

# Clinical Diagnosis of Ventriculoperitoneal Shunt Failure Among Children With Hydrocephalus

Joseph H. Piatt, Jr, MD\*† and Hugh J.L. Garton, MD, MHSc‡

**Objective:** To define the significance of various symptoms and signs in the diagnosis of ventriculoperitoneal shunt failure and infection.

**Methods:** The observations that form the basis of this study were made in the course of 2 multicenter, prospective, randomized, controlled clinical trials of technical aspects of ventriculoperitoneal shunt surgery—the Shunt Design Trial and the Endoscopic Shunt Insertion Trial. At registration, basic demographic and baseline clinical data were recorded. At scheduled follow-up visits 3 months and 1, 2, and 3 years after surgery and at unscheduled visits, the presence or absence of various symptoms or signs was recorded. At each visit, the neurosurgeon-investigator made a determination about whether the shunt had reached an end point: mechanical obstruction, infection, overdrainage, or loculation of the ventricular system. Observations at the last follow-up visit for each patient constituted the data for the current study. Sensitivities, specificities, and likelihood ratios were calculated for each symptom and sign as tests for shunt failure from any cause and for failure by infection. Decision trees were constructed to analyze the relationships of various symptoms and signs in the diagnosis of shunt failure and infection.

**Results:** Observations were available for analysis from 647 patient visits. A total of 248 shunts were judged to have failed (38%), and 55 were judged specifically to have failed by infection (8.5%). Bulging fontanel, fluid collection along the shunt, depressed level of consciousness, irritability, abdominal pain, nausea and vomiting, abnormal shunt pump test, accelerated head growth, and headache were strongly associated with shunt failure. Fever was strongly associated with shunt infection. Gross signs of wound infection were associated with shunt infection but were observed infrequently. Decision tree analysis confirmed the salience of bulging fontanel as a predictor of shunt failure. Fever and time since initial surgery were powerful predictors of shunt infection. Irritability emerged as an important observation in the identification of both shunt failure and shunt infection. Among children who underwent initial shunt insertion after 2 months of age, the absence of irritability, nausea/vomiting, and headache were powerful and generalizable predictors of the absence of shunt failure or infection.

**Conclusions:** Analysis of symptoms and signs of ventriculoperitoneal shunt complications can inform clinical judgment in the assessment of children with hydrocephalus.

**Key Words:** complications, diagnosis, hydrocephalus, signs, symptoms, ventriculoperitoneal shunt

Hydrocephalus is a common, chronic condition, most often beginning early in childhood, requiring continual medical surveillance and surgical intervention for maintenance of optimal quality of life.

There are few reliable data on the prevalence of hydrocephalus in childhood. Population-based studies of congenital and infantile hydrocephalus from Sweden have demonstrated increasing prevalences over time from 4.8 per 10,000 in 1967 to 1970 to 6.3 per 10,000 in 1979 to 1982 to 8.2 per 10,000 in 1989 to 1998.<sup>1,2</sup> This trend has been attributed to increasing survival of preterm infants with posthemorrhagic hydrocephalus, although the actual prevalence of hydrocephalus among very preterm infants seems to have peaked in the late 1980s.<sup>3</sup> Reports from other countries and ethnic groups cite prevalences in a similar range.<sup>4–10</sup> Published epidemiological studies have counted cases of congenital and perinatal onset, but because almost a quarter of children with hydrocephalus receive that diagnosis after 1 year of age,<sup>11,12</sup> the true prevalence may approach 1 per 1000. Thus, every general pediatrician's practice might be expected to include several affected children at least.

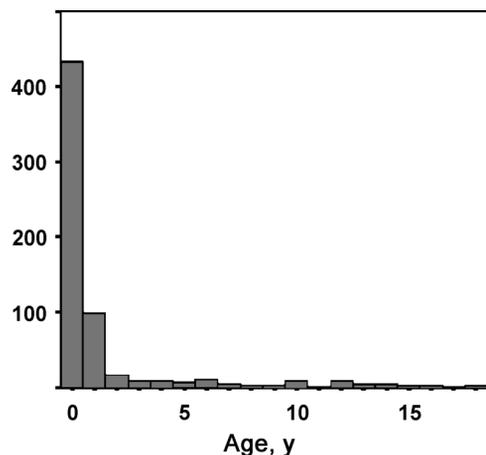
The predominant treatment of hydrocephalus continues to be diversion of cerebrospinal fluid (CSF) by means of an implanted shunt, and the most commonly chosen receptacle for diverted CSF is the peritoneal cavity. Ventriculoperitoneal shunts are not curative. They do not correct the underlying physiological disturbance, and they exhibit a variety of modes of failure: mechanical obstruction, excessive CSF drainage, fracture, migration, and infection. Retrospective institutional studies and prospective, multicenter trials have shown remarkably consistent 35% to 40% failure rates in the first year after initial insertion and continuing attrition, albeit at much lower rates, in subsequent years.<sup>11–16</sup> Thus, the possibility of ventriculoperitoneal shunt failure must be born in mind in every clinical encounter with a child carrying the diagnosis of hydrocephalus.

The clinical presentation of ventriculoperitoneal shunt failure encompasses the symptoms and signs of specifically surgical complications, such as purulent wound drainage and subcutaneous CSF collections, and the nonspecific symptoms and signs of infection and elevated intracranial pressure. The diagnosis of ventriculoperitoneal shunt failure may be obvious, but more often, the differential diagnosis includes common childhood illnesses such as otitis, gastroenteritis and other viral syndromes, and migraine. Analysis of the diagnostic reliability of particular symptoms and signs may therefore be helpful to the primary provider who must decide

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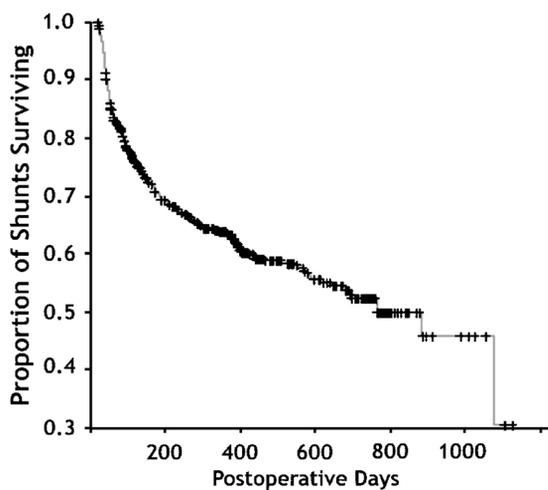


**FIGURE 1.** Ages of study patients (N = 647) at the time of ventriculoperitoneal shunt insertion.

whether to take the investigation to the next level, either brain imaging or neurosurgical consultation.

