Hunt malfunction continues to be a major concern in neurosurgery,24,44,60 carrying a risk of critical symptoms and poor outcomes.21,24 In spite of numerous studies on experimental hydrocephalus, the pathophysiological aspects of shunt malfunction have not been well examined. To undertake an experimental analysis of shunt malfunction, the hydrocephalus model should allow hydrocephalic animals to survive after induced shunt malfunction. To our knowledge, there is only one experimental study in which the effect of shunt removal has been studied. In that study,13 in which a feline model was used, shunt removal resulted in an increase in ICP that lasted 6 hours. There have been no studies in which a longer follow-up period following shunt malfunction has been included. We recently established a highly successful canine model of obstructive hydrocephalus;19 using this model, a long survival period can be achieved. This model was used to address the effects of shunt malfunction by evaluating alterations in physiological parameters during untreated, shunted, and shunt-removed stages. In that study the parameters under investigation included ventricular volume, ICP, cerebral oxygenation, response to hyperventilation, and brain compliance. The present study is the

Effects of ventriculoperitoneal shunt removal on cerebral oxygenation and brain compliance in chronic obstructive hydrocephalus

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Object. The pathophysiology of shunt malfunction has not been fully examined, probably because of the paucity of appropriate animal models. Using a canine model of chronic obstructive hydrocephalus, the effects of shunt placement and removal on physiological parameters were evaluated.

Methods. Fifteen dogs, nine in which chronic hydrocephalus was induced and six controls, were used in the experiment. Thirteen weeks after the induction of hydrocephalus, intracranial pressure (ICP), tissue and cerebrospinal fluid O2 saturation, response to hyperventilation, and brain compliance at low (5–15 mm Hg) and high (15–25 mm Hg) pressures were measured (untreated stage). Following this procedure, ventriculoperitoneal shunts were implanted in the dogs suffering from hydrocephalus. Two weeks later, the same series of measurements were repeated (shunted stage), following which the shunt systems were removed. One week after shunt removal, the last measurements were obtained (shunt-removed stage). All dogs underwent magnetic resonance imaging four times: before induction of hydrocephalus and before each measurement. All dogs with hydrocephalus also had ventriculomegaly (1.42 ± 0.89 ml before induction of hydrocephalus compared with 3.4 ± 1.64 ml 13 weeks after induction, p = 0.0064). In dogs in the untreated hydrocephalus stage, ICP remained within the normal range (8.33 ± 2.60 mm Hg)—although it was significantly higher than that in the control group (5 ± 1.41 mm Hg; p = 0.014). Tissue O2 saturation in the hydrocephalus group (48.7 ± 4.27 mm Hg) was lower than that in the dogs in the control group (52.7 ± 5.33 mm Hg; p < 0.0001). After the dogs underwent shunt placement, significant improvement was observed in their ICP (5.22 ± 2.17 mm Hg, p = 0.012) and tissue O2 saturation (35.2 ± 6.80 mm Hg, p = 0.0084). However, removal of the shunt reversed these improvements back to the preshunt status. Hyperventilation induced significant decreases in ICP and O2 saturation at every measurement time and induced a significant decrease in tissue O2 saturation during the shunted stage, but not during the untreated and shunt-removed stages. Brain compliance measured at high pressure demonstrated a significant gradual decrease at every measurement.

Conclusions. In chronic obstructive hydrocephalus, shunt placement improves ICP and cerebral oxygenation as well as the response to hyperventilation in the tissue. Shunt removal reverses these improvements back to levels present during the untreated stage. The decrease in brain compliance may be one of the factors responsible for symptoms in shunt malfunction.

Key Words • brain compliance • hyperventilation • obstructive hydrocephalus • shunt malfunction • dog

Abbreviations used in this paper: CBF = cerebral blood flow; CSF = cerebrospinal fluid; ICP = intracranial pressure; LIAS = late-onset idiopathic aqueductal stenosis; MR = magnetic resonance; NPH = normal-pressure hydrocephalus; PaCO2 = arterial pressure of CO2; PaO2 = arterial pressure of O2; PcsfO2 = pressure of O2 in the CSF; PtiO2 = pressure of O2 in tissue; VP = ventriculoperitoneal.
first in which the focus is on the pathophysiological effect of shunt malfunction in shunted chronic hydrocephalus.

