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Patterns in neurosurgical adverse events: cerebrospinal fluid shunt surgery

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Object. As part of a project to devise evidence-based safety interventions for specialty surgery, the authors sought to review current evidence in CSF shunt surgery concerning the frequency of adverse events in practice, their patterns, and the state of knowledge regarding methods for their reduction. This review may also inform future and ongoing efforts for the advancement of neurosurgical quality.

Methods. The authors performed a PubMed search using search terms "cerebral shunt," "cerebrospinal fluid shunt," "CSF shunt," "ventriculoperitoneal shunt," "cerebral shunt AND complications," "cerebrospinal fluid shunt AND complications," "CSF shunt AND complications," and "ventriculoperitoneal shunt AND complications." Only papers that specifically discussed the relevant complication rates were included. Papers were chosen to be included to maximize the range of rates of occurrence for the adverse events reported.

Results. In this review of the neurosurgery literature, the reported rate of mechanical malfunction ranged from 8% to 64%. The use of programmable valves has increased but remains of unproven benefit even in randomized trials. Infection was the second most common complication, with the rate ranging from 3% to 12% of shunt operations. A meta-analysis that included 17 randomized controlled trials of perioperative antibiotic prophylaxis demonstrated a decrease in shunt infection by half (OR 0.51, 95% CI 0.36–0.73). Similarly, use of detailed protocols including perioperative antibiotics, skin preparation, and limitation of OR personnel and operative time, among other steps, were shown in uncontrolled studies to decrease shunt infection by more than half.

Other adverse events included intraabdominal complications, with a reported incidence of 1% to 24%, intracerebral hemorrhage, reported to occur in 4% of cases, and perioperative epilepsy, with a reported association with shunt procedures ranging from 20% to 32%. Potential management strategies are reported but are largely without formal evaluation.

Conclusions. Surgery for CSF shunt placement or revision is associated with a high complication risk due primarily to mechanical issues and infection. Concerted efforts aimed at large-scale monitoring of neurosurgical complications and consistent quality improvement within these highlighted realms may significantly improve patient outcomes.

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Key Words • **surgical safety** • **adverse events** • **perioperative care**

Progress in the science of improving surgical safety has been notable in recent years. Methods for evaluating outcomes have been developed and deployed.[17,28,29,47,56,61,95] The resulting data have been used to investigate patterns of errors and complications. From these findings, solutions have been designed and tested, sometimes with striking improvements, whether using simple process tools like checklists[17,18,38,94] or technological and conceptual changes.[31,69,91] Neurosurgery is a high-risk surgical specialty and is beginning to pursue systematic, nationwide approaches to measuring and improving outcomes and to developing evidence-based guidelines for a variety of neurosurgical disorders. As part of a project funded by the US Agency for Healthcare Research and Quality to devise evidence-based checklists and protocols for specialty surgery, we sought to review current evidence in neurosurgery concerning the frequency of adverse events in practice, their patterns, and the state of knowledge about how to improve them. This review

Abbreviation used in this paper: AIC = antibiotic-impregnated catheter.

represents part of a series of papers written to consolidate information about these events and preventive measures as part of an ongoing effort to ascertain the utility of devising system-wide policies and safety tools to improve neurosurgical practice. This paper reviews the patterns of neurosurgical adverse events in CSF shunt surgery in both adult and pediatric populations. Although pediatric and adult hydrocephalus represent distinct entities with wide disparities in etiology that influence treatment outcome, in this paper CSF shunt surgery is considered more generally, in order to identify universal areas of potential improvement.

Methods

We performed a PubMed search for studies published in or translated into English, using the search terms "cerebral shunt," "cerebrospinal fluid shunt," "CSF shunt," "ventriculoperitoneal shunt," "cerebral shunt AND complications," "cerebrospinal fluid shunt AND complications," "CSF shunt AND complications," and "ventriculoperitoneal shunt AND complications." Only papers that specifically discussed the relevant complication rates were included. Papers were chosen for inclusion in order to maximize the range of rates of occurrence for the adverse events reported rather than to include all possible studies. The majority of the studies discussed in this review pertain to ventriculoperitoneal shunts; however, studies were not excluded if their sample contained patients who received pleural or atrial shunts.

Scope of the Problem

Cerebrospinal fluid shunts are the mainstay of therapy for hydrocephalus of various causes[43] and are among the most common procedures in pediatric neurosurgery.[62] According to the Healthcare Cost and Utilization Project, 14,683 new ventricular shunts were placed in 2008 (http://hcupnet.ahrq.gov). Shunt failure is, and historically has been, a very serious problem. Reported failure rates are as high as 70% in the 1st year after surgery and approximately 5% annually thereafter; indeed, the shunt failure rate has not changed significantly since 1960.[66,82] CSF shunt-related hospital admissions are costly, accounting for $1.4–2.0 billion in hospital charges yearly.[60,81]

The vast majority of shunt-related complications consist of failure from valvular or mechanical dysfunction and/or infection. Shunt infection is a feared entity, and patients who develop infection have approximately twice the risk of death and undergo approximately 3 times the number of shunt-related procedures as those who do not develop infection.[76] Other adverse events include intraabdominal complications, intracerebral hemorrhage, and perioperative epilepsy (Table 1). Many of these events are interrelated.

