

A Decision Rule for Identifying Children at Low Risk for Brain Injuries After Blunt Head Trauma

Michael J. Palchak, MD
 James F. Holmes, MD
 Cheryl W. Vance, MD
 Rebecca E. Gelber, MD
 Bobbie A. Schauer, MD
 Mathew J. Harrison, BS
 Jason Willis-Shore, MD
 Sandra L. Wootton-Gorges, MD
 Robert W. Derlet, MD
 Nathan Kuppermann, MD, MPH

From the Division of Emergency Medicine, Department of Internal Medicine (Palchak, Holmes, Vance, Gelber, Schauer, Harrison, Derlet, Kuppermann), the Department of Pediatrics (Vance, Kuppermann), and the Department of Radiology (Wootton-Gorges), University of California–Davis School of Medicine, Davis, CA; and the Department of Emergency Medicine, Oregon Health Sciences University, School of Medicine, Portland, OR (Willis-Shore).

This article is dedicated to the memory of our beloved friend and colleague, James Seidel, MD, PhD, who was a tireless and vocal advocate for the health and welfare of children.

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Study objective: Computed tomography (CT) is frequently used in evaluating children with blunt head trauma. Routine use of CT, however, has disadvantages. Therefore, we sought to derive a decision rule for identifying children at low risk for traumatic brain injuries.

Methods: We enrolled children with blunt head trauma at a pediatric trauma center in an observational cohort study between July 1998 and September 2001. We evaluated clinical predictors of traumatic brain injury on CT scan and traumatic brain injury requiring acute intervention, defined by a neurosurgical procedure, antiepileptic medications for more than 1 week, persistent neurologic deficits, or hospitalization for at least 2 nights. We performed recursive partitioning to create clinical decision rules.

Results: Two thousand forty-three children were enrolled, 1,271 (62%) underwent CT, 98 (7.7%; 95% confidence interval [CI] 6.3% to 9.3%) had traumatic brain injuries on CT scan, and 105 (5.1%; 95% CI 4.2% to 6.2%) had traumatic brain injuries requiring acute intervention. Abnormal mental status, clinical signs of skull fracture, history of vomiting, scalp hematoma (in children ≤ 2 years of age), or headache identified 97/98 (99%; 95% CI 94% to 100%) of those with traumatic brain injuries on CT scan and 105/105 (100%; 95% CI 97% to 100%) of those with traumatic brain injuries requiring acute intervention. Of the 304 (24%) children undergoing CT who had none of these predictors, only 1 (0.3%; 95% CI 0% to 1.8%) had traumatic brain injury on CT, and that patient was discharged from the ED without complications.

Conclusion: Important factors for identifying children at low risk for traumatic brain injuries after blunt head trauma included the absence of: abnormal mental status, clinical signs of skull fracture, a history of vomiting, scalp hematoma (in children ≤ 2 years of age), and headache.

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INTRODUCTION

Trauma is the leading cause of childhood death.¹ Traumatic brain injury is the leading cause of death and disability caused by trauma in children,²⁻⁴ resulting in approximately 3,000 deaths, 50,000 hospitalizations, and 650,000 emergency department (ED) visits per year in the United States.^{5,6} Cranial computed tomography (CT) is routinely used in the assessment of children evaluated in the ED with head trauma; however, less than 10% of these CT scans are diagnostic of traumatic brain injuries.⁷⁻¹⁰

Some studies have proposed that clinical signs and symptoms may be used to identify children at low risk for traumatic brain injuries after blunt head trauma.^{7,11} Others have concluded that clinical signs and symptoms are inadequate for identifying these children.^{9,10,12-14} Many studies, however, were limited by small size of the study populations, retrospective design, uncontrolled or univariable data analyses, and nonstandardized age inclusion criteria and outcome variable definition.

Although CT is the diagnostic test of choice for evaluating children with head trauma, this procedure has disadvantages, including exposure to ionizing radiation,¹⁵⁻¹⁸ transport of the child away from the direct supervision of emergency physicians, the frequent requirement for pharmacologic sedation,¹⁹⁻²¹ additional health care costs, and increased time for completing ED evaluation. Therefore, CT scans should ideally be selectively used.

Because the results of previous studies are inconclusive, variation exists in physicians' practice patterns regarding the use of CT scans in the ED evaluation of children with blunt head trauma.^{22,23} Published guidelines acknowledge the limitations of available data and highlight the need for larger, prospective studies on this topic.^{8,24-26} In this study, we sought to derive a clinical decision rule with high sensitivity for traumatic brain injury and high negative predictive value for identifying children without traumatic brain injuries after blunt head trauma, with the goal of maximizing the clinical efficiency of CT use. We hypothesized that a set

of clinical signs and symptoms can accurately identify individuals at very low risk of traumatic brain injuries.

MATERIALS AND METHODS

We conducted a prospective observational cohort study in the pediatric ED of a Level I trauma center. The study was approved by the study site's Human Subjects Research Committee.

From July 1998 to September 2001, we enrolled children younger than 18 years and presenting to the pediatric ED after a history of nontrivial blunt head trauma with historical or physical examination findings consistent with head trauma. These findings included a history of loss of consciousness, amnesia, seizures, vomiting, current headache, dizziness, nausea, or vision change or physical examination findings of abnormal mental status, focal neurologic deficits, clinical signs of skull fracture, or scalp trauma. This patient population included children with head injuries of all severities. We excluded children with trivial head trauma defined by falls from ground level or trauma resulting from walking or running into stationary objects if the only abnormal finding was a scalp laceration or abrasion. We also excluded children transferred to the study facility if CT scans were performed before transfer.

Patients were examined by faculty emergency physicians. The aforementioned clinical findings were recorded on a standardized data sheet before CT scan (if CT imaging was obtained). Abnormal mental status was considered to be present if the patient had a Glasgow Coma Scale (GCS) score or pediatric GCS score²⁷ of less than 15 or if the patient was confused, somnolent, repetitive, or slow to respond to verbal communication. Clinical signs of skull fractures were defined as a palpable skull fracture, retroauricular bruising, periorbital bruising, hemotympanum, or cerebrospinal fluid otorrhea or rhinorrhea. Two faculty emergency physicians independently evaluated a convenience sample of 5% of patients to assess interobserver agreement.

A study research assistant reviewed the medical records for patients in whom predictor data fields were incomplete and abstracted the missing information

from the medical record. Abstracted information was used on an average of less than 1% of all data fields, with a range of 0% to 3% for each variable studied.