Materials and Methods

This experimental study was approved by the Cleveland Clinic Foundation Animal Research Committee and was performed in accordance with National Institutes of Health and Cleveland Clinic Foundation guidelines for the care and use of laboratory animals. All surgical procedures were performed using standard sterile surgical methods.

General Protocol

Adult male mongrel dogs, each weighing 20 to 30 kg, were used for this study. All dogs underwent baseline MR imaging, and those dogs with ventricular enlargement before induction of hydrocephalus were excluded from the study. Fifteen dogs were used: nine for induction of hydrocephalus and six for control surgery. After baseline MR imaging, obstructive hydrocephalus was induced by an injection of cyanoacrylic saline into the fourth ventricle. In six animals, only a suboccipital craniectomy with dural opening was performed. Thirteen weeks following surgery, a second MR imaging examination was performed. On the day after this examination, the animals received an endotracheally delivered anesthetic agent and measurements of various parameters were obtained. The parameters included the following: 1) ICP at normoventilation and hyperventilation; 2) local tissue oxygen saturation (PtiO2) at normoventilation and hyperventilation. Measurements of ICP, PtiO2, and PcsfO2 were obtained in the manner described in the following paragraph.

A 5-mm-diameter burr hole was made in the right parietal skull at a point 17 mm anterior to the external auditory meatus and 8 mm lateral to the midline. For ICP monitoring, a small twist-drill hole was made 10 mm lateral to the burr hole and an ICP microsensor (Codman Microsensor, Raynham, MA) was inserted subcutaneously. The drilled hole was completely sealed with bone wax. Another hole was drilled 7 mm anterior to the center of the first burr hole, and a flexible polarographic Clark-type microcatheter (LICOX System; Gesellschaft für medizinische Sondentechnik mbH, Kiel, Germany) was inserted to a depth of 17 mm for continuous monitoring of PtiO2. This microcatheter was stabilized with a cranial bolt. A ventriculostomy was then performed vertically through the burr hole. The depth of the ventriculostomy was approximately 25 mm for animals with hydrocephalic brains and 30 mm for animals with healthy brains. After CSF had been identified in the ventricular catheter, the device was promptly connected and sealed with another microcatheter so that PcsfO2 could be measured. After allowing at least 30 minutes to pass for the stabilization of PtiO2 and PcsfO2, the system was used to confirm the effect of the VP shunt on ventricular volume. On the following day, a second set of measurements were obtained for the same parameters in the same fashion and the VP shunt was then removed. One week later a third set of measurements was obtained after a final MR imaging examination. The dogs were killed after the third set of measurements had been obtained, and their brains were removed for histological evaluation.

Magnetic Resonance Imaging

After each animal had been sedated using intramuscularly administered ketamine (20 mg/kg) and xylazine (5 mg/kg), MR imaging was performed. This imaging occurred four times: 1) before induction of hydrocephalus; 2) 13 weeks after induction of hydrocephalus (untreated stage); 3) 15 weeks after the induction (shunted stage); and 4) 16 weeks after the induction (shunt-removed stage). Magnetic resonance imaging was performed using a 0.23-tesla MR imaging system (Outlook; Picker International, Inc., Highland Heights, OH) with field-echo sequences and the following parameters: TR 30 msec, TE 10 msec, flip angle 50°, matrix 200 × 256, and slice thickness 6 mm. Volumes of the lateral and third ventricles were obtained using computerized volumetric calculation with UNIX platform-based software that was developed at the Cleveland Clinic Foundation.

Induction of Hydrocephalus

The details of the induction of hydrocephalus have been previously reported. Briefly, after general endotracheal anesthesia had been induced in the animal, a midline suboccipital craniectomy was performed and the dura mater was opened along the midline. The cerebellum vermis was retracted up slightly, and a flexible silicone tube (1.5 mm in diameter) connected to a 1-ml syringe was inserted through the foramen of Magendie. Cyanoacrylic gel glue (0.35 ml) was injected into the fourth ventricle. After injection, the silicone tube was cut at the foramen of Magendie and left in place.

