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A mathematical model of survival in a newly inserted ventricular shunt

Sherman C. Stein, M.D.,[1] and Wensheng Guo, Ph.D.[2]

[1]Department of Neurosurgery, and [2]Center for Clinical Epidemiology and Biostatistics, University of Pennsylvania School of Medicine, Philadelphia, Pennsylvania

Object. The object of this study was to mathematically model the prognosis of a newly inserted shunt in pediatric or adult patients with hydrocephalus.

Methods. A structured search was performed of the English-language literature for case series reporting shunt failure, patient mortality, and shunt removal rates after shunt insertion. A metaanalytic model was constructed to pool data from multiple studies and to predict the outcome of a shunt after insertion. Separate models were used to predict shunt survival rates for children (patients < 17 years old) and adults.

Results. Shunt survival rates in children and adults were calculated for 1 year (64.2 and 80.1%, respectively), 5 years (49.4 and 60.2%, respectively), and the median (4.9 and 7.3 years, respectively). The longer-term rates predicted by the model agree closely with those reported in the literature.

Conclusions. This model gives a comprehensive view of the fate of a shunt for hydrocephalus after insertion. The advantages of this model compared with Kaplan–Meier survival curves are discussed. The model used in this study may provide useful prognostic information and aid in the early evaluation of new shunt designs and techniques.
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Key Words • cerebrospinal fluid shunt • hydrocephalus • pediatric neurosurgery • shunt failure • shunt malfunction

Although ventricular shunts have been remarkably effective in treating hydrocephalus, their rate of failure remains quite high. Yet it is difficult to predict the fate of the average patient in whom a shunt is placed. There are several causes for shunt failure, including under- and overdrainage, mechanical blockage, valve failure, disconnection, and infection. Follow-up durations vary in published studies of ventricular shunts. Many case series are hampered by incomplete follow-up, because not all patients return to the same institution in which shunt insertion occurred. Shunt-related complications occur at varying rates in different series, in part due to different shunt devices, surgical practices, and definitions of complications. Rates of complication and death also vary according to patient age and the diseases causing the hydrocephalus. Some patients never require shunt revision, whereas others need several revisions in a single year. Thus, despite experience with many thousands of shunt procedures, physicians find it difficult to find reliable predictions when counseling patients and their families on the prognoses of newly implanted shunts.

The purpose of this report is to simulate the outcome of a recently placed shunt over time in the average child or adult with hydrocephalus. These projections are compared with measurements reported in the literature.

Clinical Material and Methods

We performed a structured literature search of English-language articles in the MEDLINE database for the years between 1950 and 2007 (March), using the key words "hydrocephalus," along with various combinations of the key words "treatment," "shunt" ("shunts," "shunted," "shunting"), "complications," "mortality," and "death." This search was supplemented with additional references from the bibliographies of articles previously read by the authors and by using the "Related Articles" feature of PubMed. We excluded animal studies, editorials, case reports, letters to the editor, reviews, and studies duplicating data from previous reports. This process yielded 1993 publications, which were reviewed for data relating to rates of shunt complication, removal, and replacement, or patient mortality rates. In the 126 case series used in this study, one or more of these rates were reported or could be calculated from the data given.

We abstracted estimates of the probability of patient death, shunt failure, and shunt removal. Data for children (Table 1) and adults (Table 2) were pooled separately. Following the convention in the literature, we used the age of 17 years as the separation between childhood and adulthood. The reported point estimates of pooled data represent

TABLE 1

*Abstracted estimates of the probability of death, shunt failure, and shunt removal in pooled data for children**

Category	No. of Patients	Probability	95% CI	Reference No.
mortality rate at yr 1	5,574	0.0410	0.0355–0.0465	1,4,23,52,54,61,62,99,125,130
annual mortality rate after yr 1	2,236	0.0141	0.0086–0.0251	
shunt failure rate at yr 1	18,213	0.3128	0.2579–0.3678	1–3,8,9,11,20,21,23,24,26–28,31,33,35,39–42,44,46,
annual shunt failure rate after yr 1	7,150	0.0454	0.0307–0.0600	47,49,50,57,59,62,63,68,74,76,77,85,87,88,93,96–98,101,103,107–110,124,130,132,136
annual shunt removal rate	1,976	0.0039	0.0014–0.0064	33,51,56,134

* Rate = perioperative + annual rate. Abbreviation: CI = confidence interval.

variance-weighted means and were tested for heterogeneity.[38,67] The rate of shunt removal in adults is so low that it is considered zero for modeling purposes.[51,71] All probabilities that vary over time (such as mortality rates) were corrected for rates in 2000, the latest year for which accurate data are available.

We calculated the rate of shunt failures in the first year and annual failure rates for subsequent years, where available. In studies not listing delayed complication rates explicitly, we estimated these rates from the number of delayed shunt failures and the mean number of patient–years beyond 1 year on follow-up (for each study, the former number divided by the latter equals the mean annual failure rate). In reports employing Kaplan–Meier survival curves, calculating the mean annual failure rate usually involved manually calculating the number of subjects at risk for shunt failure and the number of shunt failures at each step in the published curves.