**METHODS**

The data were originally developed in the conduct of 2 multicenter, prospective, randomized, controlled trials examining surgical techniques for insertion of ventriculoperitoneal shunts in children with hydrocephalus. The Shunt Design Trial compared the survival of shunts incorporating 3 distinct valve designs.<sup>11,17</sup> The data were collected between 1993 and 1995 from 12 participating centers in North American and Europe. The Endoscopic Shunt Insertion Trial compared survival of shunts inserted with or without the use of a ventriculoscope.<sup>12</sup> The data were collected between 1996 and 1999 from 16 centers in North America and Europe. The 2 trials used the same data collection instruments for recording baseline demographic and historical data, for details regarding the initial surgical procedure, and for documentation of the presence or absence of symptoms and signs at follow-up visits to the offices of the neurosurgical investigators at



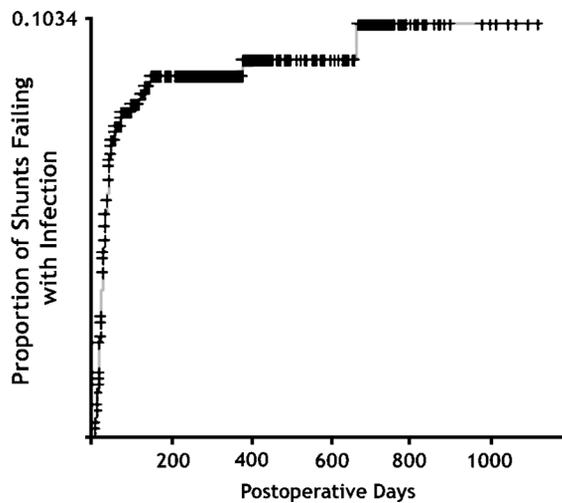
**FIGURE 2.** Actuarial survival of ventriculoperitoneal shunts among patients in the study group.

prescribed intervals after the initial insertion of the shunt. The same set of symptoms and signs was documented at unscheduled “sick” visits as well. At the conclusion of each postoperative visit, taking into account clinical findings, brain imaging, and other investigations, the treating neurosurgeon recorded a determination about whether the shunt had reached one of the following end points: obstruction, excessive CSF drainage, loculation of the ventricular system, or infection. In the current study, only the findings on the last recorded postoperative visit, whether scheduled or unscheduled, were analyzed. Ventriculoperitoneal shunts that reached an end point were said to have “failed.” With few exceptions, failed shunts were subjected to surgical revision, and the intraoperative findings were recorded as well.

In the conduct of the 2 prospective trials, the final status of each shunt was subjected to central review by the principal investigator and, if necessary, adjudication by a panel of blinded neurosurgical judges. Concordance between the judgments of the treating neurosurgeons and the blinded adjudicators was very high.<sup>18</sup> Because the results of the adjudications were not available for all of both datasets, the current study analyzed only the determinations of the treating neurosurgeons.

The goal of this study was to analyze statistical models of ventriculoperitoneal shunt failure and infection using symptoms, signs, and other data that might be available to an office-based, primary practitioner as independent variables. The clinical trials that generated the data for this study examined 2 aspects of surgical technique, valve design selection and the use of an endoscope for ventricular catheter insertion, which likely would not be known to a primary practitioner. Furthermore, the trials demonstrated that the technical factors in question had no influence on shunt survival.<sup>12,19</sup> Valve design and endoscopy were therefore not included among the independent variables.

The cumulative probability of shunt survival without failure of any kind and the cumulative risk of failure by infection were estimated using the Kaplan-Meier method.



**FIGURE 3.** Actuarial risk of ventriculoperitoneal shunt infection among patients in the study group.

**TABLE 1.** Symptoms, Signs, and Other Data in Relation to Ventriculoperitoneal Shunt Failure

Symptom or Sign	No. Observations	P*	Sensitivity	Specificity	Likelihood Ratio (95% CI)	Negative Likelihood Ratio (95% CI)
Young age	647	0.001	0.56	0.58	1.32 (1.13–1.55)	1.31 (1.11–1.54)
Early visit	647	<0.0005	0.76	0.74	2.91 (2.43–3.48)	3.06 (2.43–3.83)
Intraoperative complication	647	0.038	0.09	0.96	1.99 (1.07–3.69)	1.05 (1.00–1.09)
Headache	509	<0.0005	0.22	0.95	4.28 (2.52–7.57)	1.22 (1.12–1.34)
Nausea/Vomiting	643	<0.0005	0.39	0.96	11.1 (6.48–19.0)	1.58 (1.43–1.75)
Irritability	642	<0.0005	0.45	0.97	13.7 (7.89–23.8)	1.75 (1.56–1.97)
Seizures	599	0.656				
Developmental delay	558	0.570				
School failure	317	0.140				
Papilledema	411	0.071				
Bulging fontanel	503	<0.0005	0.46	0.99	44.6 (14.3–139)	1.84 (1.63–2.09)
Accelerated head growth	506	<0.0005	0.45	0.93	6.02 (3.95–9.18)	1.68 (1.48–1.91)
Depressed level of consciousness	643	<0.0005	0.20	0.99	26.2 (8.24–83.1)	1.24 (1.16–1.32)
Nuchal rigidity	633	1.000				
CN6 palsy	634	0.122				
Loss of upgaze	623	<0.0005	0.05	1.00	ZD	1.05 (1.02–1.09)
Fluid tracking	632	<0.0005	0.21	0.99	20.1 (7.37–55.0)	1.25 (1.17–1.34)
CSF leak	643	<0.0005	0.06	1.00	22.3 (2.95–169)	1.06 (1.02–1.09)
Purulent drainage	644	0.021	0.02	1.00	ZD	1.02 (1.00–1.03)
Skin erosion	643	<0.0005	0.03	1.00	ZD	1.03 (1.01–1.06)
Fever	643	<0.0005	0.16	0.99	10.8 (4.63–25.0)	1.18 (1.11–1.24)
Meningismus	643	0.056				
Erythema	644	<0.0005	0.05	1.00	ZD	1.06 (1.02–1.09)
Abdominal pain	640	< 0.0005	0.07	1.00	12.8 (2.97–55.2)	1.06 (1.03–1.10)
Pseudocyst	639	0.056				
Peritonitis	638	0.006	0.03	1.00	11.3 (1.40–91.3)	1.03 (1.00–1.05)
Shunt pump test	272	<0.0005	0.23	0.97	7.54 (3.00–19.0)	1.27 (1.13–1.41)

\*Fisher exact test.

CI indicates confidence interval; ZD, zero in denominator.