Measurement of Parameters

Anesthesia was induced using intramuscularly administered ketamine and xylazine and maintained by inhalation of 1% isofluorane. During surgery, a saline solution of Ringer’s lactate was infused through an intravenous line placed in the animal’s front leg at 5 to 10 ml/kg/hr. Hematocrit levels were measured to ensure proper hydration. A popliteal artery was catheterized for both blood pressure monitoring and arterial blood sampling. Blood pressure was maintained between 110 and 160 mm Hg during surgery by volume and anesthesia modulation. Body temperature was maintained at 37 ± 0.5°C by using a thermal blanket set at 40°C. Ventilation was mechanically controlled and respiratory parameters were adjusted to a PaO2 of 95 to 105 mm Hg and a PaCO2 of 37 to 40 mm Hg (normoventilation). After stabilization of blood gas parameters, measurements of ICP, PtiO2, and PcsfO2, were obtained in the manner described in the following paragraph.

The volume of this first saline infusion was measured to calculate brain compliance at low pressure. A second saline infusion was given until ICP increased from 15 to 25 mm Hg in the untreated stage. Hyperventilation was induced by increasing tidal volume. The range of induced hyperventilation was 30–34 mm Hg of PaCO2, with less than a 5 mm Hg change in PaO2. After a steady hyperventilation period, the fractional inspired O2 was increased to 60% to detect any response in PtiO2 and PcsfO2, and thus to confirm the appropriate location and function of the microcatheter. Compliance was then measured after normoventilation returned, and the microcatheter used to assess PcsfO2 was removed. The CSF was drawn out gently to decrease the ICP to 5 mm Hg. Following this, we injected a saline infusion at a rate of 0.025 ml/second, until the ICP reached 15 mm Hg. The volume of the first saline infusion was used to calculate brain compliance at low pressure. A second saline infusion was given until ICP increased from 15 to 25 mm Hg in the same manner. The volume of the second saline infusion was used to determine brain compliance at high pressure. Brain compliance was calculated by dividing the infused saline volume (in ml) by 10 mm Hg. The ICP was then decreased promptly by drawing out CSF. These series of measurements were performed at three separate times (for untreated, shunted, and shunt-removed stages) for each animal. For the second and third measurements, the same holes were used; however, the microcatheter used to assess PtiO2 was inserted at a different angle to reach new brain tissue.

Ventriculoperitoneal Shunt Placement and Removal

After the first measurement was obtained to assess the untreated condition (13 weeks after hydrocephalus induction), a VP shunt was placed. The ventricular catheter was connected to a peritoneal shunt tube without a valve. For the second set of measurements to reflect the shunted condition (2 weeks after the shunt placement), the shunt tube was disconnected after an ICP monitor had been placed. The pressure of the shunt system was confirmed by observing a few drops of CSF emerging spontaneously from the proximal catheter and by finding no resistance pressure on the distal catheter. After confirmation of shunt patency, the whole shunt system was removed and the second series of physiological measurements were obtained, as described earlier.
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Final Physiological Measurements and Histological Evaluation of Tissue

The third series of physiological measurements, which were obtained to assess the shunt-removed condition (1 week after shunt removal), were made just before the animal was killed. Before saline infusion, which was performed for measurement of brain compliance, CSF was aspirated to assess decreasing ICP and was immediately sealed into the syringe tube. The microcatheter used to assess PcsfO2 in vivo was immersed into this syringe to obtain the value of PcsfO2 in vitro. The in vivo and in vitro values were then compared. After completion of the third set of measurements, the bilateral carotid arteries were catheterized and perfused with 0.9% saline and 4% parafomaldehyde. After perfusion, the brains were removed and used for histological evaluation by staining them with hematoxylin and eosin.

Statistical Analysis

The results of this study are expressed as the means ± standard deviations. Statistical comparisons in the time-course study were assessed using repeated-measures analysis of variance together with the Student–Newman–Keuls test. For analyses between hydrocephalus and control groups, two-tailed unpaired t-tests were used. In the hydrocephalus group, correlations among ventricular volume, ICP, PtiO2, and PcsfO2 at each measurement time point were examined using the Spearman rank correlation analysis. Statistical significance was accepted at a probability level less than 0.05.