Valvular/Mechanical Malfunction

The rate of mechanical shunt malfunction is very high, ranging from 8% to 64%.[20,23,36,37,42,53,57] It can occur in various locations along the shunt, including the proximal catheter, valve, or distal catheter, and occurs for various reasons, including obstruction, disconnection of tubing and/or a valve, valve malfunction/occlusion, or overdrainage.[51,79] The rates reported here include all etiologies, but we discuss obstruction in detail as it is the most common and therefore the most logical target for safety interventions. To prevent complications associated with proximal blockage, placement of the catheter in a location away from the choroid plexus is advised. Indeed, shunts placed in frontal or occipital locations had lower failure rates than those placed elsewhere in a multicenter post hoc analysis.[85] However, accurate placement is often difficult given that most ventricular catheters are passed into the ventricular system using anatomical landmarks only.[79] In uncontrolled series, stereotactic guidance has been found beneficial, particularly with slit-ventricle conditions.[10,70,98] Intraoperative ultrasonography has also been used with

TABLE 1: Frequency of adverse events reported in CSF shunt surgery*

AE w/ Authors & Year	No. of Cases	Pt Age	AE Freq (%)
valvular/mechanical dysfunction			
Notarianni et al., 2009	253	ped	64
Hardie et al., 1986	129	mixed	47
Kestle et al., 2000	344	ped	42
McGirt et al., 2007	279	ped	40
Drake et al., 1998	344	ped	35
Hanlo et al., 2003	557	mixed	15
Farahmand et al., 2009	450	adult	8
infection			
Casey et al., 1997	155	ped	12
Govender et al., 2003	110	mixed	12
Kulkarni et al., 2001	299	ped	10
Hardie et al., 1986	129	mixed	9
Drake et al., 1998	344	ped	8
Hanlo et al., 2003	557	mixed	8
Kestle et al., 2000	344	ped	8
Kestle et al., 2011	1571	ped	6
Farahmand et al., 2009	450	adult	6
Ritz et al., 2007	258	mixed	6
Steinbok et al., 2010	433	mixed	3
intraabdominal complications†			
Grosfeld et al., 1974	185	ped	24
Hanlo et al., 2003	557	mixed	0.9
Gutierrez & Raimondi, 1976	1585	mixed	0.7
intracerebral hemorrhage			
Savitz & Bobroff, 1999	125	adult	4
perioperative epilepsy			
Bourgeois et al., 1999	802	ped	32
Klepper et al., 1998	283	ped	20

* AE = Adverse Event; Freq = Frequency; ped = pediatric; Pt = Patient.
† The frequency reported by Grosfeld et al. represents all intraabdominal complications, including hernia and pseudocyst formation. The frequencies reported by Hanlo et al. and Gutierrez and Raimondi are for pseudocyst only.

good effect;[96] larger controlled trials are now underway. Shunts frequently disconnect at stress points where plastic or metal connectors rub against the tubing. Disconnections at these points may be prevented by securing the connection with 2-0 nonabsorbable suture, avoidance of kinking of the shunt components against the bur hole, and allowing for some slack in the tubing.[79] Coordination of these techniques within the operating room requires good communication among surgical teams.

The use of adjustable shunt valves has increased as a means for providing better regulation of CSF flow. Despite their theoretical advantages, the relationship between these valves and complications is not clear. The only randomized trial of a programmable versus conventional valve system did not show any difference between rates of valve or shunt obstruction, though it was only powered as a safety and efficacy study.[65] Similarly, other series do not convincingly support the use of programmable over conventional valves, though one study did find the programmable feature useful in the management of postoperative subdural fluid collection.[8,57] However, there are a small number of uncontrolled series suggesting that the use of programmable valves decreases overall revision rates and the incidence of proximal catheter obstruction.[4,23,53,99] It is similarly unclear whether the use of an antisiphon device improves shunt survival. A multicenter randomized trial compared 2 valves with antisiphon devices against a standard differential pressure valve in the management of pediatric hydrocephalus. This trial showed no significant difference in shunt survival among any of the 3 valves in either short- (1 year)[20] or long-term (median 3 years)[42] follow-up. A small but randomized study also failed to show any statistically significant difference in shunt failure within 6 months but likely was not powered to do so.[46]

Other less common approaches have been employed with varying success. Use of distal slit valves was associated with increased risk of blockage in a single-institution observational study.[15] Others have postulated that catheter length may have an effect, but use of extended-length catheters was not associated with increased blockage in a single-institution observational study.[14] CSF protein levels have not been associated with shunt blockage in observational studies,[27,67] though for many indications such as posthemorrhage or malignancy, many surgeons delay shunt placement until protein levels drop below a certain threshold when possible.

In select patients, endoscopic third ventriculostomy with or without choroid plexus electrocoagulation is a viable option that may circumvent dependence on shunt hardware.[92,93] This technique, however, requires specialized equipment as well as surgical experience.

