J Neurosurg Pediatrics 2:1–11, 2008

The importance of the cortical subarachnoid space in understanding hydrocephalus

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Object. In this paper the authors define the role of the cortical subarachnoid space (CSAS) in poorly understood forms of hydrocephalus to cerebrospinal fluid (CSF) dynamics to improve understanding of the importance of the CSAS and its role in selecting patients for endoscopic third ventriculostomy (ETV). The secondary purpose of this work was to define testable hypotheses to explain enigmatic disorders of CSF dynamics and to suggest how these concepts could be tested.

Methods. The magnitude of the contribution of the CSAS is explored using the solid geometry of concentric spheres. With this starting point, clinical conditions in which CSF dynamics are not easily understood are explored regarding the potential role of the CSAS. Overall, problems of CSF dynamics are easily understood. Insights may be gained when the results of a pathological process or its treatment vary from what has been expected.

Results. Acute changes in ventricular volume at the time that hydrocephalus develops, the failure of shunts, and the changes in ventricular volume with shunt repair may occur very rapidly. Changes in the volume of water in the brain, especially in the brain substance itself, are unlikely to occur at this rapid rate and may be interpreted as a simple redistribution of the CSF between the ventricle and CSAS with no initial change in the actual volume of brain parenchyma. Problems such as pseudotumor cerebri, shunt failure with nonresponsive ventricles, and negative-pressure hydrocephalus can be explained by assessing the ability of ventricular CSF to flow to the CSAS and the ability of this fluid to exit this compartment. Ventricular enlargement at the time of shunt failure implies a failure of flow between the ventricles and CSAS, implying that all patients who show this phenomenon are potential candidates for ETV.

Conclusions. The important role of the CSAS in the pathophysiology of various forms of hydrocephalus has been largely ignored. Attention to the dynamics of the CSF in this compartment will improve understanding of enigmatic conditions of hydrocephalus and improve selection criteria for treatment paradigms such as ETV. These concepts lead to clearly defined problems that may be solved by the creation of a central database to address these issues.
(DOI: 10.3171/PED/2008/2/7/001)

Key Words • biophysics • cortical subarachnoid space • endoscopic third ventriculostomy • hydrocephalus • mathematical model • pseudotumor cerebri

Both in the physiology laboratory and in clinical practice, we have been studying the pathophysiology of hydrocephalus based on a mathematical model of CSF dynamics. In this multicompartmental model, the skull is a fixed volume and the 4 ventricles, CSAS, and brain parenchyma are constrained by the volume of the skull. The final compartment is the SSAS, which lies outside this volumetric constraint.[31,35,36] Our early work on this model essentially ignored the role of the CSAS in the pathophysiology of abnormalities of CSF dynamics. Instead, changes in the volume of the ventricles were explained by changes in the actual brain parenchyma itself.[26] Later we found that almost all patients with ventricles that did not expand at the time of shunt failure could be shown to have ventricular CSF in communication with the upper SSAS and CSAS. This finding led to the thought that we had underestimated the role played by the CSAS in the pathophysiology of various forms of hydrocephalus and other abnormalities of CSF dynamics.[34]

Abbreviations used in this paper: CSAS = cortical subarachnoid space; CSF = cerebrospinal fluid; ETV = endoscopic third ventriculostomy; EVD = external ventricular drain; ICP = intracranial pressure; LP = lumboperitoneal; NPH = normal-pressure hydrocephalus; NVH = normal-volume hydrocephalus; SSAS = spinal subarachnoid space; SVS = slit ventricle syndrome.

The important contribution of the CSAS to the understanding of the pathophysiology of hydrocephalus has been mostly ignored. Before CT and MR imaging became available, the size and configuration of the cerebral ventricles were evaluated using contrast agents such as air or iodine-based dyes. These studies, however, could not evaluate the volume or configuration of the CSAS. Computed tomography scans effectively image the ventricular system. However, the CSAS abuts the bone causing considerable interference and artifact. Unless the CSAS is greatly enlarged, it is difficult to assess its volume. Magnetic resonance imaging, especially T2-weighted sequences, represents a significant advance. However, the complex geometry and thinness of the CSAS prevented it from being perceived as playing an important role in the pathophysiology of hydrocephalus or even of pseudotumor cerebri. Because the anatomy of the CSAS is complex, measuring its volume remains challenging. Changes in ventricular volume are readily visible on contemporary imaging studies, but the effect of hydrocephalus, shunt failure, or shunt repair on the CSAS is seldom easy to detect.

Our interest in the importance of the CSAS in hydrocephalus resulted from our work on understanding and treating patients with severe ICP and failed shunts. This condition was termed NVH by Engel and colleagues[8] who first described it. Our work on the classification of patients with severe headaches and ventricular shunts (SVS) based on ICP monitoring has shown that NVH is a form of pseudotumor cerebri in patients whose hydrocephalus resulted from venous hypertension during infancy. Strategies that are effective in the management of this difficult condition involve increasing the resistance of the valves in moderately affected patients while requiring shunt systems that access the CSAS through LP shunts or through shunts that access the cisterna magna.[15,16,20,28,32,34] Based on these experiences and observations of a referral practice for patients with severe problems related to shunt management, we have analyzed a group of enigmatic hydrocephalic conditions that may be explained with reference to changes in the volume of the CSAS.

We recognize that making an observation does not equate to proving cause and effect. There are alternative explanations for the observations seen here and for the fact that the outcomes of various treatments described below can be predicted by the mathematical model. However, we suggest that this retrospective review of a significant number of patients with relatively rare problems has 2 potential benefits. First, it provides a systematic approach to the problem faced by each of these patients so that their treatment goals can be identified in advance. The second and perhaps the more important benefit is to describe a set of prospective studies on the role of the CSAS and the treatment of difficult conditions of CSF dynamics that would need input from several active centers (Table 1).

TABLE 1

Proposed experiments to evaluate the importance of the CSAS in the treatment of various forms of hydrocephalus

1.	Use specific MRI sequences to minimize signal-to-noise errors in calculating the volumes of CSF compartments & postprocessing to maximize the ability to define the changes in these volumes. Such studies would define the rate at which CSF can be redistributed from the ventricles to the subarachnoid space & would determine whether actual brain volume is lost.
2.	Perform a cooperative prospective trial assessing the outcomes of patients undergoing programmed shunt removals in a variety of busy centers.
3.	Compare cognitive impairment in patients whose ventricles do not expand at the time of shunt failure to that of patients with more normal production of ventriculomegaly.
4.	Use Iohexol cisternography to assess CSF dynamics in patients w/ NVH to establish the rate at which the ventricles communicate w/ the CSAS to determine if these patients are candidates for ETV.
5.	Perform Iohexol cisternography through the ventricular reservoir in patients with ventricular enlargement at the time of shunt failure to determine prospectively whether the ventricles & CSAS are in communication.*

* We have performed this study in ~ 20 such patients and could not demonstrate such communication in any of them.

Three-Dimensional Geometric Modeling

We first assessed whether acute hydrocephalus, acute shunt failure, or shunt revision could be explained by the acute displacement of CSF between the CSAS and ventricles without invoking a change in the actual volume of the brain itself. The CT scans and MR images obtained immediately after shunt revision routinely show complete ventricular decompression < 1 hour after the repair. It is difficult to imagine that this rapid change reflects a change in the volume of the brain itself or in the volume of water in the brain.

Intracranial Compartments

As a prelude to the study of this phenomenon, we observed the visual effect of small changes in the thickness of the CSAS on the volume of the central ventricular system. The intracranial compartment can be modeled as a simplified set of concentric spheres (Fig. 1). Assuming that the internal circumference of the skull is 50 cm and that the thickness of the skull is 1 cm, the radius of the intracranial compartment would be 7 cm and the internal volume would be 1372 cm^3. If the mean thickness of the CSAS is 3 mm, the volume of the brain and ventricles would be 1204 cm^3. The volume remaining for the CSAS is 168 cm^3. If the normal volume of the sphere representing the ventricles is 30 cm^3, the radius of the sphere would be 1.9 cm.

If sufficient volume is lost from the CSAS to decrease the thickness of the space from 3 to 1 mm while the volume of the brain is unchanged, the volume of the ventricle would be 134 cm^3 and the radius would be 3.2 cm (Fig. 2).

Ventricular Volume Regulation

As described briefly above, the senior author (H.L.R.) collaborated with the Electronics Design Center at Case Institute of Technology in Cleveland, Ohio (Case Western Reserve University School of Engineering), to develop a mathematical model of CSF dynamics based on principles of bulk flow. A multicompartmental model was used to produce equations to describe changes in pressure and volume in each compartment (Fig. 3).[31,36] Based on our understanding of the anatomy and physiology, the skull was modeled as a fixed volume. The brain, ventricles, and CSAS were

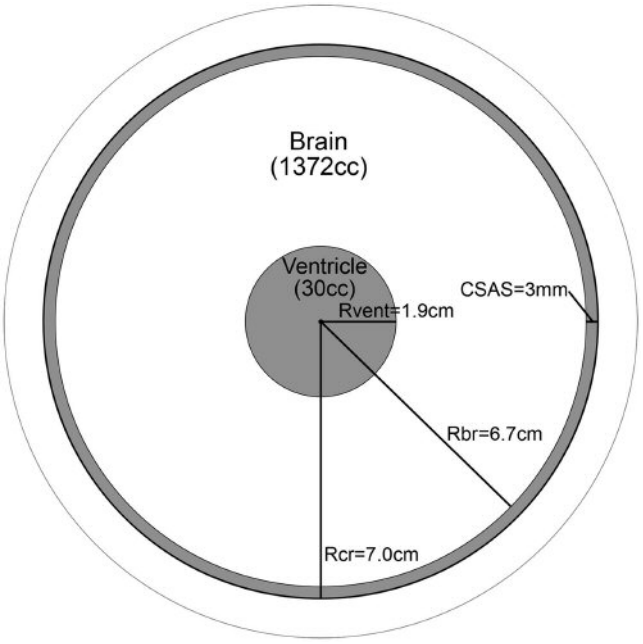

FIG. 1. Diagram showing that the intracranial compartment is modeled as a simplified set of concentric spheres. Rbr = radius of the brain; Rcr = radius of the cranium; Rvent = radius of the ventricle.

constrained so that changes in the volume of any of the compartments must be compensated by changes in another compartment (that is, the Monro-Kellie hypothesis). The SSAS lies outside this constraint and is free to increase or decrease with changes in fluid volume and pressure. Consequently, the SSAS is analogous to an electrical capacitor for the storage of volume.

We measured the resistance at different locations within this system to define various forms of hydrocephalus. Passages between the lateral and third ventricles (foramen of Monro), between the third and fourth ventricles (sylvian aqueduct), through the outlet foramina of the fourth ventricle, between the SSAS and the CSAS (basal cisterns), and from the CSAS to the point of absorption—which we postulated was in the dural venous sinuses—were studied in steady state and during the infusion of artificial CSF at various rates.[27,33] The results showed that a pressure differential of 5–7 mm Hg was always present between the CSAS and the superior sagittal sinus.[23,27,31,33,36] In experimental animals with small ventricles in which 1 lateral ventricle was drained to negative numbers, a 2- to 3-mm Hg pressure differential was measured. Presumably, the pressure differential was caused by functional obstruction at the foramen of Monro.[35] Within the sensitivity of available transducers, no pressure differentials were detected at any of the presumed points of obstruction except in this artificial circumstance approximating the effect of an overdraining shunt. The pressure in the ventricle and the pressure in the CSAS were always the same.

The brain is a viscoelastic substance. It can be displaced immediately from a point of higher pressure to a point of lower pressure. This observation stimulated our interest in the CSAS. The CSF pathway can be considered as a circuit diagram with the only testable resistor between the CSAS and the dural venous sinuses (Fig. 4).

Intracranial Hypertension With Normal or Smaller Than Normal Ventricular Volume

Headache is one of the most common afflictions in humans. It is estimated that 4% of the world's population suffers from severe and incapacitating headaches every day (chronic daily headaches). In patients with shunts, this problem is complicated by the constant fear that the headache represents shunt failure or results from a problem with the shunt.

To study this phenomenon, we routinely monitor ICP. As a result, we have identified 5 reasons for shunt-treated pa-

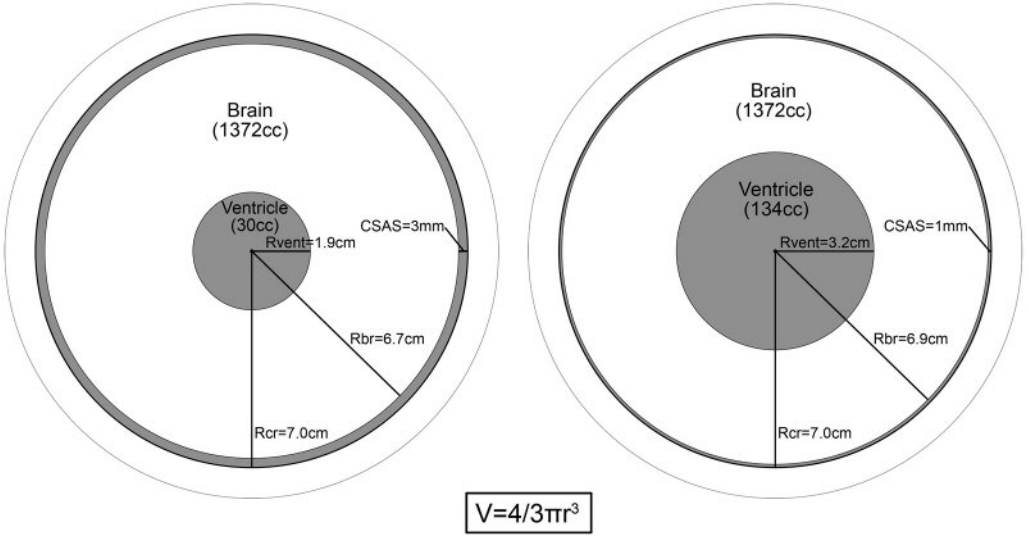

FIG. 2. Diagrams. *Left:* Representation of normal ventricular volume (V) in a normal or adequately shunt-treated individual. *Right:* Representation of the visual change in the size of the ventricular system when the thickness of the CSAS is decreased from 3 mm to 1 mm. In this illustration, the volume of the brain remains constant.

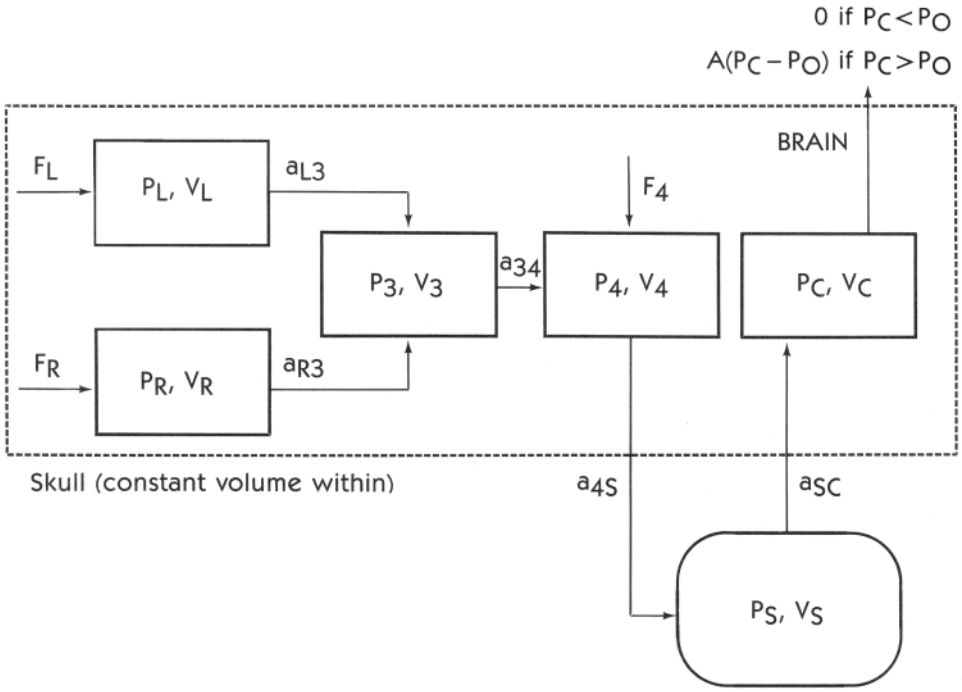

FIG. 3. Diagram of the foundation of the mathematical model. In this model the skull is a fixed volume containing compartmentalized components of the ventricles, CSAS (C), and the brain itself. The SSAS (S) lies outside the constraints of the fixed skull. A = absorption coefficient of CSF leaving the final compartment; a = leaving of CSF from one compartment to another (analogous to a resistance element); F = formation of CSF; L = left ventricle; O = out, indicative of the fact that the CSF has left the CSAS; P = pressure; R = right ventricle; 3 = third ventricle; 4 = fourth ventricle. Modified from Rekate HL, Brodkey JA, Chizeck HJ, El-Sakka W, Ko WH: Ventricular volume regulation: a mathematical model and computer simulation. **Pediatr Neurosci 14:**77–84, 1988. With permission from S. Karger AG, Basel, Switzerland.

tients to suffer from severe headaches (the condition known as SVS[11]) as follows: intermittent proximal obstruction; severely low ICP analogous to spinal headaches; increased ICP with a working shunt, which we have termed cephalocranial disproportion as it occurs in craniofacial syndromes; shunt-related migraines with no changes in ICP; and shunt failure without ventriculomegaly, which has been called NVH by Engel and colleagues.[8,28]

Headaches caused by NVH are the most difficult subtype to understand and the most controversial. This condition involves severely increased ICP without ventricular dilation in the presence of shunt failure.[28] This problem is unique to hydrocephalus in infants and is not associated with hydrocephalus that develops during adulthood.

The incidence of NVH is unknown but may be as high as 25% of patients who undergo shunt treatment during infancy (J. G. McComb, personal communication, 2000). Our work on programmed shunt removal supports the likelihood that NVH occurs in 25% of shunt-treated infants and is especially common in patients with spina bifida.[1] It is also likely to occur when hydrocephalus is present in achondroplastic dwarfs whose hydrocephalus is known to result from obstruction of CSF flow through the small jugular foramina. These patients no longer are considered to have hydrocephalus; they have pseudotumor cerebri.

Our work on the definition of pseudotumor cerebri suggests that all cases are associated with increased sagittal sinus pressure either from high right atrial pressure in the obese or from high resistances within the cerebral venous pathways.[12] When we studied the venous anatomy and venous pressure in some of these children, the latter has always been high.

Illustrative Cases 1 and 2

Case 1. This 6-year-old girl was born with a cervical myelomeningocele and a Chiari malformation Type II. The lesion was repaired when she was 2 days old. At 10 days she underwent placement of a ventriculoperitoneal shunt. At 4 years of age, she developed shunt failure with evidence of severe intracranial hypertension but no ventriculomegaly on imaging studies. On exploration the ventricular catheter was found to be fully obstructed. The catheter and valve were replaced with a high-resistance valve that has a device to retard siphoning. On numerous occasions she was brought to the emergency room with signs and symptoms of shunt failure without ventriculomegaly. She remained sick for 6–24 hours, and her symptoms resolved spontaneously. At 5 years of age she underwent a cranial expansion operation for presumed cephalocranial disproportion related to secondary craniosynostosis from the presence of a shunt. She was well for 6 months and then became severely symptomatic again.

At this time, MR imaging showed a pseudomeningocele at the site of the repair (Fig. 5 *left*). A CT study of the brain showed significant extracerebral CSF (Fig. 5 *right*), which made it unlikely that she had cephalocranial disproportion. Because the shunt was functioning, we believed that the

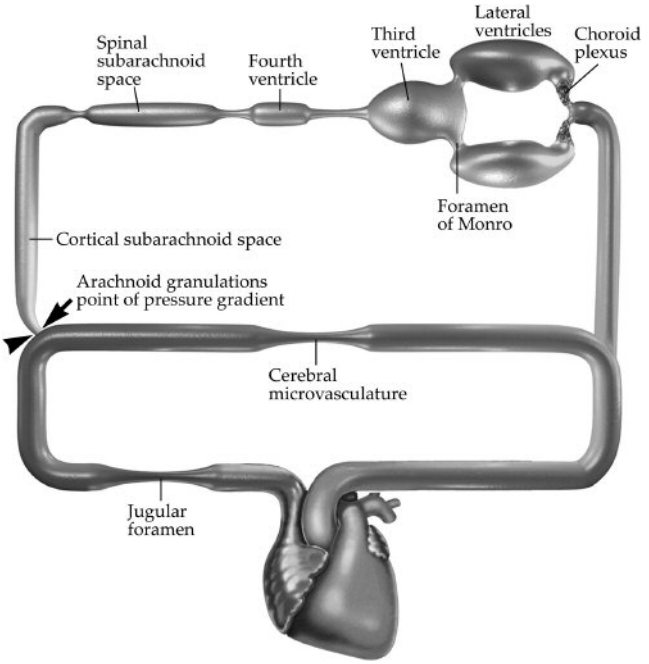

FIG. 4. Circuit diagram of the CSF pathway showing that the only place where a resistor can be measured is between the CSAS and the superior sagittal sinus. Modified from Rekate HL: Adults with hydrocephalus treated in infancy and childhood. **Semin Neurosurg 13:**19–28, 2002. Used with permission from Barrow Neurological Institute.

CSAS played a role in pushing the brain inward until it collapsed around the ventricular catheter and intermittent shunt failure resulted.

We therefore chose a treatment that would drain both the ventricles and CSAS. For most such cases, we advocate the use of LP shunts, which can drain both pathways.[15,34] In this case, however, the decision was complicated by the presence of the Chiari malformation Type II and NVH. We elected to explore the previous surgical site. We placed a piece of LP shunt tubing in the pseudomeningocele and spliced it into the existing valve system. Doing so created a cisterna magna-ventricle-peritoneal shunt with a programmable valve with a device to retard siphoning.[20,32] To ensure that the pressure dynamics were ideal, we monitored the patient's ICP by using a parenchymal monitor for 48 hours. For the last 6 months she has not suffered headaches.

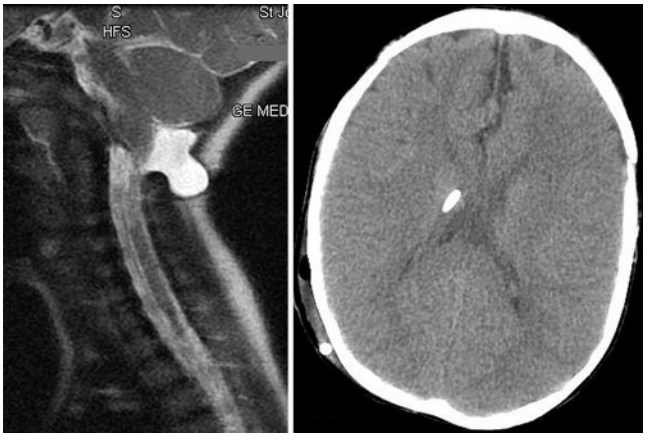

FIG. 5. Case 1. *Left:* An MR image obtained in a 6-year-old girl, showing a pseudomeningocele related to the repair of a cervical myelomeningocele during infancy. *Right:* Head CT scan showing the presence of considerable fluid in the CSAS.

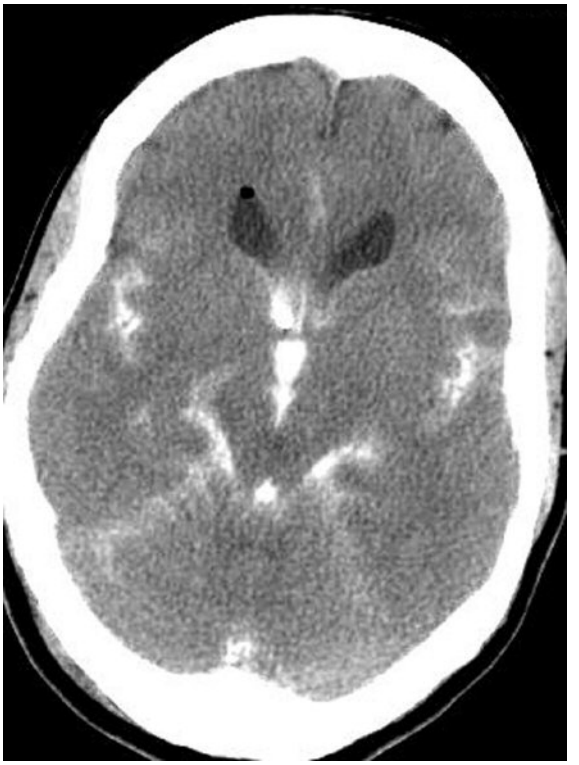

FIG. 6. Case 2. Iohexol cisternogram obtained in a patient with long-standing hydrocephalus, showing free flow of CSF through the ostium of the third ventriculostomy. Although the patient had a firm diagnosis of aqueductal stenosis, her sylvian aqueduct is now clearly open.

Case 2. This 32-year-old woman with severe headaches was first treated with shunts when she was 19 years old. At that time MR images showed moderate triventricular hydrocephalus. She underwent placement of a ventriculoperitoneal shunt without difficulty, but her headaches failed to improve. Three years before admission to our service, she was found to have an abdominal pseudocyst and a shunt infection. She underwent ETV and was discharged from the hospital with unremitting headaches. The size of her ventricles decreased, and it was thought that her hydrocephalus had been treated adequately.

She was seen at our service and was admitted for ICP monitoring. Her head circumference was a standard deviation above the 95th percentile, which implied that her hydrocephalic state began before suture closure. Her ICP was 20–26 mm Hg in the recumbent position and increased to ~ 45 mm Hg during sleep. In the sitting position her ICP was 12–15 mm Hg (normal ~ 5 mm Hg).

Iohexol cisternography (Fig. 6) showed rapid communication between the ventricular system and the CSAS through the ostium of the ETV. An open sylvian aqueduct had been obliterated before the ETV. Magnetic resonance venography showed high-grade stenosis of both transverse sinuses (Fig. 7).