CT scans were obtained at the discretion of the treating faculty physicians. Institutional recommendations for obtaining CT scans in head-injured children, however, included a history of loss of consciousness, amnesia, seizure, vomiting, or headache; or physical examination findings of abnormal mental status, neurologic deficit, skull fracture, or deep or multiple scalp lacerations; children younger than 2 years with scalp hematomas; children with multiple trauma; or concern about shaken baby syndrome. Ethical considerations precluded obtaining CT scans on all enrolled patients.²⁸ CT scans were performed with a GE High Speed CT/i (GE Medical Systems, Waukesha, WI) or Toshiba 900 scanner (Toshiba America Medical Systems, Tustin, CA), with 5-mm cuts from the foramen magnum to the vertex of the skull.

We reviewed the medical records of hospitalized patients to determine interventions and outcomes. All patients discharged to home from the ED received a follow-up telephone call approximately 1 week after ED evaluation to inquire about symptoms of head injury, the need for reevaluation by a physician, or a missed diagnosis of traumatic brain injury. We mailed a questionnaire to those unavailable by telephone. Children who were discharged from the ED and did not have a traumatic brain injury demonstrated by subsequent brain imaging and did not require subsequent hospitalization were considered not to have traumatic brain injuries. At study completion, we reviewed the county morgue records and hospital trauma center registry for the names of patients who were unavailable by telephone or mail follow-up to ensure that they were not subsequently diagnosed with a traumatic brain injury.

We defined 2 outcome variables: (1) traumatic brain injury identified on CT scan; and (2) traumatic brain injury requiring acute intervention. These 2 outcome variables have an overlapping but nonhierarchical relationship.

Traumatic brain injury identified on CT imaging was defined by the presence of intracranial hemorrhage,

hematoma, or cerebral edema according to the faculty radiologists' interpretations of the initial CT scans conducted in the ED. CT scans with equivocal readings were given to a faculty pediatric radiologist for definitive interpretation, masked to clinical information. Isolated skull fractures (ie, without visible brain injury) were not considered traumatic brain injuries, because children with isolated skull fractures do not routinely require hospitalization.^{29,30}

We defined traumatic brain injury requiring acute intervention by 1 or more of the following: the requirement for a neurosurgical procedure, ongoing anti-epileptic pharmacotherapy beyond 7 days, the presence of a neurologic deficit that persisted until discharge from the hospital, or 2 or more nights of hospitalization because of treatment of the head injury. This novel definition excludes children routinely admitted for overnight observation because of a small traumatic brain injury identified on CT scan, children who are given an empirical prophylactic 1-week course of antiepileptic medication after head trauma, and children hospitalized for social or other reasons not directly related to the head trauma. In constructing the definition of traumatic brain injury requiring acute intervention, we sought to define an outcome that was meaningful to clinical decisionmaking, independent of the sensitivity of neuroimaging technology, and independent of physician accuracy in recognition of subtle traumatic brain injuries on CT.

We performed descriptive and univariable analyses with Fisher's exact test for categorical data, the Wilcoxon rank sum test for ordinal data, and Student's *t* test for continuous data by using Stata statistical software (version 7.0, Stata Corporation, College Station, TX). Statistical significance was determined with 95% confidence intervals (CIs). Interobserver agreement was calculated with the κ coefficient.

We used Answer Tree 2.1 (SPSS, Inc., Chicago, IL) binary recursive partitioning software to create decision trees with 9 clinical variables for each of the following outcomes: (1) traumatic brain injury identified on CT scan, (2) traumatic brain injury requiring acute intervention, and (3) traumatic brain injury identified

on CT scan or traumatic brain injury requiring acute intervention. This software package used the classification and regression tree algorithm and the Gini measure of impurity in decision tree creation. Binary recursive partitioning is a nonparametric analytic technique used to classify observations according to risk profiles for the outcome of interest by using a treelike structure with decision “nodes.”³¹ Recursive partitioning analysis may be preferable to multiple logistic regression when the objective is derivation of a highly sensitive clinical decision rule.³²

Recursive partitioning allows for the inclusion of patients with missing predictors by substituting “surrogate” variables containing information similar to that contained in the missing variables. Therefore, preverbal children, who cannot provide information about headache and amnesia, were not excluded from the analyses.

In the construction of the trees, we assigned “costs” to misclassification errors that would parallel clinical decisionmaking. For the analysis of traumatic brain injury identified on CT imaging, we assigned a relative cost of 100 for the misclassification error of not identifying a patient who has a traumatic brain injury compared with the error of identifying patients as having a traumatic brain injury when they do not. For the analysis of traumatic brain injury requiring acute intervention, we assigned a relative cost of 500 to the error of missing a traumatic brain injury because of the greater clinical implications of this type of error. By making incorrect underdiagnoses more costly in these analyses, we sought to minimize these more important mistakes at the expense of overclassifying patients without traumatic brain injuries.

We internally validated the decision trees developed in the main analyses by using 10-fold cross-validation. The results of this cross-validation are demonstrated by a cross-validated “risk-estimate” of making a misclassification error, which is calculated by adding the probability of the 2 types of misclassification errors (false negative and false positive), each multiplied by their assigned relative costs.

The 9 predictor variables considered in the recursive partitioning analyses included a history of loss of con-

sciousness, amnesia, seizure, or vomiting; current headache; and physical examination findings of abnormal mental status, focal neurologic deficits, signs of skull fracture, and scalp hematomas in children aged 2 years and younger because of the known association of scalp hematomas and traumatic brain injury in this age group.^{25,26,33-37}

We determined the sensitivity and negative predictive values of each resulting decision tree, with 95% CIs and calculated positive and negative likelihood ratios for each tree. Only children who underwent CT scans were included in the analyses for traumatic brain injury identified on CT scan. All patients, however, were included in the analysis for traumatic brain injury requiring acute intervention.

We performed subanalyses on children with GCS scores of 14 or 15, as well as on children aged 2 years and younger, for the outcome of traumatic brain injury identified on CT scan, recognizing the importance of these subpopulations. We also performed a separate analysis on the full study population to identify those with traumatic brain injuries requiring neurosurgical procedures.