Infection

Infection is the second most common complication of CSF shunt procedures and is estimated to occur in 3% to 12% of shunt operations.[9,20,23,30,36,37,42,44,50,71,83] A 2009 study of infection rates following initial CSF shunt placement procedures across pediatric hospitals in the US, including 7071 pediatric patients, demonstrated that the rate of shunt infection depended in part on surgeon and hospital volume.[80] The mortality rate associated with shunt infection is reported to be 10.1%, and shunt infection is associated with worse Glasgow Outcome Scale scores and worse school performance in the long term.[90]

Risk factors include young age, female sex, African-American race, public insurance, etiology of hydrocephalus from intraventricular hemorrhage, complex chronic respiratory conditions, subsequent revision procedures, hospital volume, and surgeon case volume.[25] There are also a number of procedural factors that may reduce the rate of CSF shunt infections. As with other surgical procedures, antibiotic prophylaxis appears to reduce shunt infections. A 2008 meta-analysis that included 17 randomized controlled trials of perioperative antibiotic prophylaxis demonstrated a significant decrease in the rate of shunt infection (OR 0.51, 95% CI 0.36–0.73). These results remained consistent across all ages, shunt types, and pre- and postoperative durations of antibiotic use.[68]

Recently introduced antibiotic-impregnated catheters (AICs) have been shown to decrease shunt colonization by *Staphylococcus* species,[3,30,35] though controversy remains whether their use should be standardized. Several nonrandomized studies showed a reduction in early shunt infection and hospital costs with their use.[2,41,77,78] A retrospective before-and-after study suggested benefit in the adult population as well.[24] The only prospective, randomized study on the subject was performed at a single institution and involved 110 patients (age range 1 month to 72 years. This study showed a significant reduction in shunt infection within 2 months with AIC use, but although the trend remained, this difference was not statistically borne out at longer-term follow-up. Additionally, it remains unclear whether randomization resulted in 2 groups that were demographically balanced and whether the results of the study are truly generalizable.[30] Two recent meta-analyses suggest that AICs may be of benefit, reducing shunt infection rates as well as hospital costs.[49,84] Another review suggests the same, for both pediatric and adult populations.[59] All these pooled data need to be interpreted in the context of the lack of prospective controlled studies. The existing studies are characterized by heterogeneity in the examined patient populations and definition of shunt infection, as well as lack of control of other confounders affecting shunt infection rates. There is also concern for publication bias, in that positive studies are more likely to be published.[45] On the other hand, a number of other uncontrolled studies do not show benefit to AICs.[40,71,83] There is also some concern that use of AICs may select for resistant, harder-to-treat organisms.[19]

Other mechanisms aimed at preventing shunt infections have been employed as well, to some effect. One study noted that a risk factor for shunt infection appeared to be an unrecognized defect in gloves worn by the surgical team.[50] Double gloving has since been shown to reduce this complication by more than 50% in one retrospective, before-and-after study.[86] This technique also appears to decrease infection rates when combined with others in the protocols outlined below.

Perioperative shunt protocols integrating these and other strategies have demonstrated beneficial effect. In the most recent of these reports, Kestle et al.[44] describe the results of a prospective, nonrandomized study of 1571

pediatric procedures performed after implementation of the Hydrocephalus Clinical Research Network (HCRN) protocol. Their findings suggested a reduction in the shunt infection rate from 9% to 6% after implementation of the protocol, which included a sign on the OR door to limit traffic, positioning the patient's head away from the door, perioperative administration of antibiotics, appropriate use of ChloraPrep, traditional hand scrub, double gloves, use of Ioban drape, and intrathecal antibiotic administration. Another observational study implemented a strict infection-control protocol including limitation of OR personnel and traffic, limitation of implant and skin edge manipulation, scheduling shunt surgery as first case of the day, avoidance of postoperative CSF leakage, double gloving, limitation of operative time to less than 30 minutes, and antibiotic prophylaxis; during the 4- to 70-month follow-up period the authors found no shunt infections among the 100 pediatric patients included in the study.[64] Other older studies found similar results with the use of similar infection-control protocols, with the only additional steps of changing gloves prior to handling shunt hardware, and opening the sterile hardware packaging at the last minute.[11,72] Another uncontrolled, before-and-after study found a significant decrease in infections with a "no-touch" policy wherein the shunt hardware was handled only with instruments and shunt tubing was kept on a separate table from instruments used for skin incision.[22] Full adherence to such protocols requires good communication within the surgical team. The importance of communication and effective team dynamics are discussed in the summary paper of this series.[97]

Intraabdominal Complications

The majority of CSF shunts placed in the modern era are ventriculoperitoneal shunts, and placement of the distal catheter into the peritoneal cavity can be difficult in the setting of multiple shunt revisions, prior abdominal surgery, prior abdominal infection, or obesity. These difficulties may result in placement of the distal catheter into the preperitoneal fat instead of the peritoneal space, or worse, may result in bowel or visceral injury.[55,79]

Laparoscopic placement of the distal catheter is becoming more common and has potential advantages. These include direct visualization of the catheter in the intraperitoneal space, avoidance of an abdominal incision overlying shunt tubing, potentially shorter operative times and postoperative stays, and reduced bowel or catheter complications. One prospective, uncontrolled study demonstrated an infection rate of 0.9%, a mean operative time of 49 minutes (during the final 4 months of the study), and a 1-year shunt survival rate of 91%.[87]

Delayed bowel injury may also occur with erosion of a hollow viscus by the shunt catheter, sometimes extruding through the anus.[89] In fact, the distal catheter may penetrate or migrate into multiple locations including the oral cavity, bladder, colon, umbilicus, gall bladder, and scrotum.[5,21,52,54,58] Methods of preventing such injury are debated but may include limiting distal catheter length and minimizing the angle at which the distal catheter is cut prior to insertion, though these techniques remain unproven in a systematic way.

