

COMPARATIVE EFFECTIVENESS RESEARCH

Variation in Intracranial Pressure Monitoring and Outcomes in Pediatric Traumatic Brain Injury

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Objectives: To describe between-hospital and patient-level variation in intracranial pressure (ICP) monitoring and to evaluate ICP monitoring in association with hospital features and outcome in children with traumatic brain injury (TBI).

Design: Retrospective cohort study.

Setting: Children's hospitals participating in the Pediatric Health Information System database (January 2001 to June 2011).

Participants: Children (aged <18 years) with TBI and head Abbreviated Injury Scale scores of at least 3 who were ventilated for at least 96 consecutive hours or who died in the first 4 days after hospital admission.

Main Outcome Measures: Monitoring of ICP.

Results: A total of 4667 children met the study criteria. Hospital mortality was 41% (n=1919). Overall, 55% of patients (n=2586) received ICP monitoring. Expected

hospital ICP monitoring rates after adjustment for patient age, cardiac arrest, inflicted injury, craniotomy or craniectomy, head Abbreviated Injury Scale score, and Injury Severity Score were 47% to 60%. Observed hospital ICP monitoring rates were 14% to 83%. Hospitals with more observed ICP monitoring, relative to expected, and hospitals with higher patient volumes had lower rates of mortality or severe disability. After adjustment for between-hospital variation and patient severity of injury, ICP monitoring was independently associated with age 1 year and older (odds ratio, 3.1; 95% CI, 2.5-3.8) vs age younger than 1 year.

Conclusions: There was significant between-hospital variation in ICP monitoring that cannot be attributed solely to differences in case mix. Hospitals that monitor ICP more frequently and hospitals with higher patient volumes had better patient outcomes. Infants with TBI are less likely to receive ICP monitoring than are older children.

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PEDIATRIC TRAUMATIC BRAIN injury (TBI) is estimated to cause approximately 2300 deaths, 42 000 hospitalizations, and 404 000 emergency department visits annually in children aged 0 to 14 years.^{1,2} It is also a major cause of disability in children.³ Elevated intracranial pressure (ICP), a marker of severe injury, may develop after TBI via several mechanisms, including intracranial hemorrhage, cellular swelling, and blood-brain barrier disruption.⁴

Monitoring of ICP is used to detect elevated ICP and is required for goal-directed treatment of intracranial hypertension. Treatment of intracranial hypertension is known to improve outcomes in adults⁵; however, the pediatric evidence linking ICP monitoring to improved outcomes is less robust.⁶

Wide variation in treatment methods unexplained by patient-level factors is a marker for opportunities for care improvement.^{7,8} The between-hospital variation in ICP monitoring for children with TBI in the United States is unknown. We suspected that variation in ICP monitoring might be present based on previous reports of significant between-hospital variation in ICP monitoring in the United Kingdom⁹ and wide hospital variation in ICP monitoring for meningitis in the United States.¹⁰ We reported significant between-hospital variation in the use of a medical treatment, osmolar therapy, for children with TBI.¹¹

In addition, it is unknown whether hospital pediatric TBI volume, hospital American College of Surgeons (ACS) pediatric trauma designation, and hospital ICP monitoring rate are associated with improved outcomes in children with TBI. We evaluated these hospital factors because adults with severe injuries have better outcomes at large or level I trauma centers.^{12,13} Hospital experience and ACS certification requirements are factors that logically might be associated with decreased variation in ICP monitoring and patient outcome.

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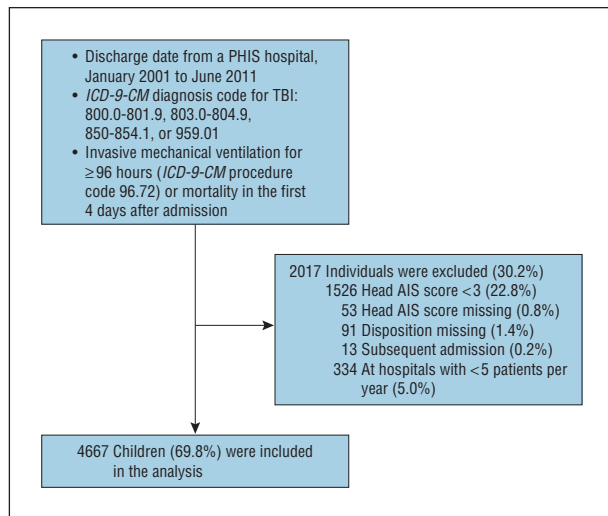


Figure 1. Patient selection method for children younger than 18 years with traumatic brain injury (TBI). AIS indicates maximum Abbreviated Injury Scale for the head body region derived using ICDMAP-90 software; ICD-9-CM, International Classification of Diseases, Ninth Revision, Clinical Modification; and PHIS, Pediatric Health Information System.

This study describes between-hospital variation in ICP monitoring, evaluates whether hospital factors and ICP monitoring practices are associated with outcomes, and describes patient-level variation in ICP monitoring using a large, retrospective, severely head-injured cohort from the Pediatric Health Information System (PHIS) database.

METHODS

STUDY DESIGN

The PHIS database was developed by the Child Health Corporation of America.¹⁴ To define a retrospective cohort with severe TBI, we identified children who received care for TBI at a PHIS hospital and were mechanically ventilated for at least 96 consecutive hours or died in the first 4 days of hospitalization.

SETTING

The Child Health Corporation of America is a business alliance of 43 children's hospitals, and the PHIS contains administrative data, including demographics, diagnoses, procedures, and charges. In addition, most PHIS hospitals submit level II data, including billing information for pharmacy, imaging, laboratory, supply, nursing, and therapy services.¹⁵ Inpatient data on 36 PHIS hospitals have been published previously.¹⁵ Conway and Keren¹⁶ described the extensive data reliability and quality monitoring processes for PHIS data.

SELECTION OF PARTICIPANTS

We obtained data from the PHIS database regarding patients who met the inclusion criteria and had supplemental billing (level II) data recorded (**Figure 1**). We identified children younger than 18 years discharged from a PHIS hospital between January 1, 2001, and June 30, 2011, with an *International Classification of Diseases, Ninth Revision, Clinical Modification* (ICD-9-CM) discharge diagnosis code for TBI (**Figure 1**). This set of ICD-9-CM diagnosis codes is used by the Centers for Disease Control and Prevention to track hospitalizations and emergency department visits for TBI rates nationally.¹⁷ To be

included, patients were required to have either ICD-9-CM procedure code 96.72, which represents continuous invasive mechanical ventilation for 96 consecutive hours or more,¹⁸ or mortality in the first 4 days after admission.

We calculated the Injury Severity Score (ISS, or specifically, ICD/ISS) and maximum Abbreviated Injury Scale (AIS) body region scores from ICD-9-CM diagnosis codes using ICDMAP-90 software (Johns Hopkins University and Tri-Analytics, Inc).¹⁹ To refine a cohort with severe TBI, we excluded patients with maximum head body region AIS scores of less than 3 (serious), patients with missing head AIS scores, patients with missing disposition, and patients with subsequent admissions (**Figure 1**). We excluded hospitals with fewer than 5 patients per year (**Figure 1**). We analyzed a less restrictive subset of the same cohort in an earlier work.¹¹

COVARIATES AND OUTCOMES

We analