

# Pediatric Hydrocephalus: Current State of Diagnosis and Treatment

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## Practice Gap

Hydrocephalus is a neurologic condition that requires lifelong vigilance by various health care professionals. Nonsurgical clinicians treating children with hydrocephalus, with or without shunts, often have questions about disease recognition, shunt infection, and shunt malfunction. Imaging modalities such as nonsedated magnetic resonance imaging and nonshunt endoscopic surgery have changed the landscape of the primary pediatric clinician's interaction with this patient population. This article addresses the practice gap between pediatric outpatient and neurosurgical management of children with hydrocephalus in both the acute and chronic care settings.

**Objectives** After completing this article, readers should be able to:

1. Understand basic pathophysiology related to hydrocephalus and available treatments.
2. Recognize presenting signs and symptoms of hydrocephalus.
3. Recognize when neurosurgical consultation is appropriate and manage hydrocephalus until a neurosurgeon is available.

## ETIOLOGY, DIAGNOSIS, AND PRESENTATION

Hydrocephalus in the pediatric population is characterized by an initial increase in intraventricular pressure, resulting in pathologic dilation of the cerebral ventricles with an accumulation of cerebrospinal fluid (CSF). Although the pressure may be slight or severe, the balance between CSF production, flow, and absorption is lost in hydrocephalus. This condition is a significant cause of morbidity and mortality within the pediatric population, with a prevalence of approximately 6 in 10,000 live births and a neonatal mortality rate before initial hospital discharge of 13%. (1) The impact of this complex neurologic pathology on society is extremely large. According to nationally representative data sets, every year pediatric hydrocephalus accounts for 38,200 to 39,900 hospital admissions, 391,000 to 433,000 hospital days, and \$1.4 to \$2.0 billion in total hospital charges in the United States. (2)

**AUTHOR DISCLOSURE** Drs Wright, Larrew, and Eskandari have disclosed no financial relationships relevant to this article. This commentary does not contain discussion of an unapproved/investigative use of a commercial product/device.

In the healthy child, CSF is primarily produced in the choroid plexus, which is attached to the ependyma (lining) of the ventricles. Choroid plexus exists in all 4 ventricles, but most CSF is produced in the lateral ventricles. CSF travels from the lateral ventricles through the foramen of Monro to the third ventricle, where it passes through the cerebral aqueduct into the fourth ventricle. It exits the fourth ventricle through the foramina of Luschka and Magendie. CSF circulates in the subarachnoid space around the brain and spinal cord until it reaches arachnoid granulations. These are projections of the arachnoid membrane into the venous system adjacent to the superior sagittal sinus at the vertex of the skull, where it is absorbed. Normal and hydrocephalic anatomy is depicted in Fig 1.

The causes of hydrocephalus vary, but 2 broad subsets of the condition exist in the nomenclature: communicating and noncommunicating (ie, obstructive). They are differentiated by whether the normal anatomic flow is preserved within the cerebral ventricular system. In communicating hydrocephalus, as the name suggests, there is no blockage of fluid within the ventricular system and into the subarachnoid space, and fluid build-up is due to improper CSF absorption. In noncommunicating or obstructive hydrocephalus, a pathologic accumulation of CSF occurs because normal anatomic flow is impeded at a point within the ventricular system. An example of this is (cerebral) aqueductal stenosis which causes dilation of the third and lateral ventricles. This distinction is vital for differentiating between causes and is also valuable in the decision-making process of choosing the most appropriate treatment.

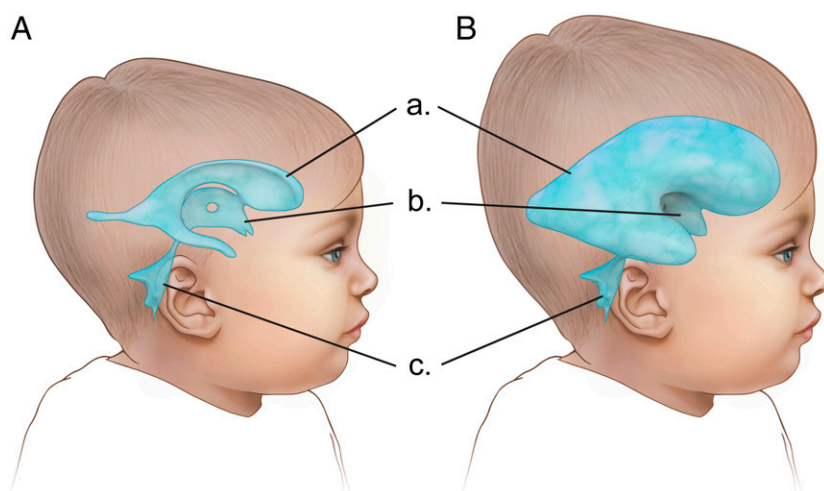
Congenital causes of hydrocephalus include Chiari malformations, primary aqueductal stenosis, intraventricular cysts or masses, gliosis due to germinal matrix hemorrhage

or intrauterine infection, Dandy-Walker cysts, and X-linked hydrocephalus (*L1CAM* disorder). (3)(4) Most pediatric hydrocephalus cases are congenital and present at birth or soon after, but definitive numbers are difficult to ascertain due to regional and genetic variability and inconsistent classification. For example, infantile posthemorrhagic hydrocephalus (PHH), a condition highly associated with prematurity, is commonly designated as congenital in some studies and acquired in others. Although the hemorrhage in PHH may initially cause blockage of the ventricular system and obstructive hydrocephalus, as blood resorbs into the subarachnoid spaces where CSF is normally resorbed, inflammation may hamper CSF resorption and cause communicating hydrocephalus.

Acquired hydrocephalus in children is commonly due to infections, intracerebral hemorrhage (particularly intraventricular and subarachnoid hemorrhage), and neoplastic and non-neoplastic mass lesions. Globally, postinfectious hydrocephalus is the most common cause of neonatal and pediatric hydrocephalus. (5) However, in the United States, PHH comprises the majority of pediatric hydrocephalus cases.

Hydrocephalus is frequently noted at the time of presentation for newly diagnosed pediatric brain tumors causing obstruction of CSF flow. Studies have demonstrated its presence in more than 50% of pediatric brain tumor cases at the time of diagnosis and as the second most common comorbidity at presentation. (6)(7) Pediatric hydrocephalus due to brain tumors is typically caused by obstruction of CSF flow at the fourth ventricle by medulloblastomas, ependymomas, juvenile pilocytic astrocytomas, and choroid plexus tumors or cerebral aqueduct compression by pineal region tumors. On rare occasion, hydrocephalus can be caused by

**Figure 1.** A. Normal ventricular system. a. Lateral ventricles, b. Third ventricle, c. Fourth ventricle. B. Dilated ventricular system (ventriculomegaly) as could be caused by obstructive hydrocephalus or aqueductal stenosis, with enlargement of the lateral and third ventricles and preservation of normal volume of the fourth ventricle.



CSF overproduction, as with CSF-producing tumors such as choroid plexus tumors.

Neural tube defects, especially myelomeningoceles, are highly associated with congenital hydrocephalus. The impact of myelomeningoceles on cases of hydrocephalus is substantial, with studies in the 1970s demonstrating myelomeningocele-associated hydrocephalus to comprise approximately 33% to 50% of all congenital hydrocephalus cases. (8) The prevalence of myelomeningocele-associated hydrocephalus within the hydrocephalic population decreased in the 1990s and early 2000s to 17.2%, likely due to national recommendations for prenatal folic acid supplementation in 1992. (1)(9) Interestingly, myelomeningocele-associated hydrocephalus rates have also decreased in countries without folic acid supplementation programs, likely due to improved prenatal diagnosis leading to pregnancy termination. (10)

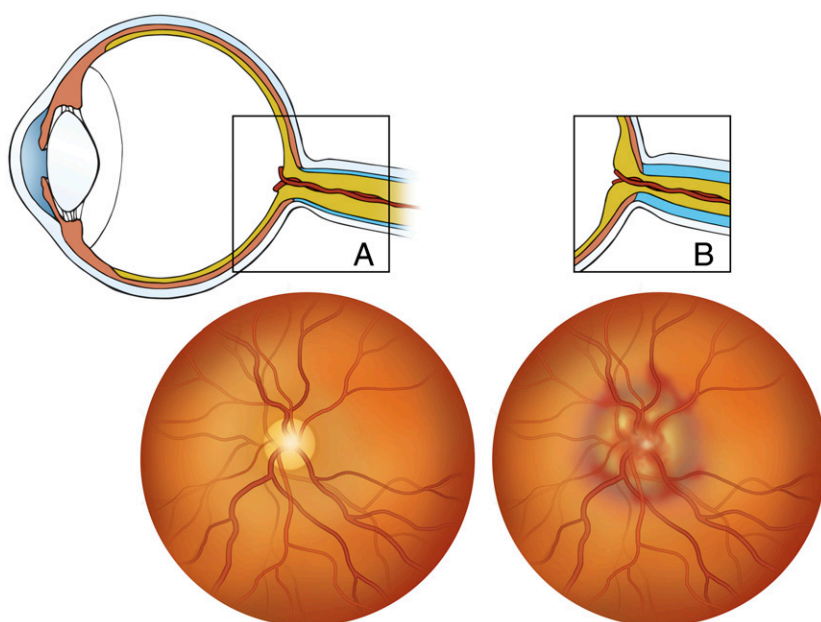
Children with myelomeningoceles have varying degrees of spinal cord herniation through their spina bifida defect. Myelomeningoceles may be open with persistent leakage of CSF or covered by tissue without a leak. Either way, newborns with myelomeningoceles have type II Chiari malformations, which are characterized by herniation of medullary, and at times cerebellar, tissue through the foramen magnum, causing dysfunctional brainstem cytoarchitecture at birth. One cause of hydrocephalus in this patient population is this abnormal anatomic arrangement at the skull base, which may cause deformation of the fourth ventricle and obstruction of the fourth ventricular outflow

through the foramina of Luschka and Magendie. Other causes of hydrocephalus are not as easily identifiable and are from a mismatch of CSF absorption to CSF production. Overall, the incidence of symptomatic hydrocephalus is estimated to be 80% in children with myelomeningoceles. (11)

Although the overall prevalence of hydrocephalus remains stable, there has been an increase in obstructive hydrocephalus within the hydrocephalus population. (1) This is likely due to the growing number of preterm neonates and the heightened risk of PHH and obstructive hydrocephalus in low birth weight neonates. (12)

## SIGNS AND SYMPTOMS

Hydrocephalus has myriad presentations, but it often manifests in a common pattern. In neonates, the dyad of “As and Bs,” apnea and bradycardia, is notable and is part of the Cushing triad for increased intracranial pressure: hypertension, bradycardia, and irregular respirations. (13) However, these symptoms are not always seen. In infants, before closure of the fontanelles, hydrocephalus can be characterized by macrocephaly, bulging, or tenseness of the anterior (or posterior) fontanelle, splaying of the cranial sutures, irritability, lethargy, and vomiting. In older children, more common presentations include headaches, visual complaints (blurry or spotty vision), and decreasing levels of consciousness. Papilledema is an important sign in children of any age and may be associated with elevated intracranial



**Figure 2.** A. Fundus with normal optic disc. B. Fundus with bulging disc, increased cerebrospinal fluid (blue) and pressure in the subarachnoid space, and compressed optic nerve (yellow).

pressure. (Fig 2). Of note, the absence of papilledema is not a reliable indicator of the absence of hydrocephalus because the occurrence of papilledema may be delayed. (14) In rare cases, specific neurologic deficits, such as cranial nerve III, IV, and VI palsies, have been noted as a presentation of acute or chronic hydrocephalus. (15) Hydrocephalus varies in acuity of presentation according to the age of the child, cause of hydrocephalus, and whether the child is treated with a shunt.

### Neonates

In neonates, increasing head size is often the most common presentation of hydrocephalus, but the fontanelle may bulge and the sutures may become abnormally splayed as well. (13) Some patients exhibit apnea and bradycardia, although other causes of these signs must be investigated because none are specific to hydrocephalus. Lethargy and irritability may also be present at this age, but these symptoms are more apparent as infants age and their wakeful periods become more dominant.

### Infants

Apnea and bradycardia associated with hydrocephalus decrease in significance after the neonatal period, but head size and macrocephaly remain key features. Changes in behavior and level of consciousness are easier to evaluate in infants, with lethargy and irritability becoming more prominent signs. Vomiting and weight loss may also be important factors in bringing patients to medical attention. These, along with the aforementioned clinical signs, point to a diagnosis of uncontrolled hydrocephalus.

### Children

After the fontanelles and sutures have closed, hydrocephalus may present more suddenly because cranial compliance has decreased markedly. As children grow, the brain water content drops from approximately 80% to 85% in newborns to 70% to 75% in children, substantially decreasing brain compliance. Closure of the fontanelles, along with increased brain volume, makes children much more vulnerable to acute malfunctions with treated hydrocephalus and new presentations of undiagnosed decompensated hydrocephalus. The presentation of hydrocephalus in this population also differs due to the age of the patient. Patients can now express symptoms such as headaches as well as exhibit signs of lethargy and irritability. Focal neurologic deficits can also be seen, including bilateral sixth cranial nerve palsies, which manifest as the inability to abduct the eyes. (16)

Certain clinical signs are considered manifestations of late-stage presentation of hydrocephalus and usually require more urgent intervention. The 2 most common late-stage

presentations are Parinaud syndrome (dorsal midbrain syndrome) and new-onset seizures. Parinaud syndrome (Fig 3) is characterized by upgaze palsy; pseudo-Argyll Robertson pupils or pupillary light-near dissociation in which the pupils are able to accommodate but unable to react to light; convergence-retraction nystagmus, in which upon attempted upward gaze the eyes converge and are pulled into the orbit; and abnormal eyelid retraction (Collier sign). Seizures can also appear as an advanced sign of hydrocephalus, but clinicians must investigate other possible causes of seizure. If other causes are not immediately found, intervention for advanced-stage hydrocephalus should be pursued.

### MONITORING OF HYDROCEPHALUS

Although imaging is often used to diagnose hydrocephalus, the utility of serial head circumference measures in the long-term management of hydrocephalus cannot be stressed enough. Measured occipital frontal head circumference (OFC), or simply head circumference should be plotted on appropriate age-adjusted growth curves, with specific growth charts available for conditions such as prematurity and achondroplasia. Signs that warrant further investigation include upward deviations in percentiles or crossing percentile curves; continued head growth of more than 1.25 cm/week; OFC approaching 2 standard deviations above normal; and head circumference out of proportion to patient's weight or height, even if it is within normal limits for age. (17)(18) These are not definitive criteria for diagnosis, though, because head growth rate slows substantially after the infant period and other symptoms must also be present to diagnose hydrocephalus.

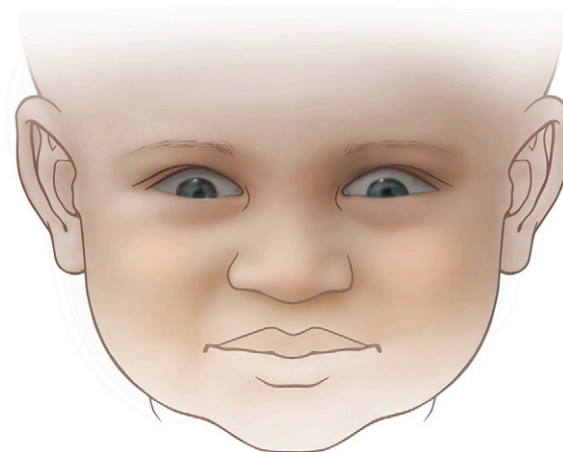


Figure 3. Parinaud syndrome with characteristic upgaze palsy (sunset sign).

It is important to note other causes of enlarged head circumference, such as familial macrocephaly. The Table contains a list of differential diagnoses for macrocephaly. If a child has normal neurologic examination findings, normal development, no syndromic clinical features, and no family history of abnormal neurologic or developmental problems, the head circumference may be due to familial traits. Weaver curves present predicted head growth patterns based on parental head circumference. An inherited component to increased head circumference can be surmised if the child falls within the range determined by his/her parents' head sizes. (19) If a child has no concerning clinical findings and has an OFC within normal ranges on the Weaver curves, radiologic evaluation is deemed unnecessary. Although OFC measurement continues to have some value as a child gets older after sutures fuse, head circumference is less likely to change due to hydrocephalic conditions. For these older patients, overall clinical assessment and findings on imaging must be taken into consideration.

## IMAGING

### Ultrasonography

Ultrasonographic imaging of the brain is performed through the anterior (and rarely, posterior) fontanelle of the head. Ultrasonography has the most utility within the first 12 to 18 months after birth, while the anterior fontanelle is patent, although less of the lateral aspects of the intracranial compartment are visible in the last third of this

timeframe because of the small size of the remaining patent fontanelle. (20) Ultrasonography produces poor clarity of the third and fourth ventricles, but the shape and size of the lateral ventricles may be readily visualized. Although its detail and resolution are often insufficient for primary diagnostic use, ultrasonography can be very useful for serial assessments of ventricular dilation in the context of intraventricular hemorrhages (IVHs) or surgical interventions. Head ultrasonography can also be helpful in differentiating hydrocephalus from benign extra-axial fluid collections of infancy, also confusingly referred to as external hydrocephalus. (21)(22) This is a common condition of infancy that may present with macrocephaly but is usually self-limiting and is characterized by excess fluid in the subarachnoid spaces, particularly overlying the frontal and parietal lobes. The finding of benign extra-axial fluid of infancy in the setting of macrocephaly without neurologic deficits or delayed milestones is not concerning and may be monitored with follow-up clinical examinations without repeat imaging. Continued increase in OFC inconsistent with an asymptotic curve paralleling the normal percentile curves, abnormal neurologic findings, or regression of neurologic milestones warrant a more detailed evaluation with brain magnetic resonance imaging (MRI).

### Magnetic Resonance Imaging and Computed Tomography

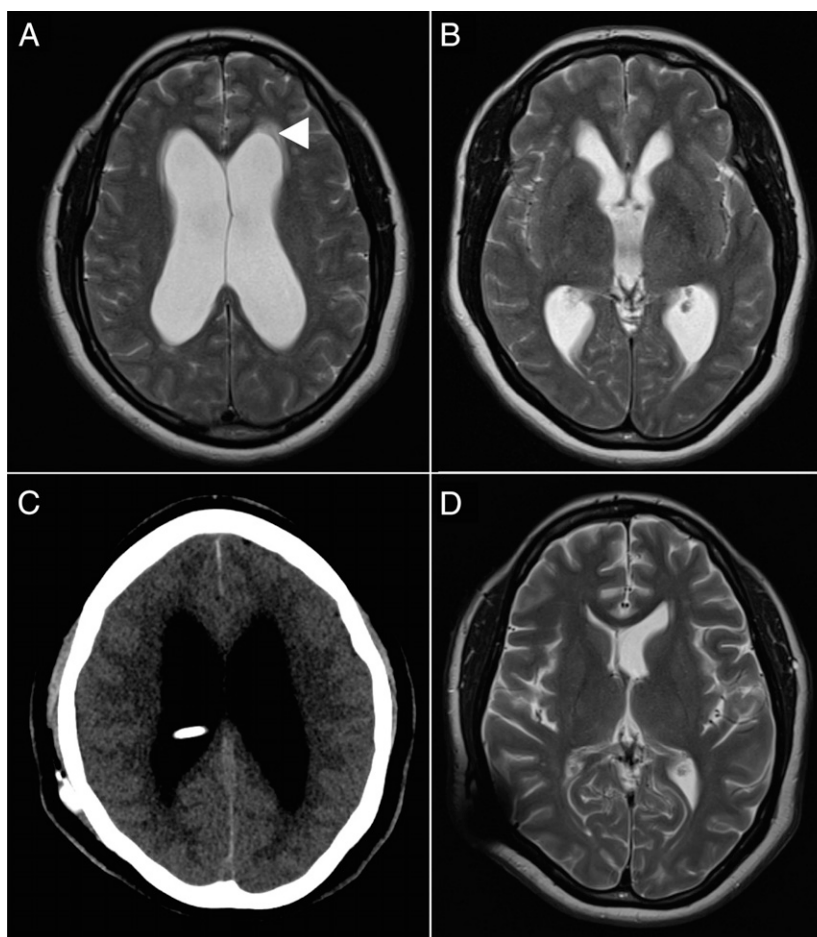
Both computed tomography (CT) and MRI are used in the diagnosis of hydrocephalus and its complications as well as for surgical planning. Figure 4 demonstrates a hydrocephalic brain in both imaging modalities. Many methods and criteria have been devised to define hydrocephalus, although no single one is universally accepted. The most reliable signs for differentiating hydrocephalus from ventricular enlargement due to white matter atrophy (hydrocephalus ex vacuo) are enlargement of the third ventricle in the anterior and inferior aspects, dilation of the temporal horns of the lateral ventricles, and a less defined ventricular border due to periventricular CSF forced across the ependymal walls of the ventricles. This is called transependymal flow (Fig 4A). (20)(23)

Although both MRI and CT scan can delineate the ventricular system, MRI yields greater anatomic detail and is much more diagnostic of the underlying cause of hydrocephalus. Such details as arachnoid membranes and presence of transependymal flow are much more readily identifiable via MRI. If a tumor or other pathology is causing hydrocephalus, MRI is far more useful in diagnosis and planning management.

TABLE. **Conditions Associated With or Causing Increased Head Circumference**

• Hydrocephalus
• Subdural hematoma/hygroma
• Benign extra-axial fluid collections of infancy (external hydrocephalus)
• Inherited familial macrocephaly
• Tumors (may or may not be associated with hydrocephalus)
• Fragile X syndrome
• Overgrowth syndromes (eg, Sotos syndrome and Weaver syndrome)
• Lysosomal storage diseases
• Leukodystrophies
• Hemimegalencephaly/megalencephaly (can be familial or nonfamilial)

**Figure 4.** Single patient before (A and B) and after (C and D) ventriculoperitoneal shunting. A. Axial T2 magnetic resonance imaging (MRI) with the arrowhead demonstrating transependymal flow. B. Axial T2 MRI with enlarged frontal and occipital horns. C. Axial computed tomography (CT) scan demonstrating placement of shunt through the parietal approach. D. Axial T2 MRI 2 months after shunting demonstrating decreased volume in cerebral ventricular system.



MRI also has the advantage of not emitting ionizing radiation. There is an emerging shift in pediatric practice to evaluate neurologic conditions, such as hydrocephalus, with fast-sequence (nonsedation) MRI rather than CT scan. Studies have shown both modalities share similar sensitivity, specificity, and frequency of anxiolytic use, but MRI is free of radiation exposure. (24) The risk of radiation from CT scan in typical surveillance of hydrocephalus is high. It is estimated that for every 97 patients receiving standard head CT scans for hydrocephalus surveillance and management, there is 1 lifetime fatal cancer caused, and for low-dose CT scan protocols, 1 fatal cancer is caused for every 230 patients. (25) The various algorithms for rapid MRI typically have a scan duration of less than 5 minutes, which is comparable to CT imaging, although limited access to scanners can delay completion of these scans. (26) In the opinion of the authors, the benefits of increased image quality, diagnostic value, and absence of radiation are well worth the slight increase in acquisition time. In addition, the image acquisition time should improve as institutions

develop protocols for the use of MRI in evaluating hydrocephalus. We recommend that the use of CT scans in evaluating children for hydrocephalus be reserved for emergency situations in which fast MRI is not readily available.

## TREATMENTS

### Acute Management

It is crucial to recognize that an acute presentation of hydrocephalus after the cranial vault has closed is a clinical emergency that requires neurosurgical consultation. However, in some cases, particularly in neonates, the treatment can be deferred while the infant grows and becomes more able to tolerate surgical procedures. In some rare cases, the patient may no longer need a procedure if the cause for their underlying hydrocephalus has self-resolved (eg, IVH that has resorbed without scarring of extraventricular resorption pathways). Placement of temporary intraventricular reservoirs with intermittent transcutaneous reservoir

punctures is often used to treat neonates with progressive hydrocephalus and IVH. The rate at which these devices need to be converted to permanent CSF diversion varies with the severity of posthemorrhagic hydrocephalus; approximately 20% of those with grade III hemorrhage and 40% of those with grade IV hemorrhage require shunting. (27)

If permanent CSF diversion is necessary, determining the cause of hydrocephalus is often helpful in deciding the method of diversion. Whenever possible, it is preferable to limit the child's exposure to multiple procedures. Presentation in extremis with acute hydrocephalus often prevents immediate definitive management of the underlying cause, such as with obstructing tumors or hemorrhagic lesions (eg, ruptured arteriovenous malformation). In emergency cases such as these, external ventricular drainage (EVD) catheters can be placed at the bedside as a lifesaving procedure. EVDs are placed into the lateral ventricle through a small cranial opening and tunneled under the skin.

In the past, serial lumbar punctures, percutaneous ventricular aspiration (fontanelle tapping), and medical therapies have been used as treatments for neonatal hydrocephalus. These are no longer recommended in current guidelines. (28)

For children who have persistent head growth, neurologic deficits, or symptoms attributable to hydrocephalus, CSF diversion procedures are the standard of care. These procedures function by allowing CSF that is inadequately absorbed or trapped to escape through alternate pathways. The most common of these procedures is the ventricular shunt. However, minimally invasive procedures employing new endoscopic techniques have re-emerged as viable and effective alternatives to placement of indwelling shunt catheters.

### CSF Shunts

Ventricular shunts are a method for diverting CSF from the intraventricular space into an alternate absorptive space, thereby relieving intraventricular pressure. Catheters with distal perforations are connected to a flow/pressure-regulating valve that is tunneled under the skin and connected to distal tubing, which enters another cavity in which CSF is absorbed. These shunts are typically placed either frontally, with the catheter traversing the frontal lobe into the frontal horn of the lateral ventricle, or parietally, traversing the parietal lobe to the lateral ventricle as depicted in Fig 4C. The distal end of a ventricular shunt can be placed into various compartments for absorption. The location of the distal portion of the ventricular catheter contributes to the types of complications, malfunctions, and infections that may present after shunting.

### Ventriculoperitoneal Shunts

In most patients, the distal catheter is placed into the peritoneal space of the abdomen, where CSF mixes with peritoneal fluid and is absorbed by transcapillary osmotic diffusion and lymphatic drainage. This is called a ventriculoperitoneal (VP) shunt. The peritoneal space is typically the preferred location for the end of the distal catheter, but in some cases, infection, adhesions, or abdominal pathology preclude placement of a VP shunt. Distal catheters can also be placed in the right atrium of the heart (ventriculoatrial shunt) or the pleural space (ventriculopleural shunt). Figure 5 depicts VP and ventriculoatrial shunts.

### Endoscopic Third Ventriculostomy

In some cases of hydrocephalus, particularly obstructive hydrocephalus, the creation of a new CSF pathway is therapeutic. In an endoscopic third ventriculostomy (ETV), an endoscope is placed into the ventricular system, and the floor of the third ventricle and surrounding arachnoid planes are fenestrated (Fig 6). This permits the third ventricle to communicate with the CSF spaces surrounding the brain stem, allowing CSF to bypass obstructions distal to the third ventricle. There is also

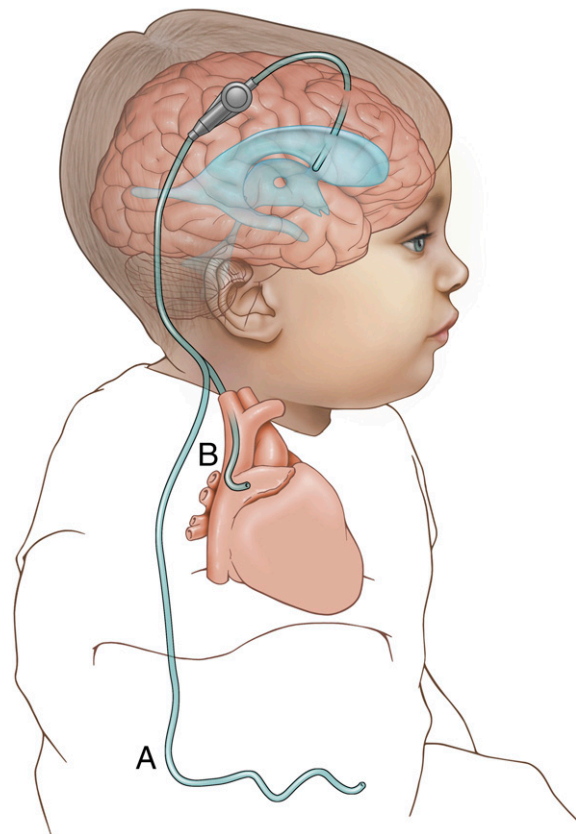


Figure 5. Ventricular shunting systems. A. Ventriculoperitoneal shunt. B. Ventriculoatrial shunt.

evidence to support use of ETV in cases of communicating hydrocephalus to restore the pulsatile movement of CSF, allowing for cisternal and spinal absorption of the fluid beyond the poor CSF absorption by the routine routes of arachnoid granulations. Recently, a multicenter pediatric hydrocephalus cooperative, the Hydrocephalus Clinical Research Network, has been reporting on the use of ETV in combination with choroid plexus cauterization (CPC) on newborns and infants. Traditionally, these methods had not been successful, but many believe that the lack of appropriate endoscopic technology and technique prevented the surgical procedure from abating the progressive hydrocephalus in these patients. Work from the Hydrocephalus Clinical Research Network has demonstrated successful management of newborn hydrocephalus with a multitude of causes using the ETV/CPC technique. (29) Currently, efforts are under way to assess prospectively endoscopic versus shunting techniques for treatment of pediatric hydrocephalus.

## OUTCOMES

As with any procedure, surgical treatment of hydrocephalus carries its own risks. Immediate procedural risks include strokes, hemorrhages (intraparenchymal or subdural), catheter misplacement resulting in a nonfunctioning shunt, need for immediate reoperation, and, in the rarest of cases, death. Following placement of the devices, shunts typically malfunction in 1 of 3 ways: mechanical hardware failure, infection, or overdrainage. The outcome of patients with

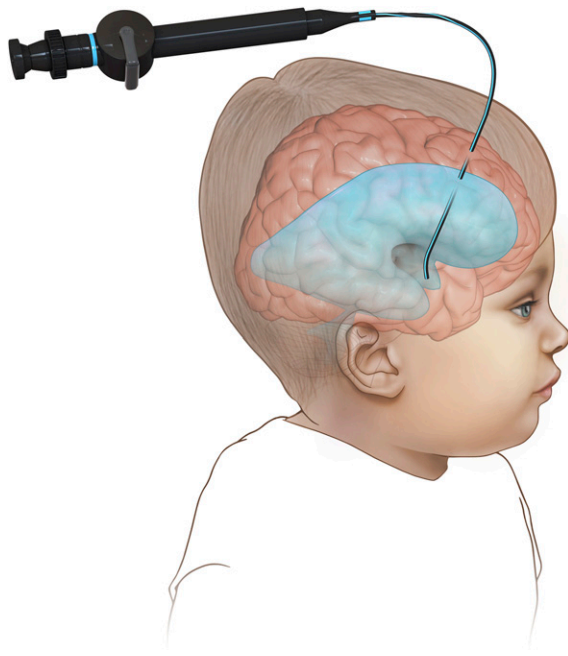


Figure 6. Endoscopic third ventriculostomy.

shunts varies, depending on the indication for shunt placement. For children in whom shunting was performed in the face of an obstructive tumor, removal of the obstruction could make them shunt-independent. Less common cases where children become shunt-independent include posthemorrhagic or postinfectious hydrocephalus in which the primary pathology resolves and the patient regains the ability to absorb and circulate their CSF without shunt assistance.

Overall failure rates, defined by the need for shunt revision or replacement, of new shunts in a 30-day period and 1-year period are approximately 13% and 29%, respectively, although these rates have been demonstrated to vary by region. (25)(26)

Malfunctions can be seen at any segment of the shunt. The proximal (ventricular) end of the catheter may become clogged with choroid plexus, scar, or other debris. It may also migrate out of the ventricle and into the surrounding brain, becoming obstructed. The connection between the proximal catheter and the valve or the connection between the distal catheter and the valve may break.

Valves can also become clogged or may be inappropriate for the particular patient, shunting too much or too little fluid. Numerous valve types are available, and there is good literature suggesting that one type is not better than another. However, surgeon preference and certain patient-specific concerns may lead to use of a specific valve type. An important distinction in valves is whether they are programmable or fixed. Until very recently, programmable valves were subject to setting changes in the face of a strong magnetic field (eg, MRI), thereby requiring recalibration. Manufacturers of newer programmable valves claim a much lower risk for unintentional setting changes, and these valves are, therefore, dubbed "MRI-resistant." All current shunt hardware is MRI-safe, meaning that an indwelling shunt for hydrocephalus is not a contraindication for MRI.

The distal catheter may also malfunction. Common causes of distal catheter malfunction include disconnection from the valve, kinking of the catheter, or fracture of a longstanding catheter that has calcified. The end of the catheter may become tangled and kinked, it may migrate out of the abdominal cavity, or the fluid may not be absorbed and subsequently form a pseudocyst. Typically, abdominal pseudocysts from malabsorption of the CSF result from a longstanding infection (typically *Propionibacterium acnes*) and often are considered shunt infections that require removal of distal tubing from the infected abdomen. (30)

The presentation of shunt malfunction is similar to the presentation of hydrocephalus but can often have a more rapid onset. Children with declining neurologic status or increasing ventricular size on imaging require rapid evaluation



by neurosurgeons. Shunt infection is an all-too-common complication of shunt-treated hydrocephalus, occasionally from intraoperative contamination but also from postoperative wound infections or from intraabdominal infection. There has been extensive research on the epidemiology, prevention, and treatment of shunt infections. A study of more than 40 children's hospitals revealed the infection rate among uncomplicated initial CSF shunt placements to be approximately 11% within 24 months. (31)

Shunt infection can present with typical signs and symptoms of infection, such as fever, nausea, and vomiting as well as with specific neurological sequelae. The presentation of shunt infection ranges from indolent infections with intermittent fevers and small cognitive changes to fulminant meningitis symptoms such as rigors, chills, sweats, and seizures. (32)(33) Redness and tenderness around the catheter or purulent discharge from incision sites can be seen, but the skin overlying the catheter may appear normal.

ETV avoids the complications associated with implanting foreign bodies, including the risk of hardware infection or colonization and malfunctioning devices. However, there are complications associated with this procedure as well. The iatrogenic opening in the floor of the third ventricle may close or the surrounding arachnoid membranes may scar in such a way as to block the flow of CSF. (34)

The effectiveness of ETV remains an active research topic, but in retrospective studies comparing ETV with VP shunt placement, the 1-year failure rates in infants were 65% and 40%, respectively. (35) Another study demonstrated the 1-year success rate of all ETV/CPC at 52% compared with 65% for shunts. In cases with cauterization of more than 90% of the choroid plexus, however, the observed success rate increased to 82%. (29) ETV/CPC remains a viable option for treatment of hydrocephalus, particularly in cases of obstructive hydrocephalus (ie, aqueductal stenosis), in low-resource locations, and in populations with poor follow-up. Prospective studies still need to be conducted to reveal its best indications.

## FOLLOW-UP EVALUATION

Although there is no standardized paradigm for follow-up care, most neurosurgical practices evaluate children with shunted hydrocephalus on an annual or biannual basis. The children are typically seen by neurosurgeons 1 to 3 months after initial shunt placement and imaged at a 6- to 12-month follow-up appointment to determine a new baseline in ventricle sizes. Universally accepted protocols for routine imaging to monitor hydrocephalus have not been established, but

surveillance imaging is standard practice. Adjunctive methods for evaluation of preverbal patients include routine ophthalmologic examination by funduscopy for visual impairment and physical therapy for children who have cognitive and physical impairments.

On rare occasions, hydrocephalus may seem to be asymptomatic and nonprogressive without treatment because of reestablishment of normal mechanisms for CSF flow and/or absorption. Patients who have this condition, deemed "arrested hydrocephalus," should have follow-up surveillance similar to those with treated hydrocephalus because the condition could be an extremely slowly progressive form of hydrocephalus that is not completely halted.

More commonly, the primary pathology causing hydrocephalus may resolve in children who have undergone shunt placement and, therefore, no longer require CSF diversion. Thus, results of a detailed history and physical examination should never be ignored in patients with shunted hydrocephalus who present to a primary care practitioner or emergency department. Patients in whom shunts have not been revised in many years may not be dependent on their shunts anymore, and other more common diagnoses for their current presentation may be more appropriate.

Shunt punctures are both a diagnostic and therapeutic measure. Most shunt valves include a reservoir proximal to the regulatory apparatus of the valve. These may be accessed percutaneously. If the proximal catheter is patent, fluid should flow, intracranial pressure can be estimated, and therapeutic drainage of the ventricles may be performed. Fluid may then be removed as a temporizing measure to relieve increased intracranial pressure due to shunt malfunction before operative intervention. Obtained CSF may also be evaluated for cell counts and cultures to rule out infectious etiologies. An inability to draw fluid from the shunt reservoir may indicate shunt hardware malfunction. To test the CSF, a lumbar puncture can also be performed, but this must be undertaken with good knowledge of the patient's pathology because it can precipitate downward herniation of the brain. (36)

## NOVEL RESEARCH

### Clinical Research

New and exciting research is constantly changing the field of pediatric hydrocephalus. As previously mentioned, research into MRI algorithms to quickly and accurately diagnose hydrocephalus and its complications are in development and are gaining popularity. Antibiotic-impregnated catheters are being investigated for their ability to reduce

shunt infections and the need for shunt replacement. Initial results are promising, with 1 retrospective study demonstrating a 63% relative risk reduction in infections related to shunts for pediatric hydrocephalus. (37) Another study has demonstrated that for every 100 patients requiring a shunt, these specialized catheters result in 11 fewer surgeries and \$128,228 net savings in hospital costs. (38) Prospective randomized studies are now underway comparing traditional shunt catheters to silver- and antibiotic-impregnated catheters. (39)

### Basic Science Research

Some of the most innovative research currently being performed in the field of neonatal/pediatric hydrocephalus involves molecular and radiographic biomarkers for evaluating injury. Examining the biomarkers present in hydrocephalic models may fill important gaps in the understanding of the pathophysiology of progressive neonatal hydrocephalus. Two biomarkers present in high concentrations in the CSF and other serum samples of infants with hydrocephalus are transforming growth factor  $\beta$ -1 (TGF- $\beta$ 1) and vascular endothelial growth factor. TGF- $\beta$ 1 is a cytokine that primarily regulates cell differentiation, proliferation, and other major cellular functions. Studies have shown that TGF- $\beta$ 1 can be secreted into CSF after an intraventricular hemorrhage and can upregulate genes responsible for synthesis of extracellular matrix proteins (eg, fibronectin, collagen). (40) Focusing on pathways in which the hydrocephalic brain is damaged, researchers have found that certain medical treatments may reduce the rate at which hydrocephalus occurs in animal models. Decorin, a growth factor  $\beta$ -antagonist, has demonstrated an impressive ability to prevent development of juvenile communicating hydrocephalus in an animal model. (41) Inflammatory/immune modulators may potentially be therapeutic in patients with high-grade hemorrhages who have high rates of posthemorrhagic hydrocephalus.

### ROLE OF THE PEDIATRICIAN

Children suffering with hydrocephalus can present diagnostic and management challenges to pediatricians, general practitioners, and emergency physicians. Differentiating problems caused by hydrocephalus from those of other causes can be difficult. In evaluating the patient who has hydrocephalus, it is important to consider the neurologic effects of the primary process, the cause of the hydrocephalus, whether the patient has undergone a surgical procedure such as a ventricular shunt or ETV/CPC, and the amount of time since the surgery. For postoperative patients who have undergone any VP shunt surgery (new

placement or revision operation), the authors recommend a “rule of 2s” approach. Within the first 2 days after an operation, surgical complications such as hemorrhage, stroke, or malpositioned shunt hardware become evident, which corresponds with many pediatric neurosurgical practices of postoperative imaging and hospital length of stay (typically 1-2 days after shunt placement). The first 2 months correspond to the highest risk period for postoperative shunt infection and the first 2 years correspond with the highest risk period for postoperative malfunction, with average infection rates estimated at 11.7% (4.1%–20.5%) and malfunction rates up to 40%. (31)(42) Studies documenting high infection rates in the first 2 to 3 weeks after insertion of the device have determined most etiologic pathogens to be skin flora such as *Staphylococcus aureus*. (42)

The identification of shunt infections or malfunction should be the highest priority for practitioners treating children who have shunts. This is especially true in the context of nonverbal patients, those with severe neurologic disabilities, or those in high-risk groups such as the immunocompromised or those with cardiac or pulmonary comorbidities. Fevers and lethargy can be signs of shunt infection, but they can also be signs of urinary tract infection, viral illness, or dehydration. Therefore, careful attention to neurologic signs and symptoms in the face of the overall clinical picture, including history and physical examination findings, is crucial to distinguish shunt pathology from more common childhood illnesses.