The study sample size goal was 90 children with traumatic brain injuries identified on CT scan. This figure is based on the suggested requirement of 10 outcomes of interest for each of the 9 predictive variables evaluated in multivariable logistic regression analyses.^{38,39} Although this suggested ratio is not necessarily applicable to recursive partitioning analysis, limiting the number of predictor variables studied minimizes the likelihood of overfitting a model to our data.

RESULTS

We enrolled 2,043 (77.4%) of 2,640 eligible children. The mean age was 8.3 years (SD 5.3 years; range 10 days to 17.9 years), 327 (16%) were 2 years or younger, 65% were male patients, and 36% had histories of loss of consciousness. The mechanisms of injury were fall (35%), motor vehicle crash (19%), automobile versus pedestrian (11%), assault (8%), fall off bicycle (7%), automobile versus bicyclist (5%), child abuse (0.2%),

and other (15%). Fifty-three percent of enrolled patients had isolated head trauma. The median GCS score of enrolled patients was 15 (interquartile range 15 to 15), and 91% had GCS scores of 14 or 15.

CT scans were performed on 1,271 (62.2%) patients, and traumatic brain injury on CT scan was present in 98 patients (7.7%; 95% CI 6.3% to 9.3%; [Table 1](#)). Of the 98 patients with traumatic brain injuries identified on CT scan, 23 (23.5%) did not meet the criteria for traumatic brain injury requiring acute intervention. Traumatic brain injuries requiring acute intervention were present in 105 (5.1%; 95% CI 4.2% to 6.2%) of the 2,043 patients ([Table 2](#)). Of these 105 patients, 12 (11.4%) died and 29 (27.6%) required neurosurgical procedures ([Table 3](#)). Twenty-nine (27.6%) of the patients with traumatic brain injury requiring acute intervention did not have a traumatic brain injury identified on the CT scan obtained in the ED ([Table 4](#)).

Table 1.
*Traumatic brain injuries identified on CT (total 98 children).**

Type of Injury	No. (% of Children)
Cerebral contusion/hemorrhage	50 (51.0)
Subdural hematoma	31 (31.6)
Subarachnoid hemorrhage	24 (24.5)
Cerebral edema	17 (17.3)
Epidural hematoma	16 (16.3)

*A total of 98 enrolled children had traumatic brain injury identified on CT scan; a combination of injuries was found in 41 of these 98 patients. Note that an isolated skull fracture was not considered a traumatic brain injury.

Table 2.
Description of children with traumatic brain injury requiring acute intervention (total 105 children).

Criteria Met	No. (% of Children)
Hospitalization ≥ 2 nights*	58 (55.2)
Neurosurgical procedure	29 (27.6)
Neurologic deficit	14 (13.3)
Antiepileptic medication >1 wk	4 (3.8)

*Without any of the other 3 criteria.

Follow-up was achieved in 88% of patients who were discharged to home from the ED, and none had a missed traumatic brain injury. Review of county morgue records and hospital trauma registry for the remaining 12% did not identify any patients with a missed traumatic brain injury.

Five hundred ninety-seven (22.6%) of the 2,640 eligible patients were inadvertently “missed” from enroll-

Table 3.
*Neurosurgical procedures performed (total 29 children).**

Neurosurgical Procedure	No. of Patients (% of Children)
Ventriculostomy	17 (58.6)
Hematoma evacuation	14 (48.3)
Intracranial pressure monitor	8 (27.6)
Tissue debridement	5 (17.2)
Dura repair to correct cerebrospinal fluid leak	2 (6.9)
Fracture elevation	1 (3.4)

*Twenty-nine enrolled children had a traumatic brain injury requiring a neurosurgical procedure; 7 of these children required a combination of procedures.

Table 4.
*Description of the 29 children with traumatic brain injuries requiring acute intervention who did not have traumatic brain injury identified on CT from the ED.**

Defining Characteristic	No.	Comment
Hospitalization ≥ 2 nights	29	Eighteen hospitalized for abnormal mental status, 4 required intravenous antibiotics for deep scalp lacerations over skull fractures, 3 required a neurosurgical procedure, 2 had persistent vomiting, 1 required observation for cerebrospinal fluid leak, 1 had persistent severe headache and dizziness
Antiepileptic medication for >7 d	7	One required a neurosurgical procedure, none had persistent neurologic deficits
Persistent neurologic deficit	4	None required anti-epileptic medication or a neurosurgical procedure
Neurosurgical procedure	3	One required antiepileptic medication, none had a persistent neurologic deficit

*Sixteen of these 29 children had skull fractures evident on CT scan, and 8 had depressed skull fractures. Six of the 29 children underwent repeated neuroimaging (CT scan or magnetic resonance imaging) after leaving the ED, and 4 of these repeated studies were interpreted as positive for traumatic brain injury.

ment, although both groups were similar (data not shown). The rate of traumatic brain injury identified on

Table 5.

Univariable risks of traumatic brain injury on CT scan, given the presence or absence of selected predictors (1,271 patients imaged, 98 with traumatic brain injury identified on CT).*

Predictor Variable	Risk of TBI if Variable Present (%) [†]	Risk of TBI if Variable Absent (%) [†]	Relative Risk	95% CI
Amnesia	32/483 (6.6)	12/373 (3.2)	2.1	1.1–3.9
Loss of consciousness	58/601 (9.7)	15/411(3.6)	2.6	1.5–5.6
Headache	26/495 (5.3)	13/380 (3.4)	1.5	0.8–2.9
Seizure	10/62 (16.1)	79/1174 (6.7)	2.4	1.3–4.4
History of vomiting	28/245 (11.4)	48/976 (4.9)	2.3	1.5–3.6
Clinical signs of skull fracture	23/67 (34.3)	75/1204 (6.2)	5.5	3.7–8.2
Focal neurologic deficit	14/39 (35.9)	84/1232 (6.8)	5.3	3.3–8.4
Scalp hematoma and ≤2 y old	14/77 (18.2)	84/1194 (7.0)	2.6	1.5–4.3
Abnormal mental status	82/545 (15.1)	16/726 (2.2)	6.8	4.0–11.5

TBI, Traumatic brain injury.
^{*}Please see methods section for definitions of predictor and outcome variables.
[†]Percentages were calculated only for patients who had known presence or absence of the variable of interest.

Table 6.

