is poorly predictive of the outcome of shunting, it still indicates a profoundly abnormal flow.

![Schematic of the model highlighting areas of interest](image)

Fig. 1. Schematic of the model highlighting areas of interest. Note that the normal pattern of CSF flow is from the third ventricle (3V) to the fourth ventricle (4V) and that this reverses in hydrocephalus. The obstruction to flow out of the subarachnoid space (SAS) to the venous sinus (vSinus) causes a reversal of the pressure gradient from the brain parenchyma to the lateral ventricles (LV), which in turn results in the flow direction change. The model predicts this reversal. The shunt reduces the gradient and brings the flow pattern back to normal. cAr = carotid artery; Ar = artery; AI = arteriole; Cp = capillary; V = vein; VI = venule. Superscript L and R refer to left and right, respectively. The thickness of the arrows indicates volume of flow and the relative size of the boxes indicate degree of wall displacement relative to the normal size.