Associations between ventriculoperitoneal shunt failure and infection and the recorded symptoms and signs were analyzed using cross-tabulation and  $\chi^2$  tests. Test sensitivity and specificity were calculated for each symptom and sign that achieved a significant ( $P < 0.05$ ) association with either of the study end points. Likelihood ratios were calculated for each significant symptom and sign for both study end points, and “negative” likelihood ratios were calculated for the nonoccurrence of end points. Because the negative and positive predictive values of a test reflect case mix, they have limited generalizability and were not calculated for this report.

To examine the relative strengths of the various significant symptoms and signs, decision trees were constructed. Decision trees are statistical models for predicting the presence or absence of qualities of interest (in this instance, shunt failure or infection) by algorithmic sorting of subjects on the basis of specified independent variables (in this instance, symptoms, signs, and other data that might be available to a pediatrician in an outpatient setting). The exhaustive Chi-square Automatic Interaction Detection (CHAID) algorithm was used.<sup>20</sup> The probability threshold for branching was set at

0.05, and the Bonferroni correction was used. The exhaustive CHAID algorithm requires selection of stopping rules: an upper limit on the number of generations of nodes, a lower limit on the number of subjects in a parent node, and a lower limit on the number of subjects in a daughter node. Extraction of useful clinical information from a decision tree model required exercise of judgment in selection of stopping rules, lest the trees be corrupted by artifact or dominated by highly predictive but infrequently observed contingencies. Stopping rules were recorded with each tree. Best analytic practice for the construction of decision trees ordinarily mandates random division of the complete dataset into development and validation subsets, but because the complete dataset was relatively small and because the goal was a heuristic understanding of the relative importance of symptoms and signs, this exercise was neglected. Likelihood ratios and negative likelihood ratios were calculated for selected terminal boxes based on comparison of the subjects within the box to all the other subjects entered into the tree.

The data from the Shunt Design Trial were archived using an Excel (Microsoft Corporation, Redmond, WA)

**TABLE 2.** Symptoms, Signs, and Other Data in Relation to Ventriculoperitoneal Shunt Infection

Symptom or Sign	No. Observations	P*	Sensitivity	Specificity	Likelihood Ratio (95% CI)	Negative Likelihood Ratio (95% CI)
Young age	647	0.12				
Early visit	647	<0.0005	0.96	0.60	2.39 (2.14–2.67)	16.4 (4.20–62.5)
Intraoperative complication	647	0.36				
Headache	509	0.51				
Nausea/Vomiting	643	0.007	0.32	0.84	2.02 (1.30–3.12)	1.23 (1.02–1.48)
Irritability	642	<0.0005	0.56	0.84	3.60 (2.67–4.85)	1.93 (1.43–2.62)
Seizures	599	0.10				
Developmental delay	558	1.0				
School failure	317	1.0				
Papilledema	411	0.39				
Bulging fontanel	503	0.009	0.35	0.81	1.90 (1.25–2.89)	1.26 (1.02–1.55)
Accelerated head growth	506	0.708				
Depressed level of consciousness	643	0.425				
Nuchal rigidity	633	0.163				
CN6 palsy	634	0.613				
Loss of upgaze	623	0.612				
Fluid tracking	632	0.316				
CSF leak	643	<0.0005	0.15	0.99	12.2 (4.60–32.4)	1.16 (1.04–1.29)
Purulent drainage	644	<0.0005	0.07	1.0	ZD	1.08 (1.00–1.16)
Skin erosion	643	<0.0005	0.15	1.0	ZD	1.17 (1.05–1.31)
Fever	643	<0.0005	0.67	0.98	39.3 (20.6–74.7)	2.95 (2.02–4.29)
Meningismus	643	<0.0005	0.06	1.0	ZD	1.06 (0.99–1.13)
Erythema	644	<0.0005	0.24	1.0	ZD	1.31 (1.13–1.52)
Abdominal pain	640	<0.0005	0.22	0.99	21.3 (8.31–54.5)	1.27 (1.10–1.46)
Pseudocyst	639	0.233				
Peritonitis	638	<0.0005	0.13	1.0	75.7 (9.49–604)	1.15 (1.04–1.27)
Shunt pump test	272	0.334				

\*Fisher exact test, 2-tailed.

CI indicates confidence interval; ZD, zero in denominator.

spreadsheet. The data from the Endoscopic Shunt Insertion Trial were archived in an Access (Microsoft Corporation) relational database. The 2 datasets were merged in a new Excel spreadsheet. Organization, recoding, and analysis of the data were performed with SPSS 11.5 for Windows (SPSS Incorporated, Chicago, IL). Decision trees were created and analyzed using AnswerTree 3.1 (SPSS Incorporated).

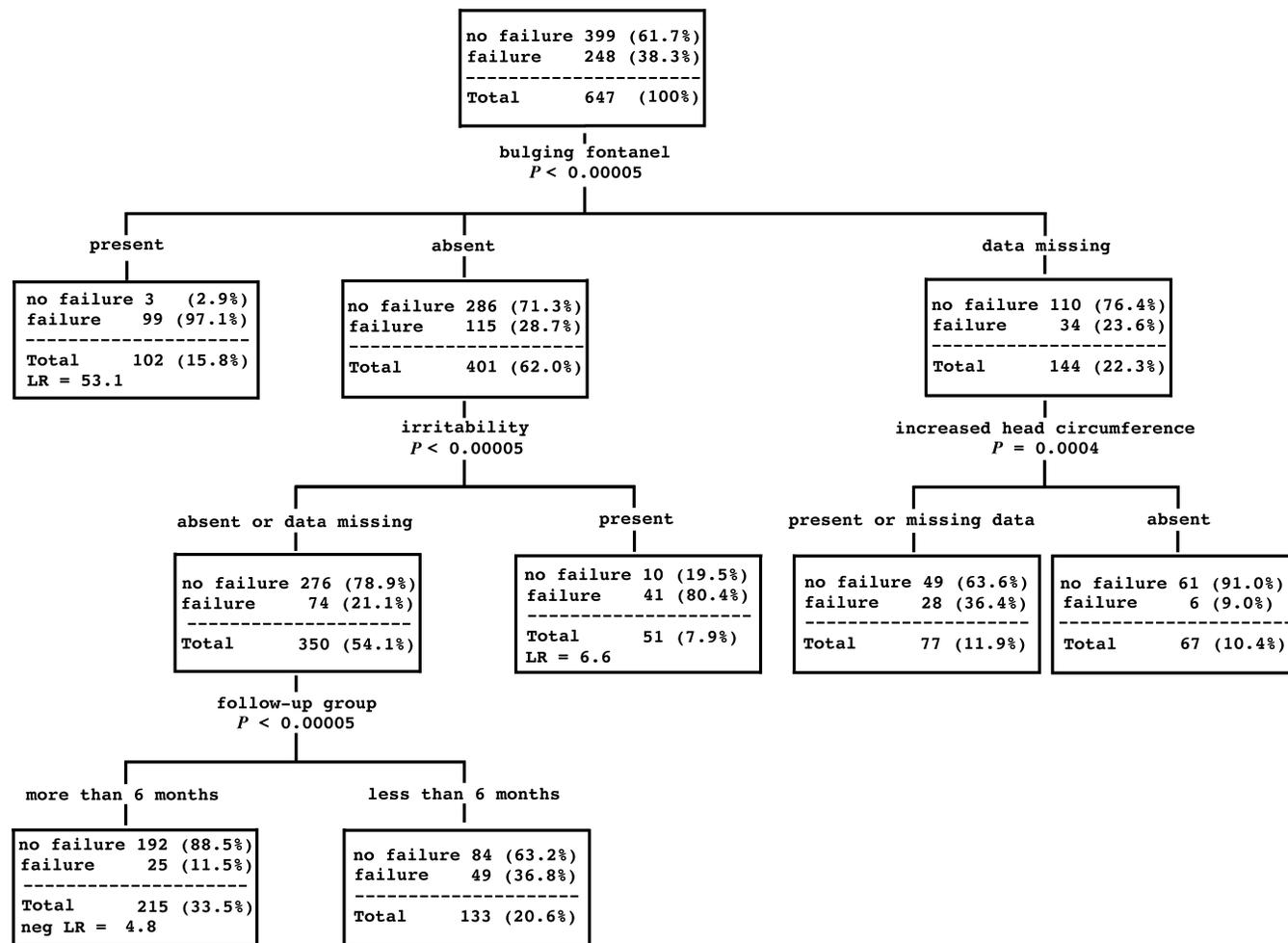
The Shunt Design Trial and the Endoscopic Shunt Insertion Trial were conducted under the supervision of institutional review boards at each participating institution. The current study was supervised by the Institutional Review Board of Drexel University College of Medicine.