Univariable risks of traumatic brain injury requiring acute intervention given the presence or absence of selected predictors (2,043 patients enrolled, 105 with traumatic brain injury requiring acute intervention).*

Predictor Variable	Risk of TBI if Variable Present (%) [†]	Risk of TBI if Variable Absent (%) [†]	Relative Risk	95% CI
Amnesia	32/522 (6.1)	12/913 (1.3)	4.7	2.4–9.0
Loss of consciousness	65/633 (10.3)	15/1114 (1.4)	7.6	4.4–13.3
Headache	29/652 (4.5)	8/813 (1.0)	4.5	2.1–9.8
Seizure	14/63 (22.2)	81/1941 (4.2)	5.3	3.2–8.9
History of vomiting	27/271 (10.0)	49/1716 (2.9)	3.5	2.2–5.5
Clinical signs of skull fracture	31/73 (42.5)	74/1970 (3.8)	11.3	8.0–16.0
Focal neurologic deficit	18/39 (46.2)	87/2004 (4.3)	10.6	7.2–15.8
Scalp hematoma and ≤2 y old	8/129 (6.2)	97/1914 (5.1)	1.2	0.6–2.5
Abnormal mental status	94/578 (16.3)	11/1465 (0.8)	21.7	11.7–40.1

*Please see methods section for definitions of predictor and outcome variables.
[†]Percentages calculated only for patients who had known presence or absence of the variable of interest.

CT scan was similar between groups (7.7% for enrolled, 5.9% for missed patients; difference 1.8%; 95% CI–1.3% to 4.9%).

The univariable association between each predictor variable studied and traumatic brain injury identified on CT scan is presented in Table 5; the univariable association between each predictor variable studied and traumatic brain injury requiring acute intervention is presented in Table 6.

Two investigators independently evaluated a convenience sample of 109 (5.3%) of the 2,043 patients. Interobserver agreement was moderate to almost perfect,⁴⁰ with κ values ranging from 0.53 to 0.91 (P<.05 for all measurements; Table 7).

In the binary recursive partitioning analysis for traumatic brain injury identified on CT scan, the most important variable was abnormal mental status (Figure 1). The other variables in this tree were clinical signs of skull fracture, scalp hematoma in children aged 2 years and younger, and a history of vomiting. The presence of any of these 4 predictors correctly identified 96 of the 98 children with traumatic brain injury on CT scan (sensitivity 98%; 95% CI 92.8% to 99.8%). Of the 526 patients who had none of the 4 findings, 524 did not have traumatic brain injury on CT scan (negative predictive value 99.6%; 95% CI 98.6% to 100%). The risk estimate of this model with our data was 0.668, and the cross-validation risk estimate was 0.876.

Table 7.

Interobserver agreement on the presence or absence of clinical predictors studied (total 109 children).

Predictor	κ*	Proportion of Agreement, %
GCS score	0.91	98.1
History of vomiting	0.88	97.0
History of loss of consciousness	0.86	93.1
Altered mental status	0.76	89.0
Clinical signs of skull fracture	0.71	97.3
Seizure	0.71	97.1
Headache	0.67	83.6
Focal neurologic deficit	0.65	96.3
Amnesia	0.63	81.7
Scalp hematoma, age ≤2 y	0.53	76.9

*P<.05 for all measurements.

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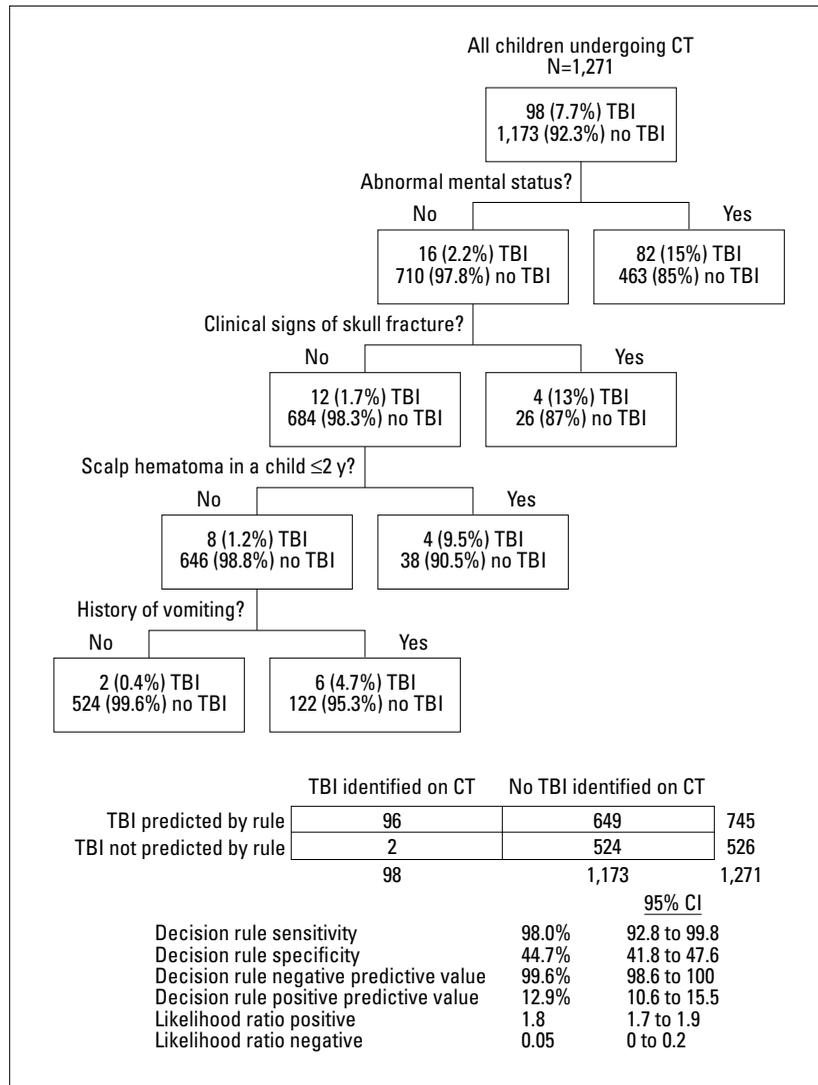
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Two children with traumatic brain injuries identified on CT scan were not identified by this decision rule. One patient's CT scan was initially interpreted as normal, and he was discharged home from the ED. This patient was notified to return to the ED the following day after the CT scan was reinterpreted to have a small extra-axial hematoma. A repeat CT scan demonstrated a decrease in the size of the hematoma, and he was discharged home from the ED after neurosurgical consultation. The second patient with a traumatic brain injury not identified by this rule had a CT scan revealing a small subarachnoid hemorrhage, and he was admitted for 1 night of observa-

tion. Neither of these 2 patients met the criteria for traumatic brain injury requiring acute intervention.

The binary recursive partitioning analysis for traumatic brain injury requiring acute intervention identified clinical signs of skull fracture as the most important variable (Figure 2). The other variables in this tree were abnormal mental status, a history of vomiting, and headache. The presence of any of these 4 findings correctly identified all 105 of the children with traumatic brain injury requiring acute intervention (sensitivity 100%; 95% CI 97.2% to 100%). Of the 900 patients without any of the 4 findings, none had traumatic brain

Figure 1.
Decision tree for predicting children with traumatic brain injuries on CT scan.



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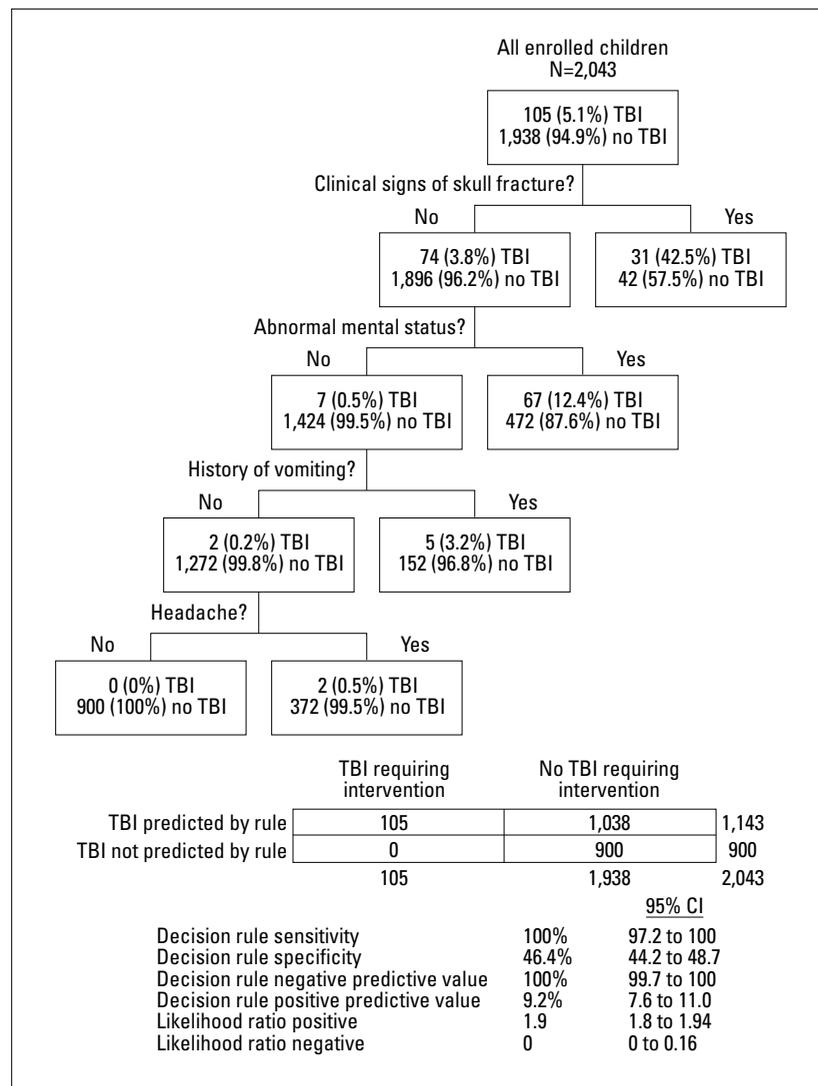
injury requiring acute intervention (negative predictive value 100%; 95% CI 99.7% to 100%), although 5 had traumatic brain injury identified on CT scan (including 4 infants ≤ 2 years with scalp hematomas). The risk estimate of this model with our data was 0.508, and the cross-validation risk estimate was 0.507.

We combined the predictors selected in the decision trees for recognizing traumatic brain injury identified on CT scan and traumatic brain injury requiring acute intervention (which differed by only 1 predictor variable) to generate a conservative decision rule for both outcomes (Figure 3). This rule, consisting of abnormal

mental status, clinical evidence of a skull fracture, a history of vomiting, scalp hematoma (for patients ≤ 2 years), and headache, identified 97 (99%; 95% CI 94.4% to 100%) of the 98 children with traumatic brain injuries identified on CT scan and all 105 of children with traumatic brain injuries requiring acute intervention (100%; 95% CI 97.2% to 100%). Of the 304 (24%) children evaluated with CT scans who had none of these 5 predictors, only 1 (0.3%; 95% CI 0% to 1.8%) had a traumatic brain injury identified on CT scan (the previously described patient discharged home from the ED). Of the 827 patients without any of the 5 predictors, none had

Figure 2.

Decision tree for predicting children with traumatic brain injury requiring acute intervention.