Abdominal pseudocysts represent an additional abdominal complication with an estimated rate between 0.7% and 10%.[7,13,32,33] They are most common in the setting of infection,[1,12,13,34,73] and are also likely to occur in the setting of prior abdominal operations and adhesions.[1] Strategies to reduce pseudocyst formation are limited but may include consideration of other drainage sites in patients who have had prior abdominal surgery.

In the setting of challenging cases such as multiple reoperations, consulting a general surgeon for assistance may be helpful or even necessary.[79]

Intracerebral Hemorrhage

Intracerebral hemorrhage from shunt placement is a rare but potentially catastrophic complication.[39] No study has carefully documented its frequency, though one retrospective study showed a 4% rate of radiographically confirmed hemorrhage following routine shunt placement. None of the hemorrhages was symptomatic.[75] Efforts aimed at minimizing risk of intracranial hemorrhage include meticulous attention to the bur-hole site and dural penetration, careful avoidance of choroid plexus during placement, perhaps using real-time image guidance,[10,70,98] perioperative screening protocols and medical optimization,[26] and use of high-dose anticoagulant therapy only when the benefits outweigh the hemorrhage risk.

Perioperative Epilepsy

Because of the association between hydrocephalus and seizures or epilepsy, seizure rates following shunt placement remain high. The risk of seizure as a result of shunt placement itself, however, is controversial.[6,48,74] Some work has suggested that frontal rather than parietal bur-hole placement was associated with increased incidence of seizure,[16] though these data have not been corroborated by other studies.[63,79,88] Thus perioperative seizures related to shunt placement are not an independent complication of surgery but warrant discussion given that they are common and can be problematic. Minimizing seizure risk parallels treating the root cause of the epilepsy, and perioperative antiseizure medication is usually given only when part of the patient's routine regimen.

Conclusions

Surgery for CSF shunt placement is associated with a high risk of complications due primarily to mechanical problems and infection. The wide ranges of adverse event rates reported here reflect the need for risk stratification and highlight the need for national data, discussed in further detail in the summary paper of this series.[97] A significant proportion of complications are likely avoidable using standardized protocols, improved teamwork and communication, and potentially increased use of beneficial technologies such as intraoperative image guidance. Although the use of these strategies is increasing, it is far from universal. Concerted efforts aimed at large-scale monitoring of neurosurgical complications and consistent quality improvement within these highlighted realms may significantly improve patient outcomes.