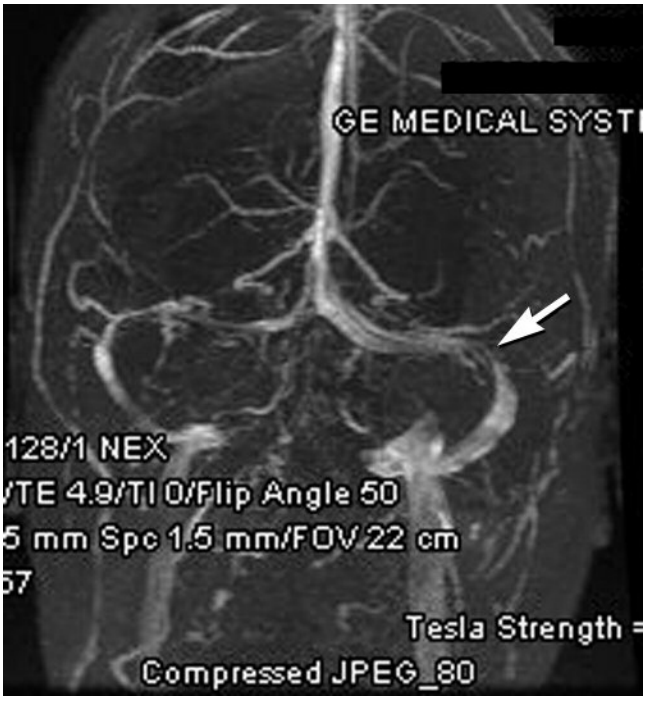

FIG. 7. Case 2. An MR venogram showing high-grade stenosis of both transverse sinuses. *Arrow* indicates the point of constriction of the transverse sinus aided by the stent.

The patient underwent retrograde venography. A venous stent was placed to treat a severe pressure gradient across the point of stenosis from 19 mm Hg to 5 mm Hg. Afterward, the gradient was no longer present. All sinus pressures averaged 5 mm Hg. Monitoring on 2 later occasions showed that her ICP was normal. Unfortunately, she continues to have headaches.

Commentary

Venous obstruction or stenosis causes hydrocephalus but only in infants and children with open fontanelles. Sainte-Rose et al.[37] recognized this phenomenon in several subsets of infants with hydrocephalus, particularly in the context of achondroplasia. In one such case they successfully treated the hydrocephalus with a venous bypass from the transverse sinus to the jugular vein. In older children and in adults with fixed skull volumes, the obstruction of venous outflow, as in the superior vena cava syndrome or after bilateral radical neck dissections, leads to pseudotumor cerebri and not to hydrocephalus. Pseudotumor cerebri develops because ICP can increase enough to force CSF from the intracranial compartment. The CSF compartments do not continue to expand as they would in babies.

These patients with NVH have several unique characteristics. In our clinic, they are often among the brightest of the shunt-treated patients. Presumably, the cause of their hydrocephalus is not a fundamental malformation of the brain itself. Rather, an obstruction to CSF flow outside the brain leads to distension of the ventricles. Usually, however, the volume of brain is normal and the head is big. If untreated, the head as well as the ventricles remains large throughout life. Many such individuals lead a normal life, and the hydrocephalus is discovered much later in life.

The second issue relates to the diagnosis of aqueductal stenosis. Many and probably most of these patients are found to have aqueductal stenosis based on imaging findings. In the genetic model of the HTX rat, which has a condition usually referred to as noncommunicating hydrocephalus or aqueductal stenosis, the ventricles enlarge before the aqueduct can be shown to be closed on imaging studies.[22] Early it was recognized that in patients with presumed aqueductal stenosis, CSF flow was open between the third and fourth ventricles after a shunt was placed.[2,21] The patient in Case 2 is 1 of 3 patients who have undergone ETV for documented aqueductal stenosis. After the floor of the third ventricle was perforated, the aqueduct was clearly seen to open.[29] As discussed, drainage of the lateral ventricle in patients with shunts leads to a smaller ventricle on the side that is being drained.[13,17,35] This functional obstruction of the foramen of Monro has been documented in our greyhound dog model of CSF dynamics. In that study, pressure differentials from the contralateral and third ventricles were 2 mm Hg higher than in the drained ventricle. Anatomical studies and cisternograms of these dogs showed that this pressure differential was due to the displacement of the intact septum pellucidum onto the head of the caudate nucleus.[35]

In patients with pseudotumor cerebri or NVH, communication between the CSAS and the ventricle is free. If ICP is high enough and there is no shunt, the CSF is absorbed. When a ventricular shunt is inserted, the CSF drains through either the shunt or normal pathways. Assuming that the opening pressure of the valve is lower than the pressure required to overcome the 5–mm Hg pressure differential between the CSAS and the dural venous sinuses, all CSF will flow through the valve. When the pressure within the ventricle falls low enough, the foramen of Monro closes. The size of the ventricle containing the shunt decreases and is displaced inward by distention in the CSAS that cannot be reduced. The result is temporary or permanent occlusion of the ventricular catheter as well as symptoms and signs of increased ICP.

In mild cases, very high pressure valves with devices that retard siphoning may increase pressure in the shunted ventricle enough to prevent distention of the CSAS. If so, the patient is asymptomatic. If not, a strategy in which the CSF is balanced between the ventricles is needed. Effective strategies include LP shunting.[14,15,20,32]

Negative-Pressure Hydrocephalus

To explain the enigmatic conditions of NPH and pseudotumor cerebri in the context of our multicompartmental model, we invoked the concept of stiffness or turgor (Kb) of the brain.[26] In our initial concept, Kb was considered a constant for each individual but would be affected by age, stroke, head injury, or radiation therapy. This concept was only partially correct. It quickly became obvious that brain turgor was a rapidly changing variable that primarily depended on cerebral blood volume.

Other authors have described this viscoelastic property of the living brain as brain compliance. We considered this term inappropriate because compliance is a precise term defined as a change in volume divided by a change in pressure ($\Delta V/\Delta P$). We therefore defined the Kb factor in our equations as brain turgor. In our report on this stratagem,

we described a young woman with hydrocephalus related to a cerebellar hemangioblastoma whose negative-pressure hydrocephalus was managed by manipulating brain turgor through the application of a gentle cervical tourniquet.[26] Subsequently, we have had an opportunity to treat several more patients with such a tourniquet and have come to understand the important role of the CSAS in the pathophysiology of this condition.

Illustrative Case 3

This 27-year-old man with neurofibromatosis Type 1 was admitted to our service in extremis in a coma with decerebrate posturing. A decade earlier he had undergone shunt treatment for hydrocephalus caused by aqueductal stenosis. He had also undergone a craniotomy for a hypothalamic chiasmatic astrocytoma and was blind in his right eye. Imaging studies showed that his lateral and third ventricles were severely enlarged. He was taken urgently to the operating room where he underwent a revision of the shunt with valve replacement. However, no clear source of shunt malfunction was found and his condition failed to improve after the revision.