Results

Overall Outcomes

No incidence of mortality or morbidity as a result of hydrocephalus induction was encountered. All dogs awoke from general anesthesia within 1 hour and started to eat or drink within 8 hours. The animals continued to do well for 13 weeks with no sign of lethargy, apparent neurological deficit, or weight loss. The animals remained stable after VP shunt implantation. Three (33.3%) of the nine dogs in the hydrocephalus group died a few days after removal of the VP shunts. These three dogs had awakened from general anesthesia smoothly and their vital signs had been stable during the postoperative period. Two of the three animals had started to eat within half a day and could walk the following morning. These dogs had become less active during the following day, although their vital signs had remained stable. On the third morning, they were found dead. Autopsy revealed no apparent intracerebral bleeding or intraventricular bleeding in these two dogs. The third dog also had awakened smoothly from anesthesia; however, he had been inactive and had not eaten well. On the second day he had undergone MR imaging to rule out intracerebral bleeding, and only reexpansion of the ventricles had been found. He was found dead on the second morning after shunt removal. We believe that these deaths resulted from recurrent hydrocephalus after shunt removal. Although the six control dogs exhibited no neurological deficit, three dogs became inactive and lost body weight. Data for the shunt-removed stage were obtained from the six surviving dogs in the hydrocephalus group.

Histological analysis demonstrated no infarction or major intracerebral bleeding. The three different tracts of microcatheters used to obtain PtiO2, measurements were confirmed to be located in the frontal subcortical white matter.
observed between the untreated and shunt-removed stages. In the control group, a lower ICP was observed when compared with that in the hydrocephalus group during the untreated (5.13 \pm 0.17 mm Hg, p = 0.014) and shunt-removed (5.17 \pm 1.94 mm Hg, p = 0.0065) stages, but not during the shunted stage (3.67 \pm 2.16 mm Hg) due to the decrease in ICP in the dogs in the hydrocephalus group after VP shunt placement.

**Tissue \( O_2 \) Saturation**

A comparison of \( P_{tiO_2} \) and changes that occur with shunt placement in the animals in the control and hydrocephalus groups is shown in Fig. 4 upper. In the hydrocephalus group, \( P_{tiO_2} \) increased significantly in response to shunt insertion (from 26.1 \pm 5.33 mm Hg to 35.2 \pm 6.8 mm Hg, p = 0.0084), although it still remained lower than that measured in the control group. In response to shunt removal, the \( P_{tiO_2} \) decreased significantly (19.7 \pm 4.72 mm Hg, p = 0.0005) to a level that did not statistically differ from that found in animals with untreated hydrocephalus. The \( P_{tiO_2} \) in the control group was stable (48.7 \pm 4.27 mm Hg during the untreated stage, 45.1 \pm 4.25 mm Hg during the shunted stage, and 47.1 \pm 1.86 mm Hg during the shunt-removed stage), and every value was higher than the corresponding value in the hydrocephalus group (p < 0.0001 for the untreated stage, p = 0.0074 in the shunted stage, p < 0.0001 for the shunt-removed stage).

**Oxygen Saturation in the CSF**

The overall pattern in \( P_{csfO_2} \) was the same as that seen in \( P_{tiO_2} \), except that there was no significant difference between groups during the shunted stage (Fig. 4 lower). In the hydrocephalus group, \( P_{csfO_2} \) increased during the shunted stage (p = 0.012) then decreased during the shunt-removed stage (p = 0.022). The values in the hydrocephalus and control groups were 22 \pm 4.26 mm Hg and 33.4 \pm 5.26 mm Hg, respectively, during the untreated stage (p = 0.0005), 31 \pm 6.77 mm Hg and 38.1 \pm 7.91 mm Hg, respectively, during the shunted stage (not significantly different), and 20.8 \pm 7.38 mm Hg and 37 \pm 4.55 mm Hg, respectively, after shunt removal (p = 0.001).