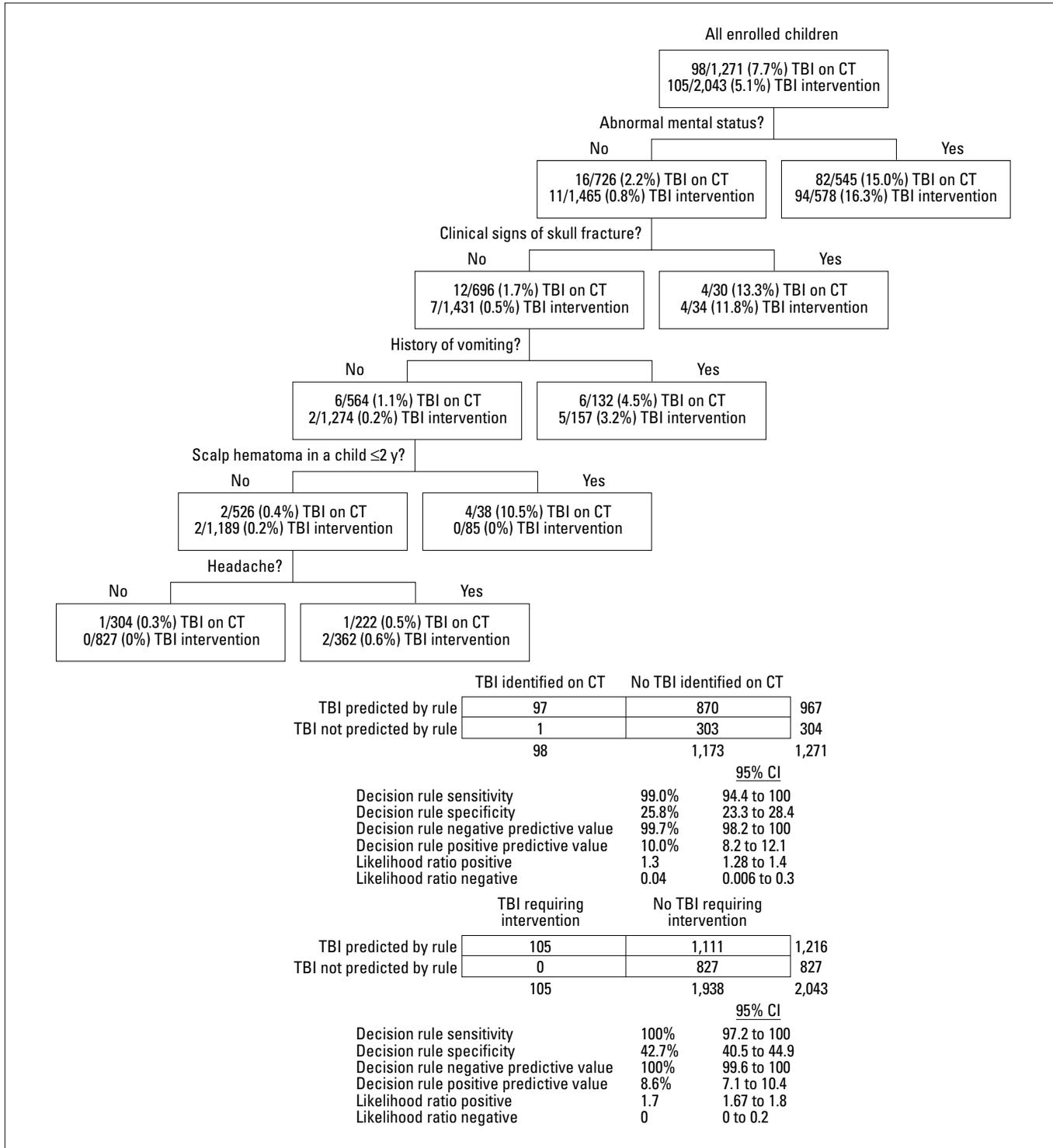


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Figure 3.

Constructed decision rule for predicting children with traumatic brain injury identified on CT or traumatic brain injury requiring acute intervention (combining decision trees).



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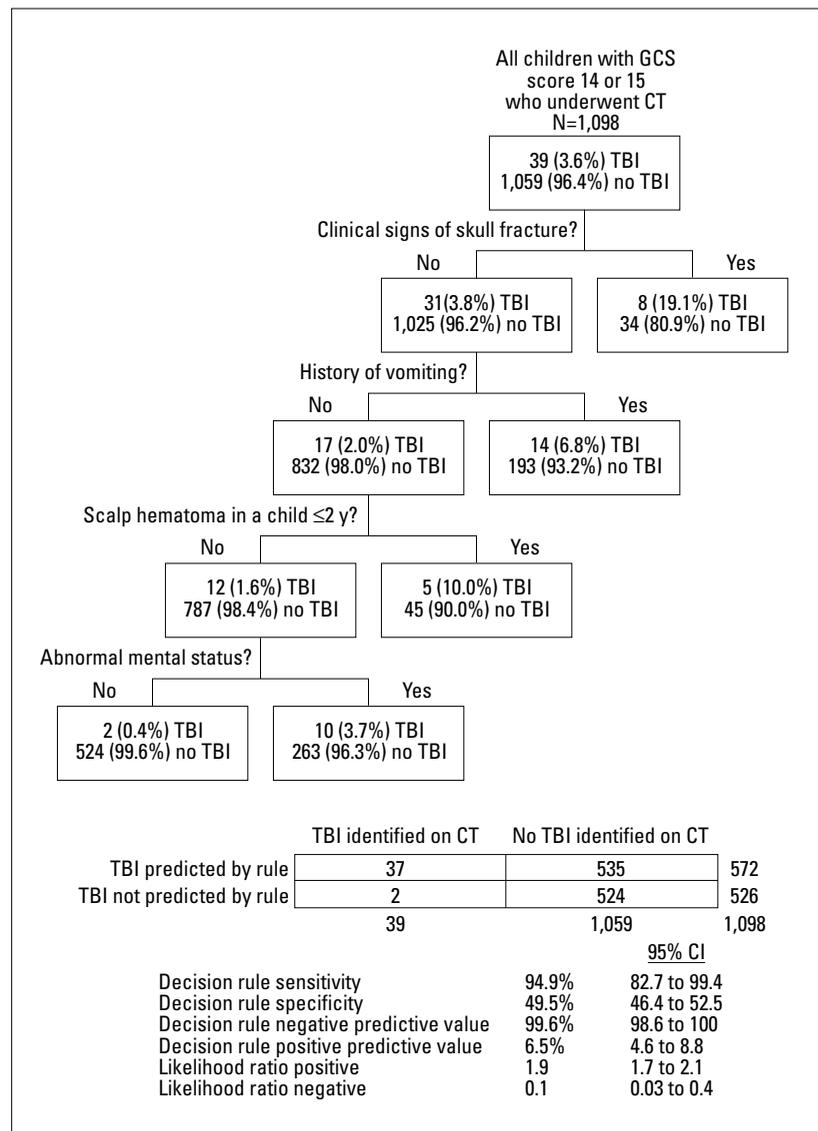
traumatic brain injuries requiring acute intervention (negative predictive value 100%; 95% CI 99.6% to 100%). Application of this rule to the children imaged by CT would have eliminated approximately one quarter of the CT scans obtained.

We performed a subanalysis on the 1,098 children with GCS scores of 14 and 15 who were evaluated with CT scan, of whom 39 (3.6%) had traumatic brain injury identified on CT scan. The decision tree for traumatic brain injury identified on CT scan included the same 4 predictor variables as in the main analysis, although the

order of the variables in the resulting tree was different (Figure 4). The presence of any of these 4 predictor variables correctly identified 37 of 39 children with traumatic brain injury on CT scan (sensitivity 94.9%; 95% CI 82.7% to 99.4%). Of the 526 patients who had none of the 4 findings, 524 did not have traumatic brain injury on CT scan (negative predictive value 99.6%; 95% CI 98.6% to 100%).