Disclosure

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References

1. Anderson CM, Sorrells DL, Kerby JD: Intra-abdominal pseudocysts as a complication of ventriculoperitoneal shunts: a case report and review of the literature. **Curr Surg 60:**338–340, 2003
2. Attenello FJ, Garces-Ambrossi GL, Zaidi HA, Sciubba DM, Jallo GI: Hospital costs associated with shunt infections in patients receiving antibiotic-impregnated shunt catheters versus standard shunt catheters. **Neurosurgery 66:**284–289, 2010
3. Bayston R, Lambert E: Duration of protective activity of cerebrospinal fluid shunt catheters impregnated with antimicrobial agents to prevent bacterial catheter-related infection. **J Neurosurg 87:**247–251, 1997
4. Bergsneider M: Management of hydrocephalus with programmable valves after traumatic brain injury and subarachnoid hemorrhage. **Curr Opin Neurol 13:**661–664, 2000
5. Berhouma M, Messerer M, Houissa S, Khaldi M: Transoral protrusion of a peritoneal catheter: a rare complication of ventriculoperitoneal shunt. **Pediatr Neurosurg 44:**169–171, 2008
6. Bourgeois M, Sainte-Rose C, Cinalli G, Maixner W, Malucci C, Zerah M, et al: Epilepsy in children with shunted hydrocephalus. **J Neurosurg 90:**274–281, 1999
7. Burchianti M, Cantini R: Peritoneal cerebrospinal fluid pseudocysts: a complication of ventriculoperitoneal shunts. **Childs Nerv Syst 4:**286–290, 1988
8. Carmel PW, Albright AL, Adelson PD, Canady A, Black P, Boydston W, et al: Incidence and management of subdural hematoma/hygroma with variable- and fixed-pressure differential valves: a randomized, controlled study of programmable compared with conventional valves. **Neurosurg Focus 7(4):**e7, 1999
9. Casey AT, Kimmings EJ, Kleinlugtebeld AD, Taylor WA, Harkness WF, Hayward RD: The long-term outlook for hydrocephalus in childhood. A ten-year cohort study of 155 patients. **Pediatr Neurosurg 27:**63–70, 1997
10. Choudhury AR: Avoidable factors that contribute to the complications of ventriculoperitoneal shunt in childhood hydrocephalus. **Childs Nerv Syst 6:**346–349, 1990
11. Choux M, Genitori L, Lang D, Lena G: Shunt implantation: reducing the incidence of shunt infection. **J Neurosurg 77:**875–880, 1992
12. Chung JJ, Yu JS, Kim JH, Nam SJ, Kim MJ: Intraabdominal complications secondary to ventriculoperitoneal shunts: CT findings and review of the literature. **AJR Am J Roentgenol 193:**1311–1317, 2009
13. Coley BD, Kosnik EJ: Abdominal complications of ventriculoperitoneal shunts in children. **Semin Ultrasound CT MR 27:**152–160, 2006
14. Couldwell WT, LeMay DR, McComb JG: Experience with use of extended length peritoneal shunt catheters. **J Neurosurg 85:**425–427, 1996
15. Cozzens JW, Chandler JP: Increased risk of distal ventriculoperitoneal shunt obstruction associated with slit valves or distal slits in the peritoneal catheter. **J Neurosurg 87:**682–686, 1997
16. Dan NG, Wade MJ: The incidence of epilepsy after ventricular shunting procedures. **J Neurosurg 65:**19–21, 1986
17. de Vries EN, Hollmann MW, Smorenburg SM, Gouma DJ, Boermeester MA: Development and validation of the SURgical PAtient Safety System (SURPASS) checklist. **Qual Saf Health Care 18:**121–126, 2009
18. de Vries EN, Prins HA, Crolla RM, den Outer AJ, van Andel G, van Helden SH, et al: Effect of a comprehensive surgical safety system on patient outcomes. **N Engl J Med 363:**1928–1937, 2010
19. Demetriades AK, Bassi S: Antibiotic resistant infections with antibiotic-impregnated Bactiseal catheters for ventriculoperitoneal shunts. **Br J Neurosurg 25:**671–673, 2011
20. Drake JM, Kestle JR, Milner R, Cinalli G, Boop F, Piatt J Jr, et al: Randomized trial of cerebrospinal fluid shunt valve design in pediatric hydrocephalus. **Neurosurgery 43:**294–305, 1998
21. Eser O, Dogru O, Aslan A, Kundak AA: Umbilical perforation: an unusual complication of a ventriculoperitoneal shunt. **Childs Nerv Syst 22:**1509–1510, 2006
22. Faillace WJ: A no-touch technique protocol to diminish cerebrospinal fluid shunt infection. **Surg Neurol 43:**344–350, 1995
23. Farahmand D, Hilmarsson H, Högfeldt M, Tisell M: Perioperative risk factors for short term shunt revisions in adult hydrocephalus patients. **J Neurol Neurosurg Psychiatry 80:** 1248–1253, 2009
24. Farber SH, Parker SL, Adogwa O, McGirt MJ, Rigamonti D: Effect of antibiotic-impregnated shunts on infection rate in adult hydrocephalus: a single institution's experience. **Neurosurgery 69:**625–629, 2011
25. Ferguson SD, Michael N, Frim DM: Observations regarding failure of cerebrospinal fluid shunts early after implantation. **Neurosurg Focus 22(4):**E7, 2007
26. Fleisher LA, Beckman JA, Brown KA, Calkins H, Chaikof E, Fleischmann KE, et al: ACC/AHA 2007 guidelines on perioperative cardiovascular evaluation and care for noncardiac surgery: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines (Writing Committee to Revise the 2002 Guidelines on Perioperative Cardiovascular Evaluation for Noncardiac Surgery). **Circulation 116:**e418–e499, 2007
27. Fulkerson DH, Vachhrajani S, Bohnstedt BN, Patel NB, Patel AJ, Fox BD, et al: Analysis of the risk of shunt failure or infection related to cerebrospinal fluid cell count, protein level, and glucose levels in low-birth-weight premature infants with posthemorrhagic hydrocephalus. Clinical article. **J Neurosurg Pediatr 7:**147–151, 2011
28. Gawande AA, Studdert DM, Orav EJ, Brennan TA, Zinner MJ: Risk factors for retained instruments and sponges after surgery. **N Engl J Med 348:**229–235, 2003
29. Gawande AA, Thomas EJ, Zinner MJ, Brennan TA: The incidence and nature of surgical adverse events in Colorado and Utah in 1992. **Surgery 126:**66–75, 1999
30. Govender ST, Nathoo N, van Dellen JR: Evaluation of an antibiotic-impregnated shunt system for the treatment of hydrocephalus. **J Neurosurg 99:**831–839, 2003
31. Greenberg CC, Diaz-Flores R, Lipsitz SR, Regenbogen SE, Mulholland L, Mearn F, et al: Bar-coding surgical sponges to improve safety: a randomized controlled trial. **Ann Surg 247:** 612–616, 2008
32. Grosfeld JL, Cooney DR, Smith J, Campbell RL: Intra-abdominal complications following ventriculoperitoneal shunt procedures. **Pediatrics 54:**791–796, 1974
33. Gutierrez FA, Raimondi AJ: Peritoneal cysts: a complication of ventriculoperitoneal shunts. **Surgery 79:**188–192, 1976
34. Hahn YS, Engelhard H, McLone DG: Abdominal CSF pseudocyst. Clinical features and surgical management. **Pediatr Neurosci 12:**75–79, 1985–1986
35. Hampl JA, Weitzel A, Bonk C, Kohnen W, Roesner D, Jansen