In the hydrocephalus group, CSF was withdrawn before saline infusion for brain compliance analysis, and the CSF \( O_2 \) saturation in vitro was compared with in vivo data to evaluate the accuracy of in vivo analysis of \( P_{csfO_2} \). The differences were 1.5 to 4.7 mm Hg (mean 3.22 mm Hg), and the percentages of this difference compared with the values in vivo were 9.2 to 14.9%.

**Response to Hyperventilation**

Table 1 shows the responses of ICP, \( P_{tiO_2} \), and \( P_{csfO_2} \) to hyperventilation in animals in the hydrocephalus group. Under each condition (untreated, shunted, and shunt-removed), ICP and \( P_{csfO_2} \) decreased significantly in response to hyperventilation. Similarly, \( P_{tiO_2} \) decreased in response to hyperventilation during shunt-treated hydrocephalus. However, \( P_{tiO_2} \) did not respond to hyperventilation in untreated hydrocephalus or after shunt removal.

**Brain Compliance**

Brain compliance was measured at both low pressure (5–15 mm Hg) and high pressure (15–25 mm Hg). Figure 5 upper shows compliance at low pressure. Shunt inser-
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and removal did not significantly alter compliance in the hydrocephalus group. In a comparison of the hydrocephalus and control groups, those animals with hydrocephalus exhibited greater brain compliance than control animals during the untreated stage (0.288 ± 0.074 ml/mm Hg compared with 0.203 ± 0.05 ml/mm Hg, p = 0.033) and during the shunt-removed stage (0.303 ± 0.082 ml/mm Hg compared with 0.21 ± 0.028 ml/mm Hg, p = 0.025). However, there was no significant difference between groups (0.28 ± 0.077 ml/mm Hg compared with 0.2 ± 0.057 ml/mm Hg, p = 0.054).

Brain compliance at high pressure (Fig. 5 lower) demonstrated a significant gradual decrease in the hydrocephalus group (p = 0.038 between the untreated and shunted stages, p = 0.021 between the shunted and shunt-removed stages, and p = 0.0012 between the untreated and shunt-removed stages). Between groups, a lower compliance was observed in the hydrocephalus group at every measurement (0.065 ± 0.0076 ml/mm Hg compared with 0.08 ± 0.011 ml/mm Hg during the untreated stage, p = 0.01; 0.053 ± 0.017 ml/mm Hg compared with 0.092 ± 0.018 ml/mm Hg during the shunted stage, p = 0.0013; and 0.033 ± 0.01 ml/mm Hg compared with 0.09 ± 0.016 ml/mm Hg during the shunt-removed stage, p < 0.0001).

**Correlation Between Parameters**

All correlation analyses among ventricular volume, ICP, PtO₂, and PcsO₂ failed to reveal any significant correlations in the hydrocephalus group.

**Discussion**

**Animal Model of Hydrocephalus**

Undoubtedly, series of extensive animal research on hydrocephalus have played a significant role in confirming the pathophysiological features of hydrocephalus, such as pressure and/or volume biomechanics, histological morphology, CBF and metabolism, neurochemistry, and, more recently, gene expression. However, one difficulty in hydrocephalus research is the diversity of hydrocephalus: infantile or adult, obstructive or communicating, and acute or chronic onset. Because each subcategory of hydrocephalus has its unique clinical features and associated pathophysiological characteristics, it is important to consider which type of clinical hydrocephalus is relevant in any particular experimental model.

In many animal models intracisternal kaolin injection has been used to induce acquired hydrocephalus. Kaolin deposition has been found most notably ventral to the brainstem; however, the location of CSF obstruction is variable and the severity of hydrocephalus may not be uniform. Moreover, inflammation caused directly by kaolin can obscure pathophysiological conditions that are

### TABLE 1

<table>
<thead>
<tr>
<th>Stage</th>
<th>ICP (mm Hg)</th>
<th>PtO₂ (mm Hg)</th>
<th>PcsO₂ (mm Hg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normo-</td>
<td>Hyper-</td>
<td>p Value</td>
</tr>
<tr>
<td>untreated</td>
<td>8.3 ± 2.6</td>
<td>6.0 ± 2.7</td>
<td>0.0022†</td>
</tr>
<tr>
<td>shunted</td>
<td>5.2 ± 2.2</td>
<td>3.8 ± 2.8</td>
<td>0.012†</td>
</tr>
<tr>
<td>shunt removed</td>
<td>9.8 ± 2.7</td>
<td>8.3 ± 3.8</td>
<td>0.045†</td>
</tr>
</tbody>
</table>