## RESULTS

There were 647 patient visits available for analysis. The ages of the study subjects at the time of shunt insertion are depicted in Figure 1. The median age was 71 days past term, with a range from 81 days before term to 18 years. Seventy-eight percent of study subjects were younger than 1 year at the time of shunt insertion. In overall follow-up, 248 shunts were

judged to have failed (38%), and 55 were judged specifically to have failed by infection (8.5%). The estimated cumulative survival rate of the study shunts is depicted in Figure 2. The estimated cumulative risk of shunt infection is depicted in Figure 3. Figures 2 and 3 represent actuarial estimations of the probabilities of shunt failure and infection, respectively, as functions of follow-up time, and these estimations necessarily differ from the overall failure and infection rates observed among the study subjects who had highly variable periods of individual follow-up.

In addition to the symptoms and signs that were recorded prospectively, 2 additional variables were defined post hoc to reflect the age of the patient and the elapsed time between surgery and the follow-up visit. Patients who underwent shunt insertion before 2 months past term were considered “young.” This age is sometimes considered the end of the neonatal period, and it lies between the median ages of patients who did and did not become infected and between the median ages of patients who did and did not experience shunt failure. Follow-up visits occurring within 6 months of surgery were considered “early.” The 6-month



**FIGURE 4.** A decision tree modeling ventriculoperitoneal shunt failure from any cause constructed from symptoms, signs, and other data analyzed in Table 1.

threshold was derived from visual inspection of Figures 2 and 3, which suggest a decline in the hazard rates for failure from all causes and failure by infection at about this time.

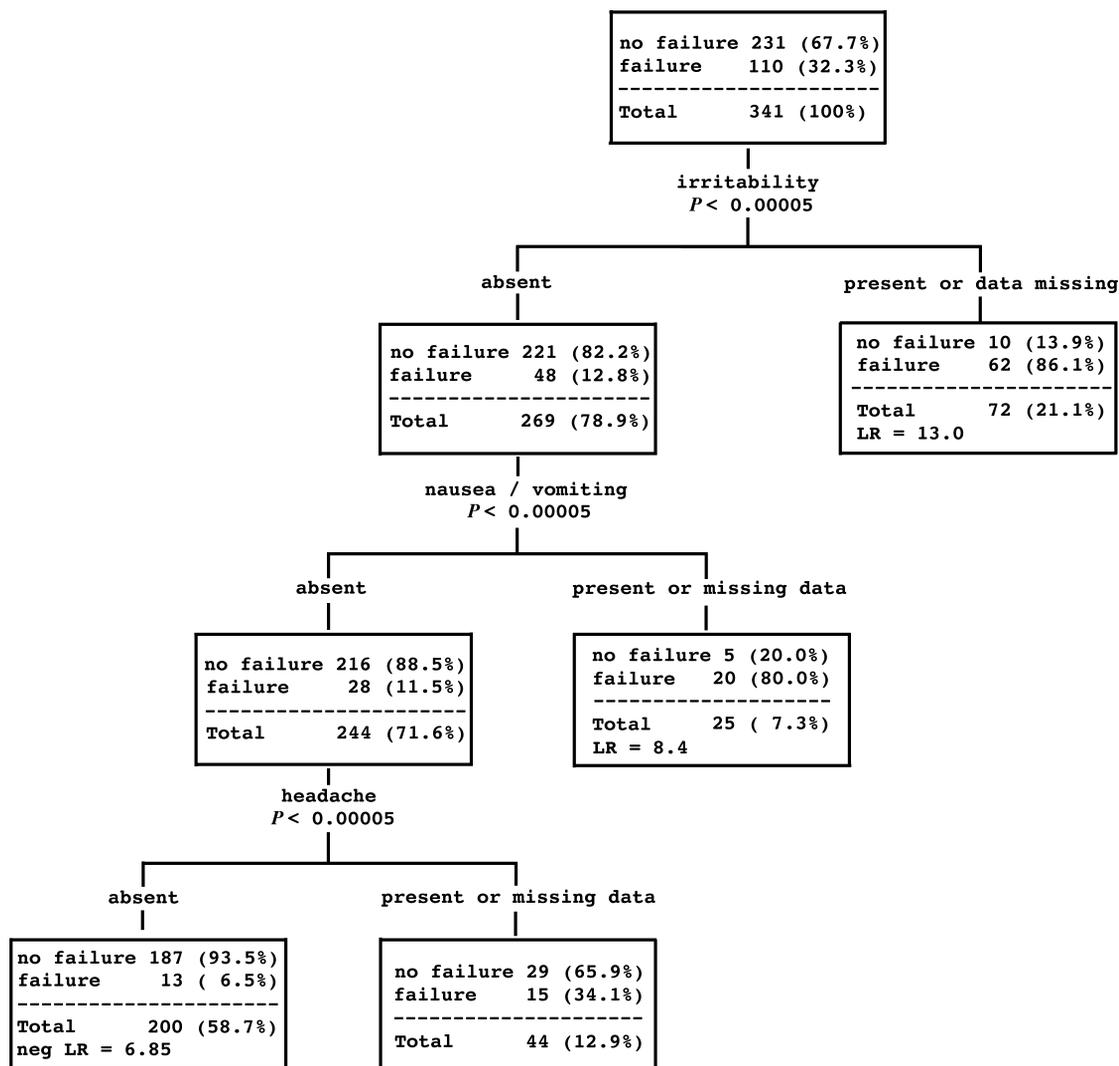
The most powerful predictor of shunt failure was whether the study visit was scheduled or unscheduled, but because this factor was essentially an artifact of the design of the original trials, it was not analyzed further.