B: Rifampin-impregnated silicone catheters: a potential tool for prevention and treatment of CSF shunt infections. **Infection 31:**109–111, 2003
36. Hanlo PW, Cinalli G, Vandertop WP, Faber JA, Bøgeskov L, Børgesen SE, et al: Treatment of hydrocephalus determined by the European Orbis Sigma Valve II survey: a multicenter prospective 5-year shunt survival study in children and adults in whom a flow-regulating shunt was used. **J Neurosurg 99:**52–57, 2003
37. Hardie NA, Molgaard CA, Laws ER, O'Fallon WM, Kurland LT: Incidence and effectiveness of cerebrospinal fluid shunts in Olmsted County, Minnesota, 1956-1981. **Neuroepidemiology 5:**95–104, 1986
38. Haynes AB, Weiser TG, Berry WR, Lipsitz SR, Breizat AH, Dellinger EP, et al: A surgical safety checklist to reduce morbidity and mortality in a global population. **N Engl J Med 360:**491–499, 2009
39. Horwitz NH, Rizzoli HV: **Postoperative Complications in Neurosurgical Practice: Recognition, Prevention, and Management.** Baltimore: Williams & Wilkins, 1967
40. Kan P, Kestle J: Lack of efficacy of antibiotic-impregnated shunt systems in preventing shunt infections in children. **Childs Nerv Syst 23:**773–777, 2007
41. Kandasamy J, Dwan K, Hartley JC, Jenkinson MD, Hayhurst C, Gatscher S, et al: Antibiotic-impregnated ventriculoperitoneal shunts—a multi-centre British paediatric neurosurgery group (BPNG) study using historical controls. **Childs Nerv Syst 27:**575–581, 2011
42. Kestle J, Drake J, Milner R, Sainte-Rose C, Cinalli G, Boop F, et al: Long-term follow-up data from the Shunt Design Trial. **Pediatr Neurosurg 33:**230–236, 2000
43. Kestle JR: Pediatric hydrocephalus: current management. **Neurol Clin 21:**883–895, vii, 2003
44. Kestle JR, Riva-Cambrin J, Wellons JC III, Kulkarni AV, Whitehead WE, Walker ML, et al: A standardized protocol to reduce cerebrospinal fluid shunt infection: the Hydrocephalus Clinical Research Network Quality Improvement Initiative. Clinical article. **J Neurosurg Pediatr 8:**22–29, 2011
45. Kestle JRW: Editorial. Pooling data on antibiotic-impregnated shunts. **J Neurosurg Pediatr 8:**257–258, 2011
46. Khan RA, Narasimhan KL, Tewari MK, Saxena AK: Role of shunts with antisiphon device in treatment of pediatric hydrocephalus. **Clin Neurol Neurosurg 112:**687–690, 2010
47. Khuri SF, Daley J, Henderson W, Hur K, Demakis J, Aust JB, et al: The Department of Veterans Affairs' NSQIP: the first national, validated, outcome-based, risk-adjusted, and peer-controlled program for the measurement and enhancement of the quality of surgical care. **Ann Surg 228:**491–507, 1998
48. Klepper J, Büsse M, Strassburg HM, Sörensen N: Epilepsy in shunt-treated hydrocephalus. **Dev Med Child Neurol 40:**731–736, 1998
49. Klimo P Jr, Thompson CJ, Ragel BT, Boop FA: Antibiotic-impregnated shunt systems versus standard shunt systems: a meta- and cost-savings analysis. Clinical article. **J Neurosurg Pediatr 8:**600–612, 2011
50. Kulkarni AV, Drake JM, Lamberti-Pasculli M: Cerebrospinal fluid shunt infection: a prospective study of risk factors. **J Neurosurg 94:**195–201, 2001
51. Kuo MF, Wang HS, Yang SH: Ventriculoperitoneal shunt dislodgement after a haircut with hair clippers in two shunted boys. **Childs Nerv Syst 25:**1491–1493, 2009
52. Martinez Hernández-Magro P, Barrera Román C, Villanueva Sáenz E, Zavala MJ: Colonic perforation as a complication of ventriculoperitoneal shunt: a case report. **Tech Coloproctol 10:**353–355, 2006
53. McGirt MJ, Buck DW II, Sciubba D, Woodworth GF, Carson B, Weingart J, et al: Adjustable vs set-pressure valves decrease the risk of proximal shunt obstruction in the treatment of pediatric hydrocephalus. **Childs Nerv Syst 23:**289–295, 2007