* Values are expressed as the means ± standard deviation.
† The difference between normoventilation and hyperventilation reaches significance.
caused by the hydrocephalus. Clinically, after intracerebral kaolin injection, animals have become transiently lethargic for several days and there have been some incidences of mortality. In these models, if the animal survives the critical acute period, it may be used as a model of chronic hydrocephalus such as LIAS. Other common symptoms of LIAS include NPH symptoms, the exact cause of which is still uncertain. Slightly elevated ICP has been considered to be one of the mechanisms of NPH; however, NPH can occur even in the presence of low ICP. Several other factors may be related to NPH symptoms, including stretching, a transmural pressure gradient, and cerebral hypoperfusion. Because our study did not include detailed behavioral analyses, the relationship between the dogs' symptoms and ICPs are unknown.

As observed in other studies, we found no relationship between ICP and ventricular volume in this study. Enlargement of the ventricles may compensate for the increase in ICP. The increase in CSF absorption or the decrease in CSF production found at high ICPs may also affect the correlation.

Cerebral Oxygenation

Use of microcatheters to measure cerebral tissue O₂ saturation has been widely applied clinically, especially in monitoring severe head injuries. The PtiO₂ reflects the balance between O₂ delivery (arterial O₂ content and CBF) and the demand for cerebral metabolism. Because arterial O₂ content was strictly monitored and controlled during our measurements, in this study PtiO₂ reflects CBF and metabolism. Theoretically, a reduction in PtiO₂ can result from an increase in metabolism; however, PtiO₂ reduction during anesthesia is thought to represent hypoperfusion of the examined local tissue. Our model exhibited clear and uniform hypoperfusion in the frontal subcortical white matter. Cerebral hypoperfusion in the hydrocephalic brain has been reported both clinically and experimentally and may be reversible after shunt implantation, as detected by clinical imaging. This improvement was confirmed in the hydrocephalus group in our study. We believe that this improvement is due to hydrocephalus treatment, as opposed to being an artifact of repeated measurements, because in the control group, the three serial measurements exhibited no significant change over the time course of the study. Cerebral hypoperfusion in animals with experimental hydrocephalus that has been induced with silicone oil injection has been associated with a reduction in the number of capillaries; this finding is in agreement with those of other studies of the acute stage of hydrocephalus. The mechanism of increased tissue oxygenation after shunt placement, which we observed in our study, may be the release of compressed capillaries, although persistent capillary compression in chronic hy-
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drocephalus has not been established. More regional histological analyses and blood flow studies will be needed to understand the effect of shunt placement on cerebral perfusion.

Response to Hyperventilation

General improvement in cerebral hypoperfusion has been well reported after shunt placement in clinical cases. However, this improvement alone does not necessarily lead to symptomatic resolution. Other factors, including fiber stretch, decreased connectivity, neurotransmitter dysfunction, and decreased metabolism, are likely to be involved. Recently, a loss of chemical autoregulation of vessel response to alteration of blood CO₂ has been proposed to play a pathophysiological role in shunt malfunction. The results of a previous experimental study have demonstrated an increase in vascular beds that are observed in chronic hydrocephalus. This may be a result of the buffering effect of an increased ventricular volume.