An EVD was placed for assured drainage and ICP monitoring. His ICP was −15 mm Hg, and a flow study revealed excellent flow through the shunt. For CSF to be drained from the EVD, the drainage height had to be maintained 20 cm below the level of the head. With adequate CSF drainage, the ventricles returned to their normal size and the patient awoke without neurological deficit. Every attempt to raise the drainage height to normal levels resulted in marked increases in ventricular size and somnolence or coma.

Based on our previous experience with using cervical venous tourniquets, we applied an elastic bandage to the patient's neck to retard jugular vein flow. This treatment normalized the size of his ventricles and his ability to tolerate normal ICP. The EVD was removed, and the patient was instructed to wear the tourniquet except while showering. A few months later the patient was admitted to the emergency room with decerebrate rigidity. His pulse rate was 160 bpm, and his blood pressure was 180/130 mm Hg. He was taken urgently to undergo diagnostic imaging with the intent of transporting him directly thereafter to the operating room for shunt repair. On the way to imaging, he was fitted with a neck wrap. By the time the scan was finished, he was fully awake and without neurological deficits.

After these maneuvers, the patient underwent placement of an ETV but still required a shunt. After undergoing an ETV, however, he no longer required a neck wrap nor has he during 15 subsequent years of follow-up.

Recently this patient was admitted to the neurosurgical service for incapacitating headaches associated with no change in ventricular volume or neurological condition. Monitoring showed that his ICP was −15 to −20 mm Hg in the erect position. Magnetic resonance imaging showed intense dural enhancement consistent with spontaneous intracranial hypotension. Further evaluation showed CSF leakage into the epidural space in the lumbar region, presumably related to dural ectasia of his neurofibromatosis. His headaches and intracranial hypotension had responded only transiently to epidural blood patches. Subsequently, he underwent a multilevel laminotomy from T-11 to L-4. The dura was found to be incompetent. Multiple leaks were detected over the course of the exploration, and the thecal sac was extremely thin. The dura was repaired where the leaks were visible, and the entire area was covered with DuraGen (Integra LifesSciences Corp.). The ICP was monitored for 72 hours postoperatively, including when the patient was standing erect, and it was found to be normal. The follow-up is brief, but the results have been reassuring. Unlike his condition before the ETV, the open flow of CSF from the ventricles to the subarachnoid space prevented ventricular expansion at the time that the patient developed spontaneous intracranial hypotension.

Commentary

What was accomplished by wrapping the patient's neck? The underlying theory was that the brain was soft and nonexpansile. Its low turgor precluded the CSF from being pushed out through the shunt or EVD. Therefore, a gentle cervical tourniquet would impede venous drainage and lead to a stiffer brain that could cause the CSF to egress. This mechanism likely was involved. In retrospect, however, when the patient was doing well, his CT scan showed normal-sized ventricles, significant prominence of the CSAS, and distention of the basal cisterns. These observations suggest that a second function of the wrap was to increase dural venous sinus pressure, which led to distention of the CSAS. As the brain was pushed inward, CSF was displaced from the ventricular system and the patient's clinical status improved. In this situation ETV prevents selective drainage of the CSAS and low-pressure ventriculomegaly.

Subsequently, we have treated 4 other young adults for negative-pressure hydrocephalus with a neck wrap. These patients shared several attributes. None had undergone shunt treatment during infancy, and all developed hydrocephalus from a definable secondary cause: 1 from an arachnoid cyst, 1 from a tectal glioma in the context of neurofibromatosis, and 2 from postoperative meningitis after undergoing far-lateral approaches for the treatment of skull base abnormalities. In all cases CSF flow from the ventricular system was obstructed completely as proven by injection of the myelographic dye and rapid performance of CT scanning.

The syndrome of negative ICP has been treated and discussed by others, probably first by Pang and Altschuler[24] in Pittsburgh. The clinical presentation of their patients was similar to that of our patients. Each of their patients was treated with prolonged external ventricular drainage until they recovered. Dias and colleagues[7] reported on a series of patients whose shunts seemed to fail after they had undergone lumbar puncture. Subsequently, the shunt failure resolved. Le and colleagues[15] reported that lumbar shunts selectively drained the CSAS after they observed that the lateral ventricles enlarged when an LP shunt was inserted for the treatment of SVS.

The common features among these patients are the presumed or documented complete obstruction of CSF outflow from the ventricular system and the presence of a shunt.[30] For some reason, the CSAS was drained in these patients who underwent shunt treatment for intraventricular obstructive hydrocephalus. The ICP then decreased as CSF was lost from the CSAS either through a shunt or a leak after placement of an LP shunt. The ICP was therefore lower than the opening pressure of the valve mechanism or level of drainage from the ventricle.

As long as the pressure remains low, there is no CSF flow. The CSF accumulates in the ventricles until ICP becomes high enough to reopen the valvular mechanism of the ventricular shunt. Drainage then resumes and the size of the ventricles decreases. The negative ICP is caused by the loss of CSF from the CSAS and not specifically by low brain turgor.

Selecting Patients for ETV

During a presentation by Dr. Jonathan Baskin on our work on programmed shunt removal as the ultimate treatment for SVS, the late Professor Fred Epstein noted that the only criterion we had used to attempt ETV on symptomatic patients was the presence of enlarged ventricles after clamping of an external drainage system.[1] This observation by Professor Epstein was indeed true, but we had not recognized it as a criterion for ETV before his comments. In that paper 80% of patients whose ventricles had expanded at the time of shunt removal and clamping of the EVD and who did not have hydrocephalus related to spina bifida underwent successful ETV and were rendered shunt free. These patients can become shunt free regardless of the initial cause of their hydrocephalus. Endoscopic third ventriculostomy is an internal bypass between the third ventricle and the CSAS. Figure 8 is an artist's representation of what actually occurs during an ETV, showing the bypass of the exit foramina of the fourth ventricle and the basal cisterns separating the spinal subarachnoid space from the CSAS. Ventricular distension only occurs if there is an obstruction between the ventricles and the CSAS. The interpeduncular cistern is part of the latter and is accessed by the ETV.

Illustrative Case 4

This 76-year-old man presented with hemorrhage from a vertebral artery aneurysm. The aneurysm was clipped uneventfully through a far-lateral approach. Postoperatively, he did well. However, he developed a pseudomeningocele at the operative site and subsequently meningitis developed. At this point he developed acute hydrocephalus and became exceedingly somnolent.