The sensitivities, specificities, likelihood ratios, and negative likelihood ratios for each of the independent variables as predictors of failure from all causes and of failure by infection are presented in Tables 1 and 2, respectively. The largest likelihood ratios for the prediction of overall failure were associated with bulging fontanel, fluid collection along the shunt, depressed level of consciousness, irritability, abdominal pain, nausea and vomiting, abnormal shunt pump test, accelerated head growth, and headache, in descending order. Other observations that attained very high levels of significance were either specific signs of infection or were seen very infrequently: loss of upgaze, CSF leakage, purulent drainage, skin erosion, fever, erythema, and peritonitis. The largest likelihood ratios for the prediction of infection were associated with purulent drainage, skin

erosion, meningismus, erythema, peritonitis, fever, abdominal pain, and CSF leakage.

The shunt pump test was considered to be abnormal if abnormal resistance to compression of the pump mechanism was perceived by the examiner or if the pump mechanism took an abnormal time to refill or failed to refill at all. The results of the shunt pump test were recorded in only 272 of 647 encounters. Patients who had undergone shunt insertion in infancy most often received miniaturized valve designs that did not incorporate pump mechanisms, so no results were recorded from encounters with such patients. The shunt pump test was strongly associated with the presence or absence of shunt failure ( $P \leq 0.0005$ ). The likelihood ratio of the shunt pump test as a predictor of shunt failure was moderately high, 7.54 (95% confidence interval, 3.00–19.0), but the negative likelihood ratio of the test as a predictor of normal shunt function was low, 1.27 (95% confidence interval, 1.13–1.41).

A decision tree model of all shunt failures, including infections, was constructed using the independent variables listed in Table 1. In this relatively young cohort, bulging fontanel and irritability were the dominant predictors (Fig. 4). Bulging fontanel was very highly predictive of shunt failure



**FIGURE 5.** A decision tree modeling ventriculoperitoneal shunt failure from any cause among patients older than 2 months at the time of surgery constructed from symptoms, signs, and other data analyzed in Table 1.

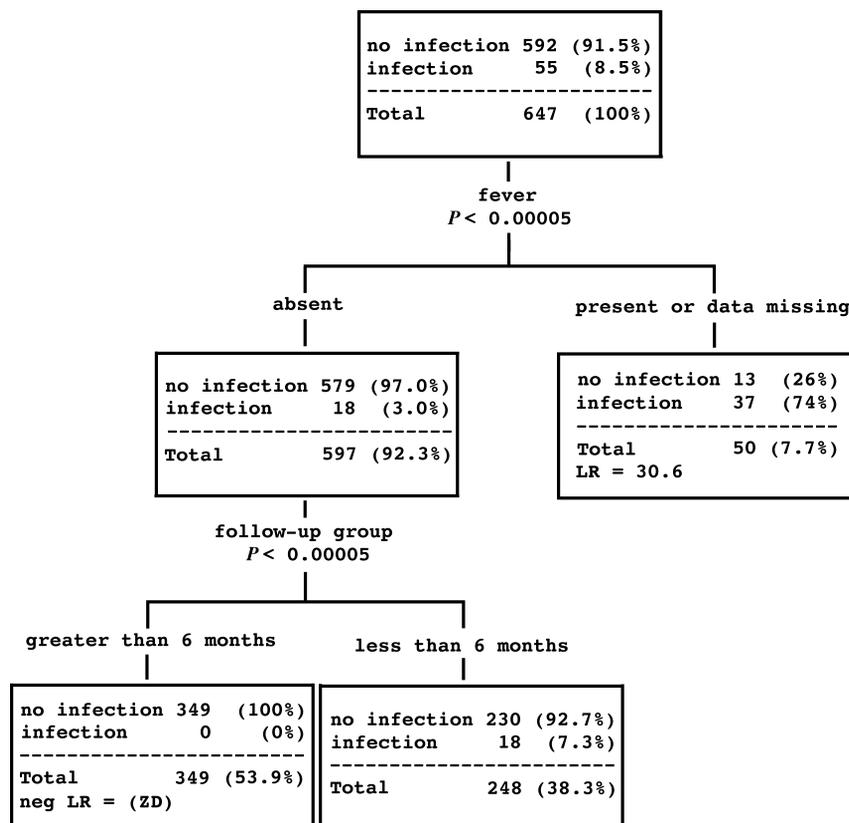
(positive predictive value = 0.97; likelihood ratio = 53.1). Either bulging fontanel or irritability was observed in more than half (140/248 or 0.56) of the instances of shunt failure recorded in this study. Another decision tree was constructed based on observations in the older patients, that is, in patients older than 2 months past term at the time of shunt insertion (Fig. 5). This restriction to older patients neutralized the importance of bulging fontanel. Irritability remained a very powerful predictor of shunt failure, along with nausea/vomiting and headache. The absence of irritability, nausea/vomiting, and headache reduced the risk of shunt failure in this older cohort from 0.32 to 0.07 (negative likelihood ratio = 6.8). The decision tree model for all patients produced an 11% false-negative misclassification, whereas the model including just those patients more than 2 months past term at the time of shunt insertion had a false-negative rate of 6%.

A decision tree model specifically predicting shunt infection was constructed using the independent variables listed in Table 2. The dominant predictors were the presence or

absence of fever and the remoteness in time of the initial shunt operation (Fig. 6). Only 2 of the 55 shunt infections observed in this study came to attention more than 6 months after surgery. A secondary analysis without the dominant factors of fever and time since surgery (Fig. 7) highlights the significance of irritability, a history of complications during the initial operation, age at surgery, and headache. Among patients older than 2 months at shunt insertion without irritability, nausea/vomiting, or headache, there were no shunt infections.