Thus, the diagnostic approach must be tailored to the child. An understanding of the child’s baseline neurologic status can yield fruitful insight into how that status has changed. In those patients with more minor, indolent changes, other causes, such as other types of infection, should be evaluated as appropriate (eg, urinalysis, viral panels). If the patient’s condition is not explained by another diagnosis, further investigation, such as imaging, should be initiated. Imaging results should be compared with previous scans to see if changes to the ventricular size can help indicate the cause of the problem. Funduscopic examination for papilledema is a useful tool when other modalities are either unavailable (prior imaging unavailable) or results are inconclusive. Because early papilledema does not typically present as visual loss, this clinical sign upon neurologic examination can guide the practitioner toward early referral for neurosurgical consultation.

Patients with stable imaging studies and presentations attributable to other causes should not be subject to procedures such as shunt or lumbar punctures because these

can be traumatic experiences for children, carry their own risks for complications and infections, and often have little diagnostic utility. If clinical suspicion of hydrocephalus is still high, close observation is recommended. However, immediate neurosurgical consultation is indicated for patients with more severe symptoms or changes in imaging. If the child is in severe neurologic distress and neurosurgical assistance is not readily available, a shunt tap or lumbar puncture to decrease intracranial pressure could be lifesaving. As often is the case with chronic conditions such as pediatric hydrocephalus, the best approach to a patient presenting with signs and symptoms suggestive of hydrocephalus is to evaluate the entire patient and not focus only on a single disease process. This patient-centric approach can ensure that a diagnosis, which could be present at the time of presentation, is not unrecognized and untreated.

#### ACKNOWLEDGMENTS

The authors would like to thank Emma Vought for producing the article's graphic depictions and Alyssa Pierce for her medical editing contributions.

## Summary

- On the basis of consensus, hydrocephalus has a substantial burden of disease, with an estimated \$2 billion dollars in hospital costs per year.
- On the basis of consensus, hydrocephalus initially should be evaluated clinically and with appropriate nonradiation imaging unless such imaging is unavailable or would delay management.
- On the basis of consensus, management of hydrocephalus should include lumbar puncture or shunt puncture if clinical concerns indicate these mildly invasive measures.
- On the basis of consensus, ventriculoperitoneal shunt placement is a lifesaving procedure and is the current gold standard treatment for patients with hydrocephalus.
- On the basis of consensus, endoscopic third ventriculostomy, with or without choroid plexus cauterization, is an effective treatment for select cases of hydrocephalus.

*References for this article are at <http://pedsinreview.aappublications.org/content/37/11/478>.*

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1. A 10-year-old boy with new-onset headache that is worse at night and early morning vomiting undergoes outpatient brain magnetic imaging, which reveals hydrocephalus and a homogenous mass inside the right lateral ventricle that exhibits intense contrast enhancement. You suspect that it is a choroid plexus papilloma, one of the few cerebrospinal fluid (CSF)-producing tumors. In which region does the choroid plexus produce the most CSF?
  - A. Arachnoid granulations.
  - B. Fourth ventricle.
  - C. Germinal matrix.
  - D. Lateral ventricles.
  - E. Third ventricle.
2. As the admitting hospitalist, you discuss the case described in the previous question with the neuroradiologist and neurosurgeon and decide to admit the patient urgently. In taking the history and conducting the physical examination for this patient, which additional sign or symptom will most likely be elicited?
  - A. Apnea.
  - B. Bilateral sixth cranial nerve palsies.
  - C. Bradycardia.
  - D. Macrocephaly.
  - E. Splaying of the cranial sutures.
3. The parents of an infant with a myelomeningocele have just been told that increasing ventriculomegaly and head circumference necessitate a CSF diversion procedure. They sit down to discuss options with the neurosurgical team. Which of the following factors is an advantage of endoscopic third ventriculostomy versus ventriculoperitoneal shunt placement?
  - A. Higher overall success rate.
  - B. Higher success rate in communicating hydrocephalus.
  - C. Lower risk of infection.
  - D. Lower risk of need for repeat surgical intervention.
  - E. Lower risk of scarring of arachnoid membranes.
4. A 2½-year-old female patient with history of spina bifida and hydrocephalus treated with ventriculoperitoneal shunt insertion at birth presents to the emergency department with vomiting and alternating episodes of lethargy and irritability. On physical examination, she seems irritable and cries when her head and neck are manipulated. According to the rule of "2s," for which of the following complications is this patient at highest risk?
  - A. Hemorrhage.
  - B. Malpositioned shunt hardware.
  - C. Shunt infection.
  - D. Shunt malfunction.
  - E. Stroke.

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5. A 3-year-old patient with cerebral palsy due to prematurity and ventriculoperitoneal shunt (placed 2 years ago) presents to the emergency department with fever and vomiting. Her older sister had similar symptoms starting yesterday. The patient appears alert, well-hydrated, and not in pain. Her abdomen is soft. She resists eye examination and you cannot check for papilledema. Which of the following is the next step in management?
- A. Dilated eye examination by ophthalmology.
  - B. Complete blood cell count, urinalysis, and viral panels.
  - C. Computed tomography scan of the brain.
  - D. Fast-sequence brain magnetic resonance imaging.
  - E. Outpatient follow-up with neurosurgery in the morning.