We used Markov modeling techniques[116] to simulate the course of patients undergoing shunt insertion. These techniques enabled us to follow the progress of a simulated cohort of patients. The possible pathways and outcomes after shunt insertion are shown in Fig. 1. During any Markov model cycle (in this case, 1 year), a patient in whom a shunt is placed may die. If he or she survives, his or her shunt may continue to work normally, fail, or be removed for arrested hydrocephalus. The probability of a shunt or patient transitioning from one state to another is determined by the pooled estimates in Tables 1 and 2. During each cycle, these probabilities are applied to patients in each state, and new percentages are calculated. The model runs until the proportion of functioning shunts approaches zero. A multistate, time-dependent, transition decision model was constructed using the TreeAge Pro 2006 software package (TreeAge Software). This transition decision model was run separately for children and adults, because of their different transition probabilities.

Results

The state of a shunt inserted into a child, predicted by our model at any point in time, is illustrated in Figure 2. Failure and mortality rates are highest in the first year, and decrease thereafter. Figure 3 shows the same categories for shunt insertions in adults. Even though patient deaths are greater in adults with shunt insertions, shunts in adults fail more slowly and tend to survive longer than those in children. Median shunt survival times, as well as 1- and 5-year shunt survival rates, agree closely with estimates from the literature.

Discussion

Our model illustrates the relative brevity of shunt survival, both in children and adults. Shunt failure is the greatest contributor to loss of a functioning shunt. In addition, the underlying illnesses and the risk of perioperative complications during shunt insertion contribute to patient mortality rates.

A number of case series have examined shunt longevity and yielded varied results. Our model yields a 1-year shunt survival rate in children of just over 64%, a rate that is well within the range reported in most case series. Median shunt survival predicted by our model is approximately 5 years in children; estimates in the literature range from less than 1 year to more than seven, varying with children's ages, hydrocephalus origins, and other factors.[2,23,27,31,35,39,60,62,74,75,88,93,101,108,110,136] Although new shunts have a somewhat longer

TABLE 2

*Abstracted estimates of the probability of death, shunt failure, and shunt removal in pooled data for adults**

Category	No. of Patients	Probability	95% CI	Reference No.
mortality rate at yr 1†	7809	0.0365	0.0269–0.0461	10,12,13,16,18,19,22,30,43,48,58,69,70,72,73,82,90,99,100,102,105,106,112–114,117,123,127,128,131,133,135
annual mortality rate after yr 1	384	0.0166	0.0070–0.0260	6,16,83,92,95,113
shunt failure rate at yr 1	3879	0.1625	0.1109–0.2139	5,7,10,12,13,15–19,22,25,29,30,32,34,37,43,45,48,
annual shunt failure rate after yr 1	1687	0.0522	0.0296–0.0749	50,53,55,58,64–66,68–70,72,73,78–82,84,89–91,94,95,102,104–106,111,112,114,115,117,118,120,121,123,126,129,131,133,135,137

* Shunt removal rate probability is effectively 0 in adults.
† Rate = perioperative + annual rate.

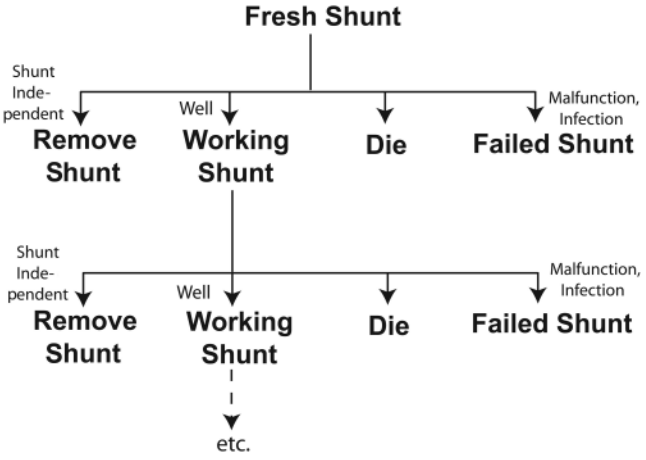

FIG. 1. Diagram of the possible states and transitions of a shunt and the patient in the Markov model. During any 1-year cycle, a newly inserted shunt may fail, be removed, or continue working. The patient may die of natural or shunt-related causes. This cycle continues in the Markov model until no working shunts are left.

survival rate in adults, the disparity of rates among case series is also quite large.

Many of the studies cited employ Kaplan–Meier curves to calculate shunt survival. Although use of these curves is a generally accepted approach, it has severe limitations.[14] The number of patients in most of the trials is relatively small and the hydrocephalus origins vary. For example, some studies include only neonates or infants, whereas others do not include children with brain tumors; these factors may alter measured shunt survival rates. It is not always clear which events lead to study censorship (exclusion from later analysis times), shunt failure, shunt removal, loss or withdrawal from follow-up, or patient death.[36,119] There are additional technical issues, and the Kaplan–Meier approach

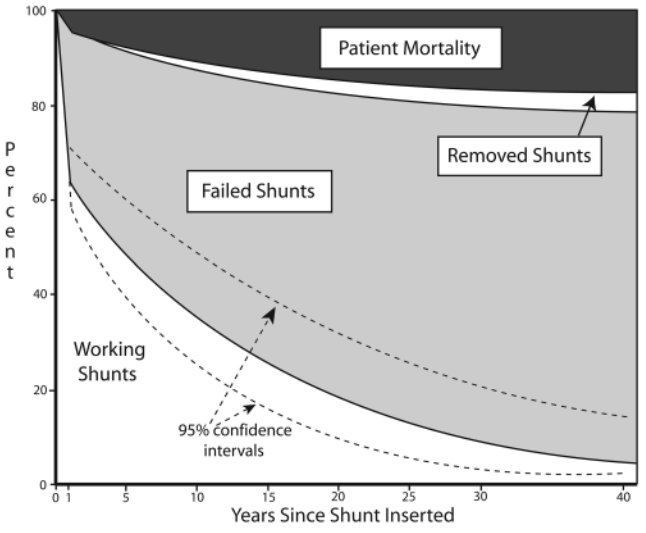

FIG. 2. Graph of the predicted survival rates of a newly inserted shunt in a child. At each point in time, the graph illustrates the relative proportion of shunts that remain functional (with 95% CIs), fail, or are removed. Also shown are the percentages of patients treated using shunts, who later died.