In the subanalysis of the 194 children aged 2 years and younger who were evaluated with CT scan, the decision tree for traumatic brain injury identified on CT scan

Figure 4.
Decision tree for predicting traumatic brain injury identified on CT in children with GCS scores of 14 and 15.



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included scalp hematoma and abnormal mental status (Figure 5), which identified all 15 (7.7%) children with traumatic brain injuries on CT scan (sensitivity 100%; 95% CI 81.9% to 100%). Fourteen of these 15 young children had scalp hematomas. Of the 60 children aged 2 years and younger who underwent CT and who had normal mental status and no scalp hematomas, none had a traumatic brain injury identified on CT scan (negative predictive value 100%; 95% CI 95.1% to 100%). Of the 194 children aged 2 years and younger who underwent CT, 15 (7.7%) had skull fractures on CT scan. Of these 15 children, 7 (46.7%) had traumatic brain injuries identified on CT.

Finally, in the analysis using the requirement for a neurosurgical procedure as the outcome, the 3 predictor variables in the decision tree included focal neurologic deficits, abnormal mental status, and a history of vomiting (Figure 6). These 3 variables identified all 29 children who required a neurosurgical procedure (sensitivity 100%; 95% CI 90.2% to 100%). Of the 1,295

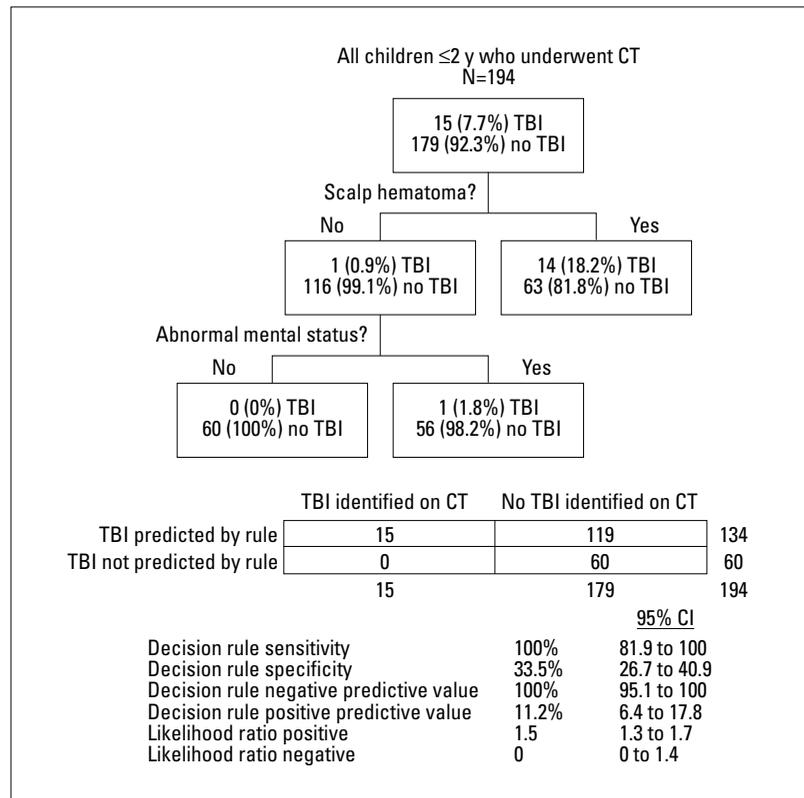
children with none of the 3 variables, none required a neurosurgical procedure (negative predictive value 100%; 95% CI 99.8% to 100%).

DISCUSSION

In this study, we derived a decision rule with high sensitivity for traumatic brain injury and high negative predictive value for identifying children without traumatic brain injury after blunt head trauma. This rule uses abnormal mental status, clinical evidence of skull fracture, a history of vomiting, scalp hematoma (in children ≤2 years), and headache. These variables are routinely assessed by emergency physicians and have a high degree of interobserver agreement. These predictors identified all but 1 of the patients with traumatic brain injuries identified on CT scan and all patients with traumatic brain injuries requiring acute intervention.

Head trauma is a common and serious childhood health problem,^{1-4,41} and evaluation of children with

Figure 5. Decision tree for predicting traumatic brain injury identified on CT in children aged 2 years and younger.



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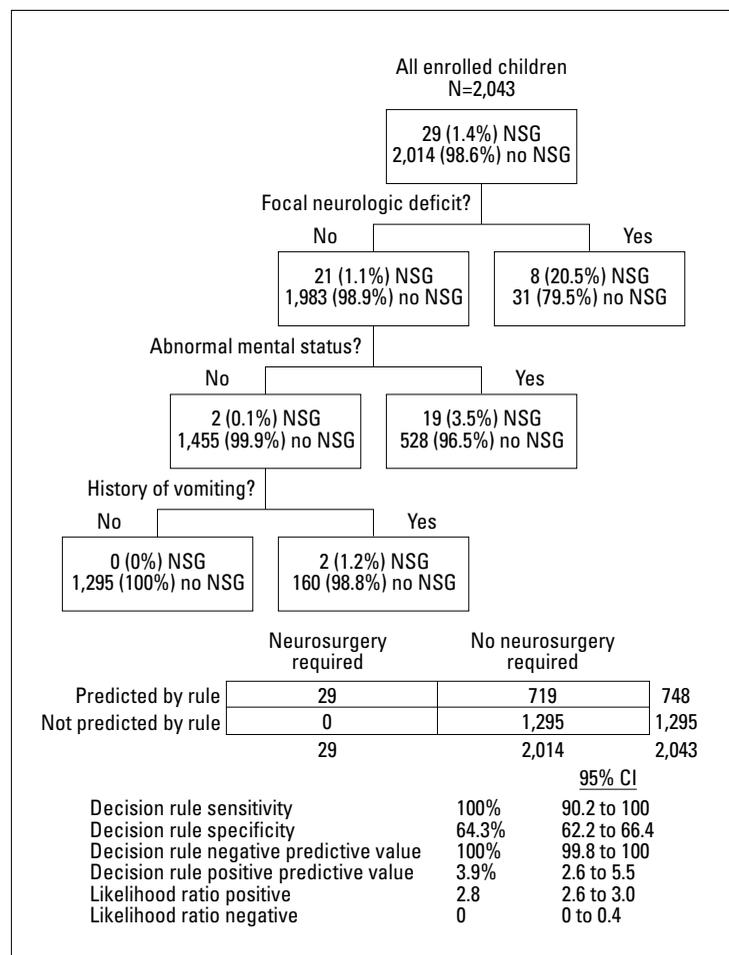
head trauma has been identified by several agencies and organizations as a priority area of research.^{8,24,42,43} Most children sustaining blunt head trauma, however, do not have traumatic brain injury.⁷⁻¹⁰ Although CT is used frequently to evaluate children with head trauma, there is little consensus regarding appropriate indications for its use.^{22,23} The benefits of information gained by CT imaging must be balanced by its disadvantages, which include exposure to ionizing radiation,¹⁵⁻¹⁸ transport of the child away from the ED, the frequent requirement for pharmacologic sedation,¹⁹⁻²¹ additional health care costs, and increased time spent in the ED.