54. Mevorach RA, Hulbert WC, Merguerian PA, Rabinowitz R: Perforation and intravesical erosion of a ventriculoperitoneal shunt in a child with an augmentation cystoplasty. **J Urol 147:**433–434, 1992
55. Nakahara K, Shimizu S, Oka H, Utsuki S, Iida H, Fujii K: Migration of the distal end of a ventriculoperitoneal shunt into the abdominal wall in an obese patient: case report. **Neurol Med Chir (Tokyo) 49:**490–492, 2009
56. Neily J, Mills PD, Young-Xu Y, Carney BT, West P, Berger DH, et al: Association between implementation of a medical team training program and surgical mortality. **JAMA 304:** 1693–1700, 2010
57. Notarianni C, Vannemreddy P, Caldito G, Bollam P, Wylen E, Willis B, et al: Congenital hydrocephalus and ventriculoperitoneal shunts: influence of etiology and programmable shunts on revisions. Clinical article. **J Neurosurg Pediatr 4:** 547–552, 2009
58. Ozveren MF, Kazez A, Cetin H, Ziyal IM: Migration of the abdominal catheter of a ventriculoperitoneal shunt into the scrotum—case report. **Neurol Med Chir (Tokyo) 39:**313–315, 1999
59. Parker SL, Anderson WN, Lilienfeld S, Megerian JT, McGirt MJ: Cerebrospinal shunt infection in patients receiving antibiotic-impregnated versus standard shunts. A review. **J Neurosurg Pediatr 8:**259–265, 2011
60. Patwardhan RV, Nanda A: Implanted ventricular shunts in the United States: the billion-dollar-a-year cost of hydrocephalus treatment. **Neurosurgery 56:**139–145, 2005
61. Paull DE, Mazzia LM, Wood SD, Theis MS, Robinson LD, Carney B, et al: Briefing guide study: preoperative briefing and postoperative debriefing checklists in the Veterans Health Administration medical team training program. **Am J Surg 200:**620–623, 2010
62. Paulsen AH, Lundar T, Lindegaard KF: Twenty-year outcome in young adults with childhood hydrocephalus: assessment of surgical outcome, work participation, and health-related quality of life. Clinical article. **J Neurosurg Pediatr 6:**527–535, 2010
63. Piatt JH Jr, Carlson CV: Hydrocephalus and epilepsy: an actuarial analysis. **Neurosurgery 39:**722–728, 1996
64. Pirotte BJ, Lubansu A, Bruneau M, Loqa C, Van Cutsem N, Brotchi J: Sterile surgical technique for shunt placement reduces the shunt infection rate in children: preliminary analysis of a prospective protocol in 115 consecutive procedures. **Childs Nerv Syst 23:**1251–1261, 2007
65. Pollack IF, Albright AL, Adelson PD: A randomized, controlled study of a programmable shunt valve versus a conventional valve for patients with hydrocephalus. **Neurosurgery 45:**1399–1411, 1999
66. Pudenz RH: The surgical treatment of hydrocephalus—an historical review. **Surg Neurol 15:**15–26, 1981
67. Rammos S, Klopfenstein J, Augspurger L, Wang H, Wagenbach A, Poston J, et al: Conversion of external ventricular drains to ventriculoperitoneal shunts after aneurysmal subarachnoid hemorrhage: effects of site and protein/red blood cell counts on shunt infection and malfunction. **J Neurosurg 109:**1001–1004, 2008 (Erratum **J Neurosurg 110:**196, 2009)
68. Ratilal B, Costa J, Sampaio C: Antibiotic prophylaxis for surgical introduction of intracranial ventricular shunts: a systematic review. **J Neurosurg Pediatr 1:**48–56, 2008
69. Regenbogen SE, Greenberg CC, Resch SC, Kollengode A, Cima RR, Zinner MJ, et al: Prevention of retained surgical sponges: a decision-analytic model predicting relative cost-effectiveness. **Surgery 145:**527–535, 2009
70. Reig AS, Stevenson CB, Tulipan NB: CT-based, fiducial-free frameless stereotaxy for difficult ventriculoperitoneal shunt insertion: experience in 26 consecutive patients. **Stereotact Funct Neurosurg 88:**75–80, 2010
71. Ritz R, Roser F, Morgalla M, Dietz K, Tatagiba M, Will BE:

Do antibiotic-impregnated shunts in hydrocephalus therapy reduce the risk of infection? An observational study in 258 patients. **BMC Infect Dis 7:**38, 2007
72. Rotim K, Miklic P, Paladino J, Melada A, Marcikic M, Scap M: Reducing the incidence of infection in pediatric cerebrospinal fluid shunt operations. **Childs Nerv Syst 13:**584–587, 1997
73. Salomão JF, Leibinger RD: Abdominal pseudocysts complicating CSF shunting in infants and children. Report of 18 cases. **Pediatr Neurosurg 31:**274–278, 1999
74. Sato O, Yamguchi T, Kittaka M, Toyama H: Hydrocephalus and epilepsy. **Childs Nerv Syst 17:**76–86, 2001
75. Savitz MH, Bobroff LM: Low incidence of delayed intracerebral hemorrhage secondary to ventriculoperitoneal shunt insertion. **J Neurosurg 91:**32–34, 1999
76. Schoenbaum SC, Gardner P, Shillito J: Infections of cerebrospinal fluid shunts: epidemiology, clinical manifestations, and therapy. **J Infect Dis 131:**543–552, 1975
77. Sciubba DM, Noggle JC, Carson BS, Jallo GI: Antibiotic-impregnated shunt catheters for the treatment of infantile hydrocephalus. **Pediatr Neurosurg 44:**91–96, 2008
78. Sciubba DM, Stuart RM, McGirt MJ, Woodworth GF, Samdani A, Carson B, et al: Effect of antibiotic-impregnated shunt catheters in decreasing the incidence of shunt infection in the treatment of hydrocephalus. **J Neurosurg 103 (2 Suppl):**131–136, 2005
79. Scott RM: **Hydrocephalus.** Baltimore: Williams & Wilkins, 1990
80. Simon TD, Hall M, Riva-Cambrin J, Albert JE, Jeffries HE, Lafleur B, et al: Infection rates following initial cerebrospinal fluid shunt placement across pediatric hospitals in the United States. Clinical article. **J Neurosurg Pediatr 4:**156–165, 2009
81. Simon TD, Riva-Cambrin J, Srivastava R, Bratton SL, Dean JM, Kestle JRW: Hospital care for children with hydrocephalus in the United States: utilization, charges, comorbidities, and deaths. **J Neurosurg Pediatr 1:**131–137, 2008
82. Stein SC, Guo W: Have we made progress in preventing shunt failure? A critical analysis. **J Neurosurg Pediatr 1:**40–47, 2008
83. Steinbok P, Milner R, Agrawal D, Farace E, Leung GK, Ng I, et al: A multicenter multinational registry for assessing ventriculoperitoneal shunt infections for hydrocephalus. **Neurosurgery 67:**1303–1310, 2010
84. Thomas R, Lee S, Patole S, Rao S: Antibiotic-impregnated catheters for the prevention of CSF shunt infections: a systematic review and meta-analysis. **Br J Neurosurg 26:**175–184, 2012
85. Tuli S, O'Hayon B, Drake J, Clarke M, Kestle J: Change in ventricular size and effect of ventricular catheter placement in pediatric patients with shunted hydrocephalus. **Neurosurgery 45:**1329–1335, 1999
86. Tulipan N, Cleves MA: Effect of an intraoperative double-gloving strategy on the incidence of cerebrospinal fluid shunt infection. **J Neurosurg 104 (1 Suppl):**5–8, 2006
87. Turner RD, Rosenblatt SM, Chand B, Luciano MG: Laparoscopic peritoneal catheter placement: results of a new method in 111 patients. **Neurosurgery 61 (3 Suppl):**167–174, 2007
88. Venes JL, Dauser RC: Epilepsy following ventricular shunt placement. **J Neurosurg 66:**154–155, 1987
89. Vinchon M, Baroncini M, Laurent T, Patrick D: Bowel perforation caused by peritoneal shunt catheters: diagnosis and treatment. **Neurosurgery 58 (1 Suppl):**ONS76–ONS82, 2006
90. Vinchon M, Dhellemmes P: Cerebrospinal fluid shunt infection: risk factors and long-term follow-up. **Childs Nerv Syst 22:**692–697, 2006
91. Walker IA, Merry AF, Wilson IH, McHugh GA, O'Sullivan E, Thoms GM, et al: Global oximetry: an international anaesthesia quality improvement project. **Anaesthesia 64:**1051–1060, 2009
92. Warf BC: Comparison of endoscopic third ventriculostomy alone and combined with choroid plexus cauterization in infants younger than 1 year of age: a prospective study in 550 African children. **J Neurosurg 103 (6 Suppl):**475–481, 2005
93. Warf BC: Hydrocephalus in Uganda: the predominance of infectious origin and primary management with endoscopic third ventriculostomy. **J Neurosurg 102 (1 Suppl):**1–15, 2005
94. Weiser TG, Haynes AB, Dziekan G, Berry WR, Lipsitz SR, Gawande AA: Effect of a 19-item surgical safety checklist during urgent operations in a global patient population. **Ann Surg 251:**976–980, 2010
95. Weiser TG, Makary MA, Haynes AB, Dziekan G, Berry WR, Gawande AA: Standardised metrics for global surgical surveillance. **Lancet 374:**1113–1117, 2009
96. Whitehead WE, Jea A, Vachhrajani S, Kulkarni AV, Drake JM: Accurate placement of cerebrospinal fluid shunt ventricular catheters with real-time ultrasound guidance in older children without patent fontanelles. **J Neurosurg 107 (5 Suppl):** 406–410, 2007
97. Wong JM, Bader AM, Laws ER, Popp AJ, Gawande AA: Patterns in neurosurgical adverse events and proposed strategies for reduction. **Neurosurg Focus 33(5):**E1, 2012
98. Woodworth GF, McGirt MJ, Elfert P, Sciubba DM, Rigamonti D: Frameless stereotactic ventricular shunt placement for idiopathic intracranial hypertension. **Stereotact Funct Neurosurg 83:**12–16, 2005
99. Yamashita N, Kamiya K, Yamada K: Experience with a programmable valve shunt system. **J Neurosurg 91:**26–31, 1999

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