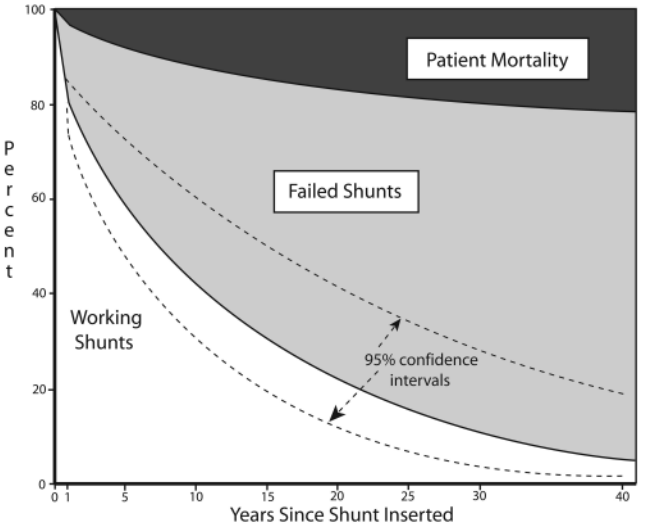

FIG. 3. Graph of the predicted survival rates of a newly inserted shunt in an adult. At each point in time, the graph shows the relative proportion of shunts that remain functional (with 95% CIs) or that fail. Also shown are the percentages of patients treated using shunts, who later died.

makes several assumptions that may render it inappropriate for tracking shunt survival.[86,122] These other issues include the dwindling number of patients in the study over time, rendering the technique least certain and hence least useful in predicting long-term events. Other shortcomings of the Kaplan–Meier technique include potential biases caused by handling competing risks (other than, as in this study, shunt failure), difficulty timing failures, or censored events. Survival rates cannot be pooled from multiple studies using Kaplan–Meier methodology.

The Markov model is dynamic and can project events into the future.[116] This model can serve as a guide for explaining shunt prognosis to patients and families before surgery. It can also be applied as a realistic baseline against which to compare the results of pilot studies in new shunt devices, experimental techniques, and other potential advances in shunt preservation. Investigators can get a sense of whether their preliminary results are superior to standard shunt survival before investing considerable time and effort on multicenter trials. This model is limited, as are all such mathematical approaches, by the quality of the underlying data. Pooling so many case series drawn from different times, geographic locales, shunt techniques, and patient populations has a homogenizing effect and minimizes differences.

Conclusions

Although many factors influence shunt survival, it is possible to model the prognosis of the average shunt inserted into a child or adult and to predict future behavior of the shunt. The results calculated for our models are well within the ranges cited in the literature.