Identification of a reliable set of clinical predictors of traumatic brain injury in children with head trauma has been the goal of previous studies; however, the results

have been inconclusive.^{7,9-14} Previous investigations have identified several signs and symptoms associated with traumatic brain injury in children^{7,9-14,44-46} similar to those identified in the univariable analyses of the current study. None of these previous studies, however, derived a decision rule that identified all children with traumatic brain injury. These previous studies were frequently retrospective and enrolled relatively small numbers of children with traumatic brain injury, and only 1 used multivariable statistical analyses.¹⁰ Recently, 2 large prospective studies generated decision rules for obtaining CT scans in patients with mild head injuries.^{47,48} One of these studies was limited to adults.⁴⁸ In the second study, the mean age of patients was 36 years, and children younger than 3 years were excluded.⁴⁷ Decision rules resulting from these studies,

Figure 6.

Decision tree for predicting the need for a neurosurgical procedure (a subset of individuals with traumatic brain injury requiring acute intervention). NSG, neurosurgical procedure.



therefore, are unlikely to apply to children, particularly preverbal children. Given the conflicting nature of studies on this topic to date, there is limited consensus regarding the indications for use of CT scan for the evaluation of children with blunt head trauma. As a consequence, physicians' practice patterns vary.^{22,23}

Children younger than 2 years and with traumatic brain injuries may have subtle clinical presentations.³³ Among these infants and young children, scalp hematoma is an important predictor of traumatic brain injury,³³⁻³⁷ and therefore we included scalp hematoma as a predictor of traumatic brain injury in children aged 2 years and younger. Scalp hematomas were present in 93% of children aged 2 years and younger with traumatic brain injuries identified on CT scan in our study and was the most important predictor variable in the subanalysis in this age group.

The current study differs from previous work in several important ways. The study sample size was relatively large, therefore allowing a powerful analysis. In addition, because our study was prospective, we were able to accurately determine the presence or absence of important clinical variables. We also defined a novel clinical outcome variable, traumatic brain injury requiring acute intervention. This clinical outcome variable is relevant to clinical decisionmaking, not dependent on neuroimaging modality, and independent of physician accuracy in interpreting the imaging study. Therefore, the decision rule for this outcome will likely be relevant in the foreseeable future, despite advances in neuroimaging technology. Finally, we used binary recursive partitioning, a multivariable analytic technique that may be preferable to multiple logistic regression for generating decision rules.³²

Our study has several potential limitations. We included children with head trauma of various degrees of severity because it allowed for the generation of a decision rule applicable to all children who have sustained nontrivial blunt head trauma. In the subanalysis of patients with mild head injury (GCS scores of 14 and 15), however, the variables in the resulting decision tree for traumatic brain injury identified on CT scan were identical to those in our main analysis. Although recog-

nition of a scalp hematoma in a child aged 2 years or younger had only a "moderate" κ value (0.53),⁴⁰ this variable was included in the recursive partitioning analysis because of the known association between scalp hematoma and traumatic brain injury. The importance of this variable in the decision trees may serve to remind physicians of the importance of a careful scalp examination, particularly in the evaluation of children aged 2 years and younger.

Although evaluators were strictly instructed to complete the study data sheet before the CT results were known, we did not verify that these instructions were uniformly followed, which may have introduced some evaluator bias into the study. We did not feel it ethically justifiable, however, to delay CT testing to complete study data sheets. Ethical concerns also precluded our obtaining CT imaging on all patients. Most patients who were not imaged with CT, however, had telephone follow-up to identify missed traumatic brain injuries. Although clinical follow-up is an acceptable endpoint when more definitive testing is not feasible or ethical,²⁸ some nonimaged patients may have had clinically silent but radiographically visible traumatic brain injuries.

The potential reduction in CT use resulting from the application of this rule at our center may not be replicated at all centers and may not result in a large net decrease in CT use of all children sustaining blunt head trauma. Application of this evidence-based rule to patients currently imaged with CT at our center would result in a substantial net decrease in CT use. Nevertheless, because of the imperfect specificity of the rule, it is possible that CT use among children not currently imaged may increase. The potential increase in CT use in patients not currently imaged is likely limited, however, because of idiosyncrasies in our variable definitions. For example, our rule treated children with ongoing vomiting the same as children who had vomited only once. This distinction was not captured by our dichotomous variable definition and in our decision rules but would likely be used in clinical decisionmaking by emergency physicians. We chose dichotomous variable definitions, however, to simplify data collection and to generate a simple decision rule.

Although this study had a relatively large sample size, the 95% CIs for the sensitivity of the decision rule may be wider than some physicians would accept.⁴⁹ A large, multicenter study is needed to further narrow the CIs. Finally, although the decision trees were constructed and validated by using internal 10-fold cross-validation, external validation with a large, diverse sample of pediatric head trauma patients is necessary.

In conclusion, we created a clinical decision rule with high sensitivity for traumatic brain injury and high negative predictive value for identifying children without traumatic brain injuries after blunt head trauma. Important variables include abnormal mental status, clinical signs of skull fracture, a history of vomiting, scalp hematoma (in children ≤ 2 years), and headache. Use of this rule may decrease CT use in patients without an appreciable risk of traumatic brain injury.

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Address for reprints: Nathan Kuppermann, MD, MPH, University of California–Davis Medical Center, PSSB 2100, 2315 Stockton Boulevard, Sacramento, CA 95817-2282; 916-734-1535, fax 916-734-7950; E-mail nkuppermann@ucdavis.edu.

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