## DISCUSSION

The current report extends the previous work of Garton et al<sup>21</sup> by analysis of a dataset roughly twice as large and by the use of decision tree methodology. Decision trees offer an intuitively accessible presentation of the relationships among predictive variables, and the parameters of their construction can be adjusted to de-emphasize infrequent but highly specific findings, such as purulent wound drainage, erythema, or papilledema. Originally proposed by Kass,<sup>20</sup> CHAID



**FIGURE 6.** A decision tree modeling ventriculoperitoneal shunt infection constructed from symptoms, signs, and other data analyzed in Table 2.

methodology offers several important benefits over logistic regression in developing predictive models, including an easy visual understanding of the dataset, the ability to handle missing data, no demand for normally distributed data, and better identification of interaction terms. Limitations include more operator dependence in the selection of the model, increased sensitivity to small samples, and lack of relational weights to predictors in a model, as is available with logistic regression, and lack of a standard “goodness of fit” test to compare different models.<sup>21</sup>

The principle strength of this report lies in its prospective data acquisition; however, there are 2 important limitations to the generalizability of the observations of this report. The first limitation derives from the setting in which the data were collected, neurosurgical practices. The subjects of this report who were ill were almost certainly screened by primary physicians or emergency physicians before their “sick” visits to the neurosurgeon, although the occurrence and the outcomes of such screening visits were not recorded. Thus, the observations in this report were purged to some degree of common childhood illnesses such as gastroenteritis, otitis, and viral upper respiratory infections. In the primary physician’s office, therefore, some of the conclusions of this report may be applicable only after common childhood illnesses have been investigated and dismissed from further consideration. The second limitation arises from the case mix. The great majority of the subjects of this report were

very young children, and none of the subjects of this report had experienced shunt failure before. The conclusions of this report will be of limited usefulness, for instance, in evaluating the teenager with long-standing, recurrent headaches and a history of many previous shunt revisions. A third limitation is that physician observations as reported on the data forms may have been made with the knowledge of the results of imaging studies or other supposedly objective tests that were performed as part of the evaluation process. If so, this diagnostic suspicion bias would tend to increase the predictive power of symptoms and signs.

The study results support the authors’ clinical experience that certain individual symptoms and signs, if present, successfully illuminate the clinical impression of shunt failure. Conversely, the absence of individual factors does little to change the underlying probability of shunt failure. This relationship can be seen by examining the likelihood ratios in Table 1. The likelihood ratios express the odds that a symptom or sign is found in a patient shunt failure as opposed to one without, whereas the negative likelihood expresses the probability that a symptom will be absent in a patient without shunt failure as opposed to one with shunt failure. Clinical use of likelihood ratios requires knowledge of the general odds of shunt failure. Thus, in this study, the general rate of shunt failure at the last follow-up visit was 38%, whereas the odds of shunt failure were 0.38/(1 - 0.38) or 0.61:1. A likelihood ratio of 4 for the symptom of

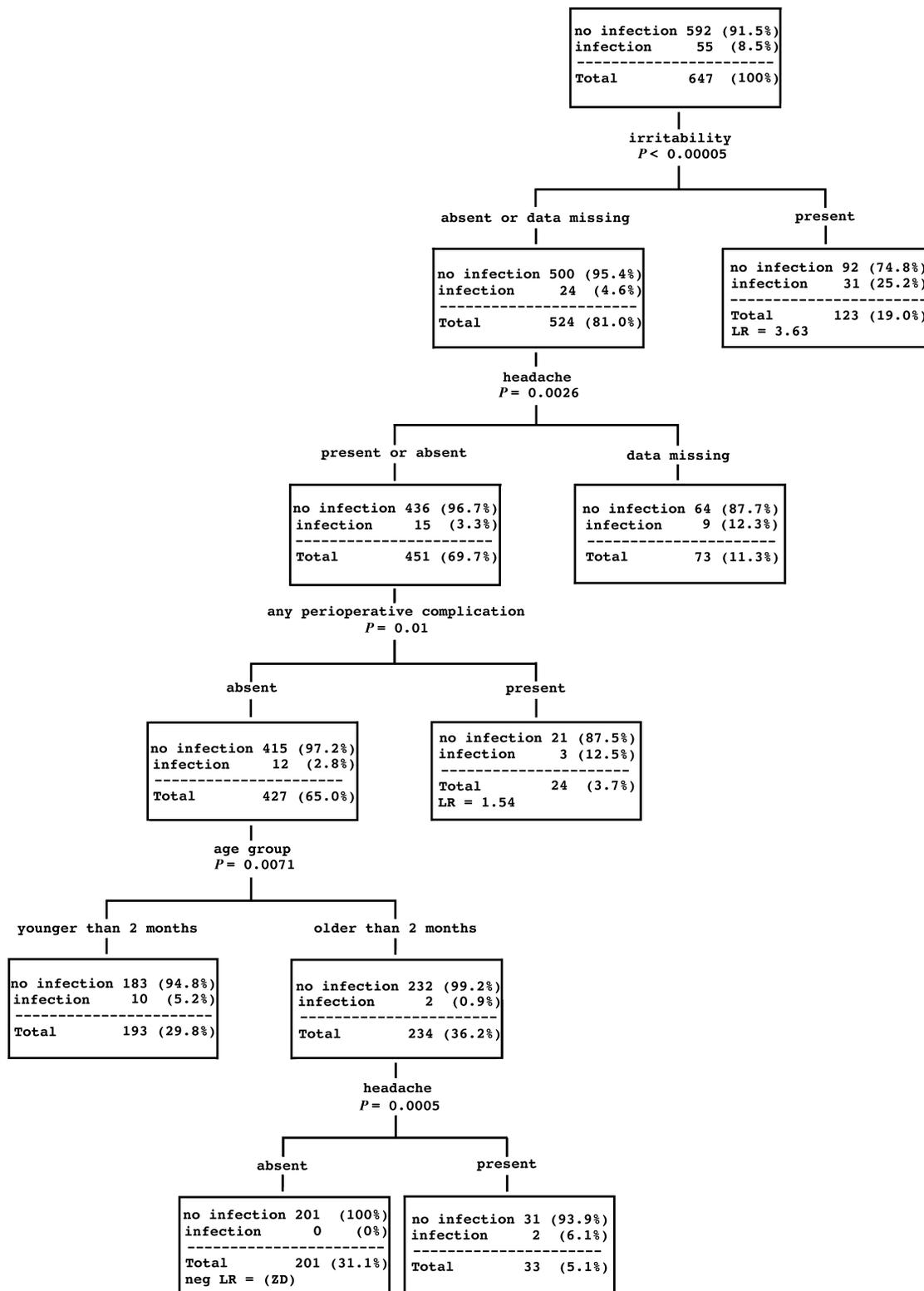


FIGURE 7. A decision tree modeling ventriculoperitoneal shunt infection constructed from symptoms, signs, and other data analyzed in Table 2 without the dominant factors of fever and time since surgery.

headache raises the odds of shunt failure to  $4 \times 0.61 = 2.4:1$ . The rate of failure is then  $2.4/(2.4 + 1)$  or 71%. Conversely, in this study, the rate of shunt nonfailure at the time of the last visit was  $1 - 0.38 = 0.62$ , translating to an odds ratio of 1.6:1. The odds of nonfailure in the absence of headache is then  $1.2 \times 1.6 = 1.9:1$ , which translates to a rate of 65%. Only the absence of an early visit (ie, a late visit), as a sole predictor (negative likelihood ratio = 3), altered the posttest probability of absence of shunt failure in a clinically meaningful way (posttest odds = 4.6:1) to 83% in this dataset. If one wishes to achieve a 95% probability of the absence of shunt failure with underlying probability of 30% shunt failure among patients presenting for evaluation, then a negative likelihood ratio of 8 is necessary.