An external drain placed urgently failed to drain at head level and had to be lowered to 15 cm below the level of the head to drain the CSF. With this drainage, the size of the patient's ventricles decreased moderately. He awoke and followed commands but could not speak. During the next 6 weeks several attempts were made to place internal shunts, but his ventricles expanded each time his shunt was internalized. Throughout this time, CSF continued to collect under the flap and his neurological condition deteriorated. He underwent a tracheostomy and gastrostomy but could not be discharged to a nursing home without an internal shunt.

At this point he was scheduled for ETV (Fig. 9 *left*), which discomfited the residents and staff because he was considered to have communicating hydrocephalus. Iodinated myelogram dye (8 ml) was injected into the ventricle through a preexisting external drain, and his skull base was imaged during the next 30 minutes. Predictably, CSF flow into the basal cisterns through the foramina of Luschka and Magendie was absent (Fig. 9 *right*).

Based on our earlier discussion, the negative-pressure hydrocephalus likely resulted from the pseudomeningocele and possibly from a CSF leak into the mastoid air cells.

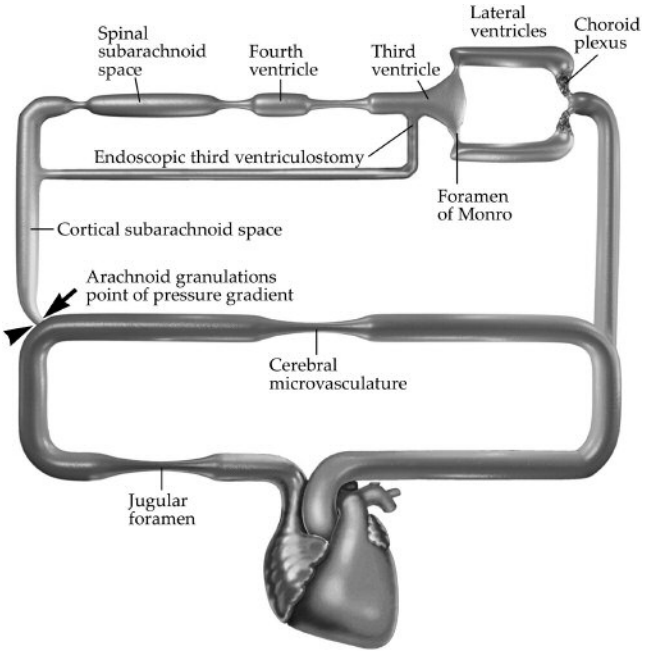

FIG. 8. Illustration representing the result of an ETV, which bypasses all points of obstruction except between the CSAS and dural venous sinuses. Modified from Rekate HL: Adults with hydrocephalus treated in infancy and childhood. **Semin Neurosurg 13:**19–28, 2002. Used with permission from Barrow Neurological Institute.

When clinicians are confronted with a similar situation, the pseudomeningocele should be treated early in a patient's course if possible.

Commentary

The concept of communicating hydrocephalus is archaic and should be abandoned. It derives from the extraordinary work of Dandy and his colleague Blackfan.[4–6] They classified hydrocephalus as communicating and noncommunicating (or obstructive) based on their ability to recover a supravital dye injected into the ventricle after a spinal tap. This concept led to several important attempts to treat hy-

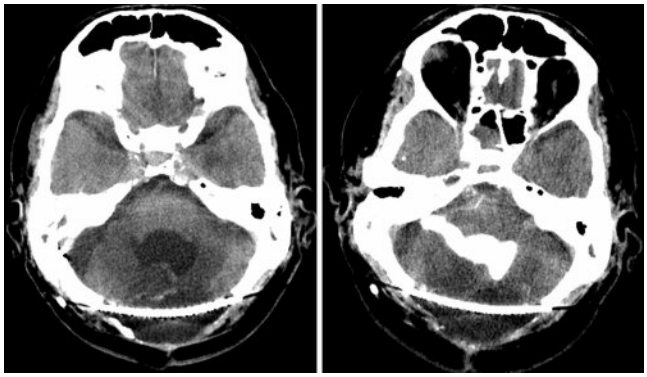

FIG. 9. Case 4. *Left:* A CT scan obtained in a patient with negative-pressure hydrocephalus and presumed communicating hydrocephalus. The size of the patient's ventricles changed, depending on the level of drainage of the EVD. *Right:* A CT scan obtained after the injection of Iohexol dye showing complete obstruction of CSF outflow from the fourth ventricle into the CSAS.

drocephalus using third ventriculostomy and ablation of the choroid plexus.

Subsequently, Ransohoff and colleagues[25] carefully studied the dynamics of hydrocephalus. They suggested changing the nomenclature so that obstructive hydrocephalus would be called intraventricular obstructive hydrocephalus, and communicating hydrocephalus would be termed extraventricular obstructive hydrocephalus. For almost a half century, this brilliant set of definitions has essentially gone unrecognized.

All hydrocephalus is obstructive, and we now have the tools to define the point of obstruction in all cases. As stated, NVH is a unique subtype of hydrocephalus in infants with distensible heads. It is the only type of hydrocephalus in which the ventricular system and the CSAS communicate freely. All the other types result from a failure of CSF to flow to the CSAS. Substituting the name extraventricular obstructive hydrocephalus for communicating hydrocephalus clarifies that some forms of communicating hydrocephalus can be treated well by ETV. Only a terminal failure of CSF absorption could not be treated with ETV. In such a case, the ventricles would not expand.

Third Ventriculostomy for NPH

The well-recognized condition of NPH was originally described by Hakim and Adams.[10] It consists of a recognizable pattern in the elderly of gait disturbance, incontinence, dementia, and enlarged ventricles on imaging studies. Recent publications have divided NPH into idiopathic and secondary forms; with shunting, the latter has a better prognosis than the former.[18]

Typically, the secondary forms include patients with a history of head trauma or aneurysmal subarachnoid hemorrhage. These conditions lead to extraventricular obstructive (previously communicating) hydrocephalus, which has been assumed to preclude its treatment by ETV. Actually, however, both posthemorrhagic hydrocephalus and postmeningitic hydrocephalus are readily treated using ETV.[38]

Initially after hemorrhage, filtration difficulty at the level of the arachnoid villi leads to increased ICP without ventriculomegaly. In the late stages severe arachnoid thickening in the area of the foramen magnum around the cerebellum restricts CSF flow into the CSAS.

The cause of idiopathic NPH is unclear, but speculation proposes a 2-hit phenomenon. Essentially, the causes of idiopathic NPH would be the same as for secondary NPH except that they are unrecognized and probably begin early in life.[3] Head circumference in many of these patients is greater than the 98th percentile, and their outcome is particularly good. Idiopathic NPH is not a single-disease process; nonetheless, it can be studied.