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References

1. Abdullah J, Naing NN: Hydrocephalic children presenting to a Malaysian community-based university hospital over an 8-year period. **Pediatr Neurosurg 34:**13–19, 2001
2. Albright AL, Haines SJ, Taylor FH: Function of parietal and frontal shunts in childhood hydrocephalus. **J Neurosurg 69:** 883–886, 1988
3. Albright AL, Pollack IF, Adelson PD, Solot JJ: Outcome data and analysis in pediatric neurosurgery. **Neurosurgery 45:**101–106, 1999
4. Amacher AL, Wellington J: Infantile hydrocephalus: long-term results of surgical therapy. **Childs Brain 11:**217–229, 1984
5. Anderson RC, Grant JJ, de la Paz R, Frucht S, Goodman RR: Volumetric measurements in the detection of reduced ventricular volume in patients with normal-pressure hydrocephalus whose clinical condition improved after ventriculoperitoneal shunt placement. **J Neurosurg 97:**73–79, 2002
6. Aygok G, Marmarou A, Young HF: Three-year outcome of shunted idiopathic NPH patients. **Acta Neurochir Suppl 95:** 241–245, 2005
7. Bárcena A, Mestre C, Cañizal JM, Rivero B, Lobato RD: Idiopathic normal pressure hydrocephalus: analysis of factors related to cerebrospinal fluid dynamics determining functional prognosis. **Acta Neurochir (Wien) 139:**933–941, 1997
8. Becker DP, Nulsen FE: Control of hydrocephalus by valve-regulated venous shunt: avoidance of complications in prolonged shunt maintenance. **J Neurosurg 28:**215–226, 1968
9. Beks JW, ter Weeme CA: Results of the treatment of hydrocephalus with ventriculo-jugular shunts. **Neurochirurgia (Stuttg) 18:** 118–120, 1975
10. Benzel EC, Pelletier AL, Levy PG: Communicating hydrocephalus in adults: prediction of outcome after ventricular shunting procedures. **Neurosurgery 26:**655–660, 1990
11. Bierbrauer KS, Storrs BB, McLone DG, Tomita T, Dauser R: A prospective, randomized study of shunt function and infections as a function of shunt placement. **Pediatr Neurosurg 16:**287–291, 1990/1991
12. Black PM: Idiopathic normal-pressure hydrocephalus. Results of shunting in 62 patients. **J Neurosurg 52:**371–377, 1980
13. Black PM, Ojemann RG, Tzouras A: CSF shunts for dementia, incontinence, and gait disturbance. **Clin Neurosurg 32:**632–651, 1985
14. Bland JM, Altman DG: Survival probabilities (the Kaplan–Meier method). **BMJ 317:**1572–1580, 1998
15. Boon AJ, Tans JT, Delwel EJ, Egeler-Peerdeman SM, Hanlo PW, Wurzer HA, et al: Dutch normal-pressure hydrocephalus study: prediction of outcome after shunting by resistance to outflow of cerebrospinal fluid. **J Neurosurg 87:**687–693, 1997
16. Boon AJ, Tans JT, Delwel EJ, Egeler-Peerdeman SM, Hanlo PW, Wurzer HA, et al: Dutch Normal-Pressure Hydrocephalus Study: randomized comparison of low- and medium-pressure shunts. **J Neurosurg 88:**490–495, 1998
17. Boon AJ, Tans JT, Delwel EJ, Egeler-Peerdeman SM, Hanlo PW, Wurzer JA, et al: Does CSF outflow resistance predict the response to shunting in patients with normal pressure hydrocephalus? **Acta Neurochir Suppl 71:**331–333, 1998
18. Borgesen SE: Conductance to outflow of CSF in normal pressure hydrocephalus. **Acta Neurochir (Wien) 71:**1–45, 1984
19. Borgesen SE, Gjerris F: The predictive value of conductance to outflow of CSF in normal pressure hydrocephalus. **Brain 105:** 65–86, 1982
20. Caldarelli M, Di Rocco C, La Marca F: Shunt complications in the first postoperative year in children with meningomyelocele. **Childs Nerv Syst 12:**748–754, 1996
21. Carrington KW: Ventriculo-venous shunt using the Holter valve as a treatment of hydrocephalus. **J Mich State Med Soc 58:** 373–376 passim, 1959
22. Caruso R, Cervoni L, Vitale AM, Salvati M: Idiopathic normal-pressure hydrocephalus in adults: result of shunting correlated with clinical findings in 18 patients and review of the literature. **Neurosurg Rev 20:**104–107, 1997
23. 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
24. Cast IP, Schurr PH: Experience in the use of ventriculoatrial shunts with the Pudenz valve. **Dev Med Child Neurol Suppl 20:**71–74, 1969
25. Chen IH, Huang CI, Liu HC, Chen KK: Effectiveness of shunting in patients with normal pressure hydrocephalus predicted by temporary, controlled-resistance, continuous lumbar drainage: a pilot study. **J Neurol Neurosurg Psychiatry 57:**1430–1432, 1994
26. Choudhury AR: Avoidable factors that contribute to the complications of ventriculoperitoneal shunt in childhood hydrocephalus. **Childs Nerv Syst 6:**346–349, 1990
27. Cochrane D, Kestle J, Steinbok P, Evans D, Heron N: Model for the cost analysis of shunted hydrocephalic children. **Pediatr Neurosurg 23:**14–19, 1995
28. Cochrane DD, Kestle J: Ventricular shunting for hydrocephalus in children: patients, procedures, surgeons and institutions in English Canada, 1989–2001. **Eur J Pediatr Surg 12 (1 Suppl):**S6–S11, 2002
29. Corkill RG, Garnett MR, Blamire AM, Rajagopalan B, Cadoux-Hudson TA, Styles P: Multi-modal MRI in normal pressure hydrocephalus identifies pre-operative haemodynamic and diffusion coefficient changes in normal appearing white matter correlating with surgical outcome. **Clin Neurol Neurosurg 105:** 193–202, 2003
30. Damasceno BP, Carelli EF, Honorato DC, Facure JJ: The predictive value of cerebrospinal fluid tap-test in normal pressure hydrocephalus. **Arq Neuropsiquiatr 55:**179–185, 1997
31. Davis SE, Levy ML, McComb JG, Sposto R: The delta valve: how does its clinical performance compare with two other pressure differential valves without antisiphon control? **Pediatr Neurosurg 33:**58–63, 2000
32. Decq P, Barat JL, Duplessis E, Leguerinel C, Gendrault P, Keravel Y: Shunt failure in adult hydrocephalus: flow-controlled shunt versus differential pressure shunts—a cooperative study in 289 patients. **Surg Neurol 43:**333–339, 1995
33. Di Rocco C, Marchese E, Velardi F: A survey of the first complication of newly implanted CSF shunt devices for the treatment of nontumoral hydrocephalus. Cooperative survey of the 1991–1992 Education Committee of the ISPN. **Childs Nerv Syst 10:** 321–327, 1994
34. Dixon GR, Friedman JA, Luetmer PH, Quast LM, McClelland RL, Petersen RC, et al: Use of cerebrospinal fluid flow rates measured by phase-contrast MR to predict outcome of ventriculoperitoneal shunting for idiopathic normal-pressure hydrocephalus. **Mayo Clin Proc 77:**509–514, 2002
35. 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
36. Duchateau L, Collette L, Sylvester R, Pignon JP: Estimating number of events from the Kaplan–Meier curve for incorporation in a literature-based meta-analysis: what you don't see you can't get! **Biometrics 56:**886–892, 2000
37. Egeler-Peerdeman SM, Barkhof F, Walchenbach R, Valk J: Cine phase-contrast MR imaging in normal pressure hydrocephalus patients: relation to surgical outcome. **Acta Neurochir Suppl 71:**340–342, 1998
38. Einarson TR: Pharmacoeconomic applications of meta-analysis for single groups using antifungal onychomycosis lacquers as an example. **Clin Ther 19:**559–569, 1997
39. Eymann R, Steudel WI, Kiefer M: Pediatric gravitational shunts: initial results from a prospective study. **J Neurosurg 106 (3 Suppl):**179–184, 2007

40. Foltz EL, Shurtleff DB: Five-year comparative study of hydrocephalus in children with and without operation (113 cases). **J Neurosurg 20:**1064–1079, 1963
41. Forrest DM, Cooper DGW: Complications of ventriculo-atrial shunts. **J Neurosurg 29:**506–512, 1968
42. Giuffré R, Palma L, Fontana M: Follow-up study of 360 children subjected to extracranial CSF shunt for hydrocephalus. **Mod Probl Paediatr 18:**198–202, 1976
43. Greenberg JO, Shenkin HA, Adam R: Idiopathic normal pressure hydrocephalus—a report of 73 patients. **J Neurol Neurosurg Psychiatry 40:**336–341, 1977
44. Gruber R, Jenny P, Herzog B: Experiences with the anti-siphon device (ASD) in shunt therapy of pediatric hydrocephalus. **J Neurosurg 61:**156–162, 1984
45. Guidetti B, Gagliardi FM: Normal pressure hydrocephalus. **Acta Neurochir (Wien) 27:**1–9, 1972
46. Guidetti B, Giuffrè R, Palma L, Fontana M: Hydrocephalus in infancy and childhood. Our experience of CSF shunting. **Childs Brain 2:**209–225, 1976
47. Guidetti B, Occhipinti E, Riccio A: Ventriculo-atrial shunt in 200 cases of non tumoral hydrocephalus in children: remarks on the diagnostic criteria, postoperative complications and long-term results. **Acta Neurochir (Wien) 21:**295–308, 1969
48. Haan J, Thomeer RT: Predictive value of temporary external lumbar drainage in normal pressure hydrocephalus. **Neurosurgery 22:**388–391, 1988
49. Hammon WM: Evaluation and use of the ventriculoperitoneal shunt in hydrocephalus. **J Neurosurg 34:**792–795, 1971
50. Hanlo PW, Cinalli G, Vandertop WP, Faber JA, Bogeskov L, Borgesen 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
51. Hayden PW, Shurtleff DB, Stuntz TJ: A longitudinal study of shunt function in 360 patients with hydrocephalus. **Dev Med Child Neurol 25:**334–337, 1983
52. Heinsbergen I, Rotteveel J, Roeleveld N, Grotenhuis A: Outcome in shunted hydrocephalic children. **Eur J Paediatr Neurol 6:**99–107, 2002
53. Hertel F, Walter C, Schmitt M, Morsdorf M, Jammers W, Busch HP, et al: Is a combination of Tc-SPECT or perfusion weighted magnetic resonance imaging with spinal tap test helpful in the diagnosis of normal pressure hydrocephalus? **J Neurol Neurosurg Psychiatry 74:**479–484, 2003
54. Hoppe-Hirsch E, Laroussinie F, Brunet L, Sainte-Rose C, Renier D, Cinalli G, et al: Late outcome of the surgical treatment of hydrocephalus. **Childs Nerv Syst 14:**97–99, 1998
55. Hughes CP, Siegel BA, Coxe WS, Gado MH, Grubb RL, Coleman RE, et al: Adult idiopathic communicating hydrocephalus with and without shunting. **J Neurol Neurosurg Psychiatry 41:**961–971, 1978
56. Iannelli A, Rea G, Di Rocco C: CSF shunt removal in children with hydrocephalus. **Acta Neurochir (Wien) 147:**503–507, 2005
57. Ivan LP, Choo SH, Ventureyra EC: Complications of ventriculoatrial and ventriculoperitoneal shunts in a new children's hospital. **Can J Surg 23:**566–568, 1980
58. Kahlon B, Sundbärg G, Rehncrona S: Comparison between the lumbar infusion and CSF tap tests to predict outcome after shunt surgery in suspected normal pressure hydrocephalus. **J Neurol Neurosurg Psychiatry 73:**721–726, 2002
59. Kang JK, Lee IW: Long-term follow-up of shunting therapy. **Childs Nerv Syst 15:**711–717, 1999
60. Kast J, Duong D, Nowzari F, Chadduck WM, Schiff SJ: Time-related patterns of ventricular shunt failure. **Childs Nerv Syst 10:**524–528, 1994
61. Kay AD, Fisher AJ, O'Kane C, Richards HK, Pickard JD: A clinical audit of the Hakim programmable valve in patients with complex hydrocephalus. **Br J Neurosurg 14:**535–542, 2000
62. Kestle JR, Drake JM, Cochrane DD, Milner R, Walker ML, Abbott R III, et al: Lack of benefit of endoscopic ventriculoperitoneal shunt insertion: a multicenter randomized trial. **J Neurosurg 98:**284–290, 2003
63. Keucher TR, Mealey J Jr: Long-term results after ventriculoatrial and ventriculoperitoneal shunting for infantile hydrocephalus. **J Neurosurg 50:**179–186, 1979
64. Kiefer M, Eymann R, Meier U: Five years experience with gravitational shunts in chronic hydrocephalus of adults. **Acta Neurochir (Wien) 144:**755–767, 2002
65. Kiefer M, Eymann R, Steudel WI, Strowitzki M: Gravitational shunt management of long-standing overt ventriculomegaly in adult (LOVA) hydrocephalus. **J Clin Neurosci 12:**21–26, 2005
66. Kiefer M, Eymann R, Strowitzki M, Steudel WI: Gravitational shunts in longstanding overt ventriculomegaly in adults. **Neurosurgery 57:**109–119, 2005
67. King JT Jr, Berlin JA, Flamm ES: Morbidity and mortality from elective surgery for asymptomatic, unruptured, intracranial aneurysms: a meta-analysis. **J Neurosurg 81:**837–842, 1994
68. Kirsch WM, Newkirk JB, Predecki PK: Clinical experience with the Denver shunt: a new silicone-rubber shunting device for the treatment of hydrocephalus. Technical note. **J Neurosurg 32:** 258–264, 1970
69. Kosteljanetz M, Nehen AM, Kaalund J: Cerebrospinal fluid outflow resistance measurements in the selection of patients for shunt surgery in the normal pressure hydrocephalus syndrome. A controlled trial. **Acta Neurochir (Wien) 104:**48–53, 1990
70. Krauss JK, Droste DW, Vach W, Regel JP, Orszagh M, Borremans JJ, et al: Cerebrospinal fluid shunting in idiopathic normal-pressure hydrocephalus of the elderly: effect of periventricular and deep white matter lesions. **Neurosurgery 39:**292–300, 1996
71. Larsson A, Stephensen H, Wikkelso C: Adult patients with "asymptomatic" and "compensated" hydrocephalus benefit from surgery. **Acta Neurol Scand 99:**81–90, 1999
72. Larsson A, Wikkelsö C, Bilting M, Stephensen H: Clinical parameters in 74 consecutive patients shunt operated for normal pressure hydrocephalus. **Acta Neurol Scand 84:**475–482, 1991
73. Laws ER, Mokri B: Occult hydrocephalus: results of shunting correlated with diagnostic tests. **Clin Neurosurg 24:**316–333, 1977
74. Lazareff JA, Peacock W, Holly L, Ver Halen J, Wong A, Olmstead C: Multiple shunt failures: an analysis of relevant factors. **Childs Nerv Syst 14:**271–275, 1998
75. Liptak GS, Masiulis BS, McDonald JV: Ventricular shunt survival in children with neural tube defects. **Acta Neurochir (Wien) 74:**113–117, 1985
76. Liptak GS, McDonald JV: Ventriculoperitoneal shunts in children: factors affecting shunt survival. **Pediatr Neurosci 12:**289–293, 1985/1986
77. Little JR, Rhoton AL Jr, Mellinger JF: Comparison of ventriculoperitoneal and ventriculoatrial shunts for hydrocephalus in children. **Mayo Clin Proc 47:**396–401, 1972
78. Lumenta CB, Roosen N, Dietrich U: Clinical experience with a pressure-adjustable valve SOPHY in the management of hydrocephalus. **Childs Nerv Syst 6:**270–274, 1990
79. Lund-Johansen M, Svendsen F, Wester K: Shunt failures and complications in adults as related to shunt type, diagnosis, and the experience of the surgeon. **Neurosurgery 35:**839–844, 1994
80. Magnaes B: Communicating hydrocephalus in adults. Diagnostic tests and results of treatment with medium pressure shunts. **Neurology 28:**478–484, 1978
81. Malm J, Kristensen B, Fagerlund M, Koskinen LO, Ekstedt J: Cerebrospinal fluid shunt dynamics in patients with idiopathic adult hydrocephalus syndrome. **J Neurol Neurosurg Psychiatry 58:**715–723, 1995
82. Malm J, Kristensen B, Karlsson T, Fagerlund M, Elfverson J, Ekstedt J: The predictive value of cerebrospinal fluid dynamic tests in patients with the idiopathic adult hydrocephalus syndrome. **Arch Neurol 52:**783–789, 1995
83. Malm J, Kristensen B, Stegmayr B, Fagerlund M, Koskinen LO:

Three-year survival and functional outcome of patients with idiopathic adult hydrocephalus syndrome. **Neurology 55:**576–578, 2000
84. Malm J, Lundkvist B, Eklund A, Koskinen LO, Kristensen B: CSF outflow resistance as predictor of shunt function. A long-term study. **Acta Neurol Scand 110:**154–160, 2004
85. Matson DD: **Neurosurgery of Infancy and Childhood.** Springfield, IL: Charles C Thomas, 1969, pp 222–258
86. May M, Sterne J, Egger M: Parametric survival models may be more accurate than Kaplan–Meier estimates. **BMJ 326:**822, 2003 (Letter)
87. Mazza C, Pasqualin A, Da Pian R: Results of treatment with ventriculoatrial and ventriculoperitoneal shunt in infantile nontumoral hydrocephalus. **Childs Brain 7:**1–14, 1980
88. McGirt MJ, Leveque JC, Wellons JC III, Villavicencio AT, Hopkins JS, Fuchs HE, et al: Cerebrospinal fluid shunt survival and etiology of failures: a seven-year institutional experience. **Pediatr Neurosurg 36:**248–255, 2002
89. McGirt MJ, Woodworth G, Coon AL, Thomas G, Williams MA, Rigamonti D: Diagnosis, treatment, and analysis of long-term outcomes in idiopathic normal-pressure hydrocephalus. **Neurosurgery 57:**699–705, 2005
90. McQuarrie IG, Saint-Louis L, Scherer PB: Treatment of normal pressure hydrocephalus with low versus medium pressure cerebrospinal fluid shunts. **Neurosurgery 15:**484–488, 1984
91. Meier U, Kintzel D: Clinical experiences with different valve systems in patients with normal-pressure hydrocephalus: evaluation of the Miethke dual-switch valve. **Childs Nerv Syst 18:** 288–294, 2002
92. Meier U, Lemcke J: Clinical outcome of patients with idiopathic normal pressure hydrocephalus three years after shunt implantation. **Acta Neurochir Suppl 96:**377–380, 2006
93. Meling TR, Egge A, Due-Tonnessen B: The gravity-assisted Paedi-Gav valve in the treatment of pediatric hydrocephalus. **Pediatr Neurosurg 41:**8–14, 2005
94. Meyer JS, Kitagawa Y, Tanahashi N, Tachibana H, Kandula P, Cech DA, et al: Evaluation of treatment of normal-pressure hydrocephalus. **J Neurosurg 62:**513–521, 1985
95. Mori K: Management of idiopathic normal-pressure hydrocephalus: a multiinstitutional study conducted in Japan. **J Neurosurg 95:**970–973, 2001
96. Nulsen FE, Becker DP: Control of hydrocephalus by valve-regulated shunt: infections and their prevention. **Clin Neurosurg 14:** 256–273, 1966
97. Olsen L, Frykberg T: Complications in the treatment of hydrocephalus in children. A comparison of ventriculoatrial and ventriculoperitoneal shunts in a 20-year material. **Acta Paediatr Scand 72:**385–390, 1983
98. Overton MC III, Snodgrass SR: Ventriculo-venous shunts for infantile hydrocephalus. A review of five years' experience with this method. **J Neurosurg 23:**517–521, 1965
99. 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
100. Petersen RC, Mokri B, Laws ER Jr: Surgical treatment of idiopathic hydrocephalus in elderly patients. **Neurology 35:**307–311, 1985
101. Piatt JH Jr, Carlson CV: A search for determinants of cerebrospinal fluid shunt survival: retrospective analysis of a 14-year institutional experience. **Pediatr Neurosurg 19:**233–242, 1993
102. Poca MA, Mataró M, Del Mar Matarín M, Arikan F, Junqué C, Sahuquillo J: Is the placement of shunts in patients with idiopathic normal-pressure hydrocephalus worth the risk? Results of a study based on continuous monitoring of intracranial pressure. **J Neurosurg 100:**855–866, 2004
103. Pople IK, Quinn MW, Bayston R: Morbidity and outcome of shunted hydrocephalus. **Z Kinderchir 45 (1 Suppl):**29–31, 1990
104. Puca A, Anile C, Maira G, Rossi G: Cerebrospinal fluid shunting for hydrocephalus in the adult: factors related to shunt revision. **Neurosurgery 29:**822–826, 1991
105. Raftopoulos C, Deleval J, Chaskis C, Leonard A, Cantraine F, Desmyttere F, et al: Cognitive recovery in idiopathic normal pressure hydrocephalus: a prospective study. **Neurosurgery 35:** 397–405, 1994
106. Raftopoulos C, Massager N, Balériaux D, Deleval J, Clarysse S, Brotchi J: Prospective analysis by computed tomography and long-term outcome of 23 adult patients with chronic idiopathic hydrocephalus. **Neurosurgery 38:**51–59, 1996
107. Robertson JS, Maraqa MI, Jennett B: Ventriculoperitoneal shunting for hydrocephalus. **Br Med J 2:**289–292, 1973
108. Robinson S, Kaufman BA, Park TS: Outcome analysis of initial neonatal shunts: does the valve make a difference? **Pediatr Neurosurg 37:**287–294, 2002
109. Sainte-Rose C: Shunt obstruction: a preventable complication? **Pediatr Neurosurg 19:**156–164, 1993
110. Sainte-Rose C, Piatt JH, Renier D, Pierre-Kahn A, Hirsch JF, Hoffman HJ, et al: Mechanical complications in shunts. **Pediatr Neurosurg 17:**2–9, 1991/1992
111. Salmon JH: Adult hydrocephalus. Evaluation of shunt therapy in 80 patients. **J Neurosurg 37:**423–428, 1972
112. Sand T, Bovim G, Grimse R, Myhr G, Helde G, Cappelen J: Idiopathic normal pressure hydrocephalus: the CSF tap-test may predict the clinical response to shunting. **Acta Neurol Scand 89:** 311–316, 1994
113. Savolainen S, Hurskainen H, Paljärvi L, Alafuzoff I, Vapalahti M: Five-year outcome of normal pressure hydrocephalus with or without a shunt: predictive value of the clinical signs, neuropsychological evaluation and infusion test. **Acta Neurochir (Wien) 144:**515–523, 2002
114. Schoonderwaldt HC, Cho Chia Yuen G, Colon EJ, Hommes OR, Notermans SL, Walder HA: The preselection value of the Doppler LP test for shunt-therapy in patients with normal pressure hydrocephalus. **J Neurol 225:**15–24, 1981
115. Shenkin HA, Greenberg J, Bouzarth WF, Gutterman P, Morales JO: Ventricular shunting for relief of senile symptoms. **JAMA 225:**1486–1489, 1973
116. Sonnenberg FA, Beck JR: Markov models in medical decision making: a practical guide. **Med Decis Making 13:**322–338, 1993
117. Sorteberg A, Eide PK, Fremming AD: A prospective study on the clinical effect of surgical treatment of normal pressure hydrocephalus: the value of hydrodynamic evaluation. **Br J Neurosurg 18:**149–157, 2004
118. Sotelo J, Arriada N, López MA: Ventriculoperitoneal shunt of continuous flow vs valvular shunt for treatment of hydrocephalus in adults. **Surg Neurol 63:**197–203, 2005
119. Southern DA, Faris PD, Brant R, Galbraith PD, Norris CM, Knudtson ML, et al: Kaplan–Meier methods yielded misleading results in competing risk scenarios. **J Clin Epidemiol 59:**1110–1114, 2006
120. Spanu G, Sangiovanni G, Locatelli D: Normal-pressure hydrocephalus: twelve years experience. **Neurochirurgia (Stuttg) 29:** 15–19, 1986
121. Stein SC, Langfitt TW: Normal-pressure hydrocephalus. Predicting the results of cerebrospinal fluid shunting. **J Neurosurg 41:** 463–470, 1974
122. Tai P, Yu E, Shiels R, Tonita J: Long-term survival rates of laryngeal cancer patients treated by radiation and surgery, radiation alone, and surgery alone: studied by lognormal and Kaplan–Meier survival methods. **BMC Cancer 5:**13, 2005
123. Takeuchi T, Kasahara E, Iwasaki M, Mima T, Mori K: Indications for shunting in patients with idiopathic normal pressure hydrocephalus presenting with dementia and brain atrophy (atypical idiopathic normal pressure hydrocephalus). **Neurol Med Chir (Tokyo) 40:**38–47, 2000
124. Tsingoglou S, Forrest DM: Complications from Holter ventriculo-atrial shunts. **Br J Surg 58:**372–377, 1971
125. Tuli S, Tuli J, Drake J, Spears J: Predictors of death in pediatric patients requiring cerebrospinal fluid shunts. **J Neurosurg 100 (5 Suppl Pediatrics):**442–446, 2004

126. Udvarhelyi GB, Wood JH, James AE Jr, Bartelt D: Results and complications in 55 shunted patients with normal pressure hydrocephalus. **Surg Neurol 3:**271–275, 1975
127. Vanneste J, Augustijn P, Dirven C, Tan WF, Goedhart ZD: Shunting normal-pressure hydrocephalus: do the benefits outweigh the risks? A multicenter study and literature review. **Neurology 42:**54–59, 1992
128. Vanneste J, Augustijn P, Tan WF, Dirven C: Shunting normal pressure hydrocephalus: the predictive value of combined clinical and CT data. **J Neurol Neurosurg Psychiatry 56:**251–256, 1993
129. Vassilouthis J: The syndrome of normal-pressure hydrocephalus. **J Neurosurg 61:**501–509, 1984
130. Vernet O, Campiche R, de Tribolet N: Long-term results after ventriculoatrial shunting in children. **Childs Nerv Syst 9:**253–255, 1993
131. Waldemar G, Schmidt JF, Delecluse F, Andersen AR, Gjerris F, Paulson OB: High resolution SPECT with [99mTc]-d, 1-hMPAO in normal pressure hydrocephalus before and after shunt operation. **J Neurol Neurosurg Psychiatry 56:**655–664, 1993
132. Warf BC: Comparison of 1-year outcomes for the Chhabra and Codman-Hakim Micro Precision shunt systems in Uganda: a prospective study in 195 children. **J Neurosurg 102 (4 Suppl Pediatrics):**358–362, 2005
133. Weiner HL, Constantini S, Cohen H, Wisoff JH: Current treatment of normal-pressure hydrocephalus: comparison of flow-regulated and differential-pressure shunt valves. **Neurosurgery 37:**877–884, 1995
134. Whittle IR, Johnston IH, Besser M: Intracranial pressure changes in arrested hydrocephalus. **J Neurosurg 62:**77–82, 1985
135. Wikkelsø C, Andersson H, Blomstrand C, Lindqvist G: The clinical effect of lumbar puncture in normal pressure hydrocephalus. **J Neurol Neurosurg Psychiatry 45:**64–69, 1982
136. Zemack G, Bellner J, Siesjo P, Stromblad LG, Romner B: Clinical experience with the use of a shunt with an adjustable valve in children with hydrocephalus. **J Neurosurg 98:**471–476, 2003
137. Zemack G, Romner B: Adjustable valves in normal-pressure hydrocephalus: a retrospective study of 218 patients. **Neurosurgery 51:**1392–1402, 2002

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Address correspondence to: Sherman C. Stein, M.D., Department of Neurosurgery, University of Pennsylvania School of Medicine, 310 Spruce Street, Philadelphia, Pennsylvania 19106. email: sherman.stein@uphs.upenn.edu.