The clinical recognition of ventriculoperitoneal shunt failure on the basis of symptoms and signs has received little analytical study. In 2001, Garton et al<sup>22</sup> reported an analysis of symptoms and signs of shunt failure from the Shunt Design Trial, based on a subset of the dataset assembled for the current study. Clinical encounters were designated “early” if they occurred within 5 months of surgery and “late” if they occurred 9 months or longer after surgery. Nausea and vomiting, irritability, depressed level of consciousness, erythema, and bulging fontanel and fluid tracking around the shunt were highly significant predictors at early visits. At late visits, only loss of developmental milestones and depressed level of consciousness were strongly associated with shunt failure. Scoring systems were developed for early and late encounters using logistic regression, and the accuracies of these systems were analyzed by receiver-operator curves. Decreased level of consciousness, wound erythema, bulging fontanel, fever, and irritability, all were strong predictors. The authors were not able to identify a rule for excluding the possibility of shunt failure on the basis of symptoms and signs. Kim et al<sup>23</sup> recently reported a retrospective examination of 352 children who presented to a pediatric emergency department during a 4-year period with complaints that raised a question of shunt failure. Univariate analysis and logistic regression identified only lethargy and swelling at the site of the shunt as significant predictors of shunt failure. That so few factors attained significance may reflect the lack of screening of the study population for confounding illnesses. Alternatively, this chart review may have been limited by incomplete assessments recorded by emergency department staff.

The preponderance of ventriculoperitoneal shunt infections are believed to be due to contamination of the shunt at or around the time of surgery.<sup>24–26</sup> Thus, the likelihood of shunt infection is strongly dependent on the time elapsed since the preceding operation.<sup>27</sup> This study confirms the findings of many previous studies that the enormous majority of infections are recognized within 6 months of surgery.<sup>14,27–29</sup> Ventriculoatrial CSF shunts are excepted from this generalization because they are exposed indefinitely to the risk of contamination by bacteremias. Very few contemporary surgeons choose the atrium for CSF diversion as initial therapy for the newly diagnosed patient with hydrocephalus. Ventriculoatrial shunts were excluded from the trials that were the sources of data for this study. Fever was a very powerful predictor of infection at “early” follow-up visits, but the usefulness of this

observation is vitiated somewhat by bias inherent in the study design. Febrile patients who reached neurosurgical attention had probably been screened to an unknowable extent by previous encounters with other providers for confounding febrile illnesses such as otitis and gastroenteritis.

The independent variable “irritability” emerged as a powerful predictor of both shunt failure and shunt infection in the current study. Precisely what this term meant to the participating neurosurgeons is not certain. Although the data were collected prospectively, study of symptoms and signs of shunt complications was not the purpose of the original clinical trials, and descriptors like “irritability” were not defined. Discomfort, restlessness, and distress are probably encompassed by the term. The significance of “irritability” in this study can be construed as an affirmation of clinical judgment in the assessment of shunt function. If a patient seems ill, and if the cause is not obvious, further investigation or referral is indicated.

Noteworthy in the decision tree analysis was the significance of the *absence* of irritability, headache, and nausea/vomiting among children older than 2 months at shunt insertion. Children meeting these criteria accounted for at least 200 of 647 clinical encounters in this study, and in this group, there were only 13 instances of shunt failure (negative likelihood ratio = 6.85; Fig. 5). With an additional exclusion of children who had experienced some perioperative surgical complications, there were no instances of shunt infections (negative likelihood ratio = zero in denominator; Fig. 7). The reliability of the reassurance provided by the absence of these factors is not likely to be affected by the coincidence of confounding childhood illnesses, which can only add symptoms, not subtract them. This observation may therefore be generalizable to other practice settings.

The clinical utility of the shunt pump test has been studied before on a lesser scale with discouraging results. In a small personal series of observations, Piatt<sup>30</sup> reported a test sensitivity of 18% and specificity of 63% for a likelihood ratio of 1.06 and a negative likelihood ratio of 0.77. That is, in that examiner’s experience, a normal shunt pump test actually *lowered* the odds ratio for nominal shunt function! The shunt pump test performed better in the current study, which featured a much larger number of observations, but the reliability of these observations is uncertain. There were many examiners and several valve designs, and the criteria for abnormality were subjective. The high likelihood ratio in the current study suggests that the shunt pump test deserves more respect than it has been accorded generally. The common neurosurgical view has been that the shunt pump test has low specificity, as the pump mechanism often refills very slowly among older patients with functioning shunts and small ventricles. Perhaps such patients were underrepresented in the current study population, which was young. The negative likelihood ratio—for identification of nominal shunt function—was greater than 1, but it was nevertheless quite small. The practical implication of this statistical observation is that a negative shunt pump test cannot provide useful reassurance about the status of the shunt. A negative shunt pump test cannot serve as a stopping point in the investigation of suspected shunt failure. If there are clinical concerns, further imaging investigations or further

consultation is still indicated, regardless of the results of the shunt pump test.

To ensure generalizability and relevance, future studies of the presentations of shunt complications should be conducted by investigators other than neurosurgeons in primary care settings such as the pediatrician's office or the emergency department. Prospective, protocol-driven data collection by a multicenter research network would be ideal. In such a setting, capture of older patients with more complicated surgical histories may enable future studies to address challenging problems such as resource utilization among children with shunts and chronic headaches.<sup>31–34</sup> As the rigor of study design improves, however, allowances will need to be made for practice variation in the neurosurgical diagnosis of shunt failure, a critical issue that has so far received very limited attention.<sup>18</sup>

## CONCLUSIONS

This secondary analysis of data acquired in prospective follow-up of patients enrolled in trials of ventriculoperitoneal shunt design and surgical technique provided some limited guidance for pediatricians evaluating children with hydrocephalus in the outpatient setting. Among infants bulging fontanel, fluid collection around the shunt, and irritability are important findings that indicate further diagnostic evaluation or neurosurgical consultation. Among patients within 6 months of surgery, particularly in the absence of any other obvious explanation, fever indicates further investigation of the possibility of shunt infection. Among patients beyond 6 months from surgery, shunt infection is very unlikely. Among children who have undergone shunt insertion after 2 months of age, the absence of irritability, headache, and nausea/vomiting greatly reduces the likelihood of shunt failure and shunt infection. Reassuring findings from pumping of the shunt valve cannot serve as a stopping point in the diagnostic evaluation of the symptomatic child with a ventriculoperitoneal shunt. Placing the recognition of ventriculoperitoneal shunt failure on a more firm evidentiary basis may benefit children with hydrocephalus not only by reducing the frequency of delayed diagnosis but also possibly by limiting unnecessary diagnostic investigations and even unnecessary surgical interventions.