Shunt Malfunction

As long as shunt operations are performed, shunt malfunctions will occur. The rate of shunt failure has not improved significantly, even though there have been extensive clinical studies over many years. The morbidity associated with failure can be severe and includes death. In spite of these problems, the pathophysiology specific to shunt malfunction has remained obscure. For this reason, the focus of this study was to evaluate the differences between untreated hydrocephalus and hydrocephalus occurring after shunt failure. In this study, three of nine dogs died within a few days after a shunt removal. At autopsy there was no evidence of intracerebral bleeding in any of these animals. This contrasts with no incidence of morbidity occurring after the original hydrocephalus induction. This finding is consistent with the idea that shunt failure can be a more dangerous condition than the initial untreated hydrocephalus. The results of a previous clinical study have shown unstable ICPs in children with shunts who have displayed acute deterioration, and findings of an experimental study have demonstrated an inexorable rise in ICP during a 6-hour period after shunts were occluded. As observed in our study, the significant lower brain compliance at the high pressure that occurs during the shunt-removed stage, compared with brain compliance during untreated hydrocephalus, may explain the mechanism of acute deterioration that occurs with shunt malfunction.

Brain compliance has been examined as an important mechanical property; it has been described as the CSF compensatory reserve, pressure-volume index, or volume-buffering capacity. One factor that defines this property is the compressibility of cerebral tissues. A cortical mantle that is compressed due to enlarged ventricles or any mass has lower compliance. Another factor is the buffering capacity of CSF; an enlarged ventricle may increase compliance because of the higher buffering capacity associated with a large ventricular volume. On the contrary, an aqueductal block itself has been shown to decrease this compliance, because as a buffer the CSF space decreases because of the isolation of the posterior fossa and the spinal CSF space. At low pressure, compliance in the hydrocephalus group was higher than in the control group, even when there was an aqueductal block. This may be a result of the buffering effect of an increased ventricular volume.

At high pressure, brain compliance exhibited a gradual decrease both in response to shunt placement and shunt removal. The effect of shunt insertion on brain compliance has not been fully determined; however, appropriate shunt placement should improve brain compliance by reducing cortical compression. On the contrary, overdrainage may have some value in predicting outcome after VP shunt placement. We avoided use of hypoventilation trials in our animals and examined, instead, the response to hyperventilation, which normally decreases ICP and reduces secondary to vasconstriction. In spite of the significant decrease in ICP in response to hyperventilation, PtiO₂ did not respond during the untreated hydrocephalus stage. Interestingly, 2 weeks after shunt implantation, PtiO₂ decreased in response to hyperventilation, indicating the recovery of autoregulation in this tissue. Because ICP decreased in response to hyperventilation, even during the untreated hydrocephalus stage, it is likely that the general response to hyperventilation was preserved in the brain as a whole. However, we have seen that local tissue response can be disturbed reversibly. This is the first experimental evidence that cerebrovascular reactivity to CO₂ may be altered by VP shunt placement.

Oxygen Saturation in the CSF

Although microcatheter measurement of CSF O₂ has been reported experimentally, it has never been used in clinical monitoring of humans. In our study, the accuracy of PcsfO₂ in vivo was evaluated by comparing the in vivo value with the in vitro value. This comparison showed less than a 15% difference. We believe PcsfO₂ can be measured reliably with this microcatheter probe, unless the ventricles are collapsed. Interesting differences were seen in the response to hyperventilation between PtiO₂ and PcsfO₂. During the untreated and shunt-removed stages, PcsfO₂ significantly decreased in response to hyperventilation, whereas PtiO₂ did not. Because ICP responded to hyperventilation during these conditions, we hypothesize that PcsfO₂ may reflect a more global cerebral condition when compared with local tissue oxygenation. Therefore, PcsfO₂ may be a substitute for jugular vein O₂ saturation, which is frequently applied clinically for monitoring global cerebral oxygenation.
Conclusions

In this study we demonstrated the physiological characteristics of our model of chronic hydrocephalus with ventriculomegaly, mildly increased ICP, and decreased O2 saturation. After shunt placement, ventricle size and ICP decreased, O2 saturation increased, and the response to hyperventilation in the local brain tissue recovered. With an induced shunt malfunction, these improvements reversed to the levels of the original untreated hydrocephalus condition. Brain compliance measured at high pressure decreased with shunt placement and further decreased with shunt removal, indicating a possible mechanism of acute deterioration in response to shunt malfunction.

Because this new model exhibits a gradual onset of hydrocephalus, it is relevant to investigating the long-term effects of shunt implantation and malfunction in cases of chronic hydrocephalus. We assert that detailed behavioral evaluations and histological comparisons be performed at multiple time points by using this model.

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