Meier et al.[19] suggested that when the floor of the third ventricle dips inferiorly, patients are excellent candidates for ETV. This suggestion implies the presence of an unrecognized obstruction between the third ventricle and the CSAS.[19] A growing number of studies have shown the value of ETV in treating idiopathic NPH.[9]

Radionucleotide cisternography is an older study that was used to select patients for shunt treatment when NPH had been suspected. This test required a spinal tap and injection of a protein-bound radionucleotide tracer. In healthy individuals the tracer is found in the ventricles of the brain in ~ 6 hours. Over the next 24 hours, the dye is distributed over the convexities and begins to clear. In patients with NPH, the dye enters the ventricles and does not clear. The flow of the tracer over the convexities takes $>$ 72 hours to reach the dural venous sinuses. The implication is that the obstruction is at the interface between the spinal subarachnoid space and the CSAS. Therefore, such patients are reasonable candidates for ETV. We have tried ETV in 2 patients who did not want to undergo shunt treatment and who showed failure of clearance of the CSF from the ventricle on cisternography. Their gait and incontinence improved a reasonable amount. The implication of this test is that an incomplete obstructive process is present between the ventricular system and the CSAS, and that the obstruction may be bypassed by ETV thereby confirming the obstructive nature of the condition.

Future Studies

We are in the earliest stages of assessing the volume of the CSAS and ventricles in both normal and pathological situations. These data may help with treatment decisions and may improve understanding of the hydrocephalic conditions of individual patients. We are attempting to measure the volume of the CSAS and ventricles with MR imaging using the FIESTA (fast imaging employing steady-state acquisition) Protocol and Analyze 7.0 software (AnalyzeDirect Inc.).

The complex geometry of the CSAS and ventricles makes this process difficult. The ventricles and CSAS are rendered 3 dimensionally. The process is tedious and time consuming. Normative data are now being collected. The pre- and postoperative volumes of the ventricles and CSAS in various hydrocephalic states need to be established and interpreted appropriately.

Over and above these proposed studies, the concepts presented here lend themselves to careful prospective analysis by others interested in the pathophysiology of hydrocephalus and in the care of children and adults with complex problems of CSF dynamics. Although prospective randomized trials would be ideal, careful collection of data on clearly defined populations of patients with rare presentations from multiple centers would be an effective way to test these hypotheses (Table 1). Our shunt-removal protocol (Fig. 10) has proved useful in assessing patients with severe problems with the function of their shunts. Prospective application of this protocol and sharing the information in a central database would help improve our understanding of this lifelong condition.

Conclusions

Previously, the important role of the CSAS in understanding the pathophysiology and treatment of hydrocephalus has not been analyzed systematically. Abnormalities related to the CSAS explain enigmatic conditions such as NVH and negative-pressure hydrocephalus. The CSAS is the final step before CSF is absorbed. Therefore, it is important to understand the role of the CSAS in the management of hydrocephalus, why its exclusion from the ventricular CSF makes a patient a good candidate for ETV, and

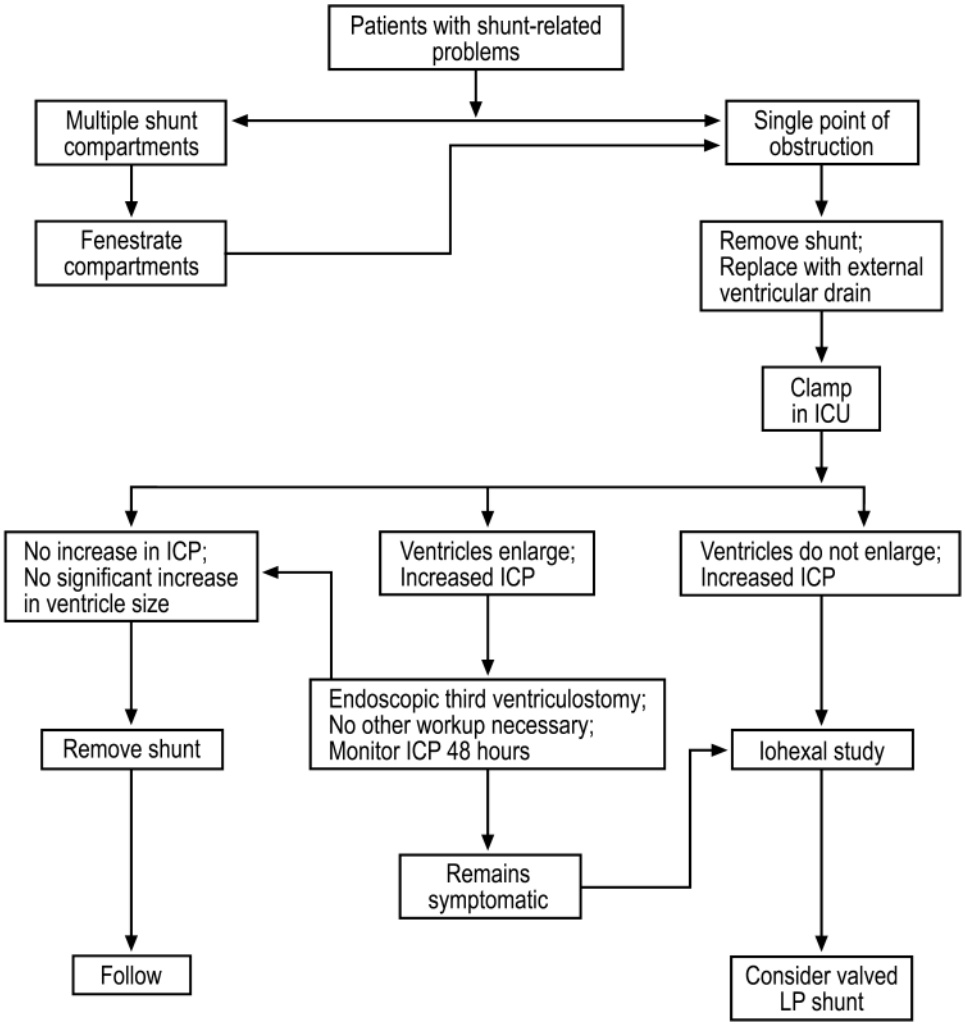

FIG. 10. Algorithm for the programmed removal of ventricular shunts with 3 possible outcomes. ICU = intensive care unit. From Rekate HL: Slit ventricle syndrome or syndromes: Diagnosis and management, in Cinalli G, Maixner WJ, Sainte-Rose C (eds): **Pediatric Hydrocephalus.** Milan: Springer, 2004. Used with permission from Barrow Neurological Institute.

why accessing this rather large reservoir of CSF is necessary in disease processes such as pseudotumor cerebri and the analogous NVH.

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Manuscript submitted October 16, 2007.
Accepted February 27, 2008.

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