## REFERENCES

- Persson EK, Hagberg G, Uvebrant P. Hydrocephalus prevalence and outcome in a population-based cohort of children born in 1989–1998. *Acta Paediatr.* 2005;94:726–732.
- Fernell E, Hagberg B, Hagberg G, et al. Epidemiology of infantile hydrocephalus in Sweden. I. Birth prevalence and general data. *Acta Paediatr Scand.* 1986;75:975–981.
- Fernell E, Hagberg G. Infantile hydrocephalus: Declining prevalence in preterm infants. *Acta Paediatr.* 1998;87:392–396.
- Stein SC, Feldman JG, Apfel S, et al. The epidemiology of congenital hydrocephalus. A study in Brooklyn, N.Y. 1968–1976. *Childs Brain.* 1981;8:253–262.
- Sipek A, Gregor V, Horacek J, et al. Congenital hydrocephalus 1961–2000—incidence, prenatal diagnosis and prevalence based on maternal age. *Ceska Gynekol.* 2002;67:360–364.
- Christensen JH, Hansen LK, Garne E. Congenital hydrocephalus—prevalence and prognosis. Mortality and morbidity in a population-based study. *Ugeskr Laeger.* 2003;165:466–469.
- Msamati BC, Igbigbi PS, Chisi JE. The incidence of cleft lip, cleft palate, hydrocephalus and spina bifida at Queen Elizabeth Central Hospital, Blantyre, Malawi. *Cent Afr J Med.* 2000;46:292–296.
- Rajab A, Vaishnav A, Freeman NV, et al. Neural tube defects and congenital hydrocephalus in the Sultanate of Oman. *J Trop Pediatr.* 1998;44:300–303.
- el Awad ME. Infantile hydrocephalus in the south-western region of Saudi Arabia. *Ann Trop Paediatr.* 1992;12:335–338.
- Kromberg JG, Jenkins T. Common birth defects in South African blacks. *S Afr Med J.* 1982;62:599–602.
- Drake JM, Kestle JR, Milner R, et al. Randomized trial of cerebrospinal fluid shunt valve design in pediatric hydrocephalus. *Neurosurgery.* 1998;43:294–303.
- Kestle JR, Drake JM, Cochrane DD, et al. Lack of benefit of endoscopic ventriculoperitoneal shunt insertion: a multicenter randomized trial. *J Neurosurg.* 2003;98:284–290.
- Kestle JR, Walker ML. A multicenter prospective cohort study of the strata valve for the management of hydrocephalus in pediatric patients. *J Neurosurg.* 2005;102:141–145.
- Piatt JH, Carlson CV. A search for determinants of cerebrospinal fluid shunt survival: retrospective analysis of a 14-year institutional experience. *Pediatr Neurosurg.* 1993;19:233–241.
- Sainte-Rose C, Piatt JH, Renier D, et al. Mechanical complications in shunts. *Pediatr Neurosurg.* 1991;17:2–9.
- Pollack IF, Albright AL, Adelson PD. A randomized, controlled study of a programmable shunt valve versus a conventional valve for patients with hydrocephalus. Hakim-medos investigator group. *Neurosurgery.* 1999;45:1399–1408.
- Drake JM, Kestle J. Rationale and methodology of the multicenter pediatric cerebrospinal fluid shunt design trial. Pediatric hydrocephalus treatment evaluation group. *Childs Nerv Syst.* 1996;12:434–447.
- Kestle J, Milner R, Drake D. An assessment of observer bias in the shunt design trial. *Pediatr Neurosurg.* 1999;30:57–61.
- Kestle J, Drake J, Milner R, et al. Long-term follow-up data from the shunt design trial. *Pediatr Neurosurg.* 2000;33:230–236.
- Kass GV. An exploratory technique for investigating large quantities of categorical data. *Appl Stat.* 1980;23:119–127.
- van Diepen M, Franses PH. Evaluating chi-squared automatic interaction detection. *Info Syst.* 2006;31:814–831.
- Garton HJ, Kestle JR, Drake JM. Predicting shunt failure on the basis of clinical symptoms and signs in children. *J Neurosurg.* 2001;94:202–210.
- Kim TY, Stewart G, Voth M, et al. Signs and symptoms of cerebrospinal fluid shunt malfunction in the pediatric emergency department. *Pediatr Emerg Care.* 2006;22:28–34.
- Shapiro S, Boaz J, Kleiman M, et al. Origin of organisms infecting ventricular shunts. *Neurosurgery.* 1988;22:868–872.
- Duhaime AC, Bonner K, McGowan KL, et al. Distribution of bacteria in the operating room environment and its relation to ventricular shunt infections: a prospective study. *Childs Nerv Syst.* 1991;7:211–214.
- Kulkarni AV, Drake JM, Lamberti-Pasculli M. Cerebrospinal fluid shunt infection: a prospective study of risk factors. *J Neurosurg.* 2001;94:195–201.
- McGirt MJ, Leveque JC, Wellons JC III, et al. Cerebrospinal fluid shunt survival and etiology of failures: a seven-year institutional experience. *Pediatr Neurosurg.* 2002;36:248–255.
- George R, Leibrock L, Epstein M. Long-term analysis of cerebrospinal fluid shunt infections. A 25-year experience. *J Neurosurg.* 1979;51:804–811.
- Ronan A, Hogg GG, Klug GL. Cerebrospinal fluid shunt infections in children. *Pediatr Infect Dis J.* 1995;14:782–786.
- Piatt JH. Physical examination of patients with cerebrospinal fluid shunts: is there useful information in pumping the shunt? *Pediatrics.* 1992;89:470–473.
- Epstein F, Marlin AE, Wald A. Chronic headache in the shunt-dependent adolescent with nearly normal ventricular volume: diagnosis and treatment. *Neurosurgery.* 1978;3:351–355.
- Obana WG, Raskin NH, Cogen PH, et al. Antimigraine treatment for slit ventricle syndrome. *Neurosurgery.* 1990;27:760–763.
- Matta AP, Carod-Artal FJ. Primary headaches in children with hydrocephalus who have a ventriculoperitoneal bypass valve. *Rev Neurol.* 2004;39:1101–1104.
- Abbott R, Epstein FJ, Wisoff JH. Chronic headache associated with a functioning shunt: usefulness of pressure monitoring. *Neurosurgery.* 1991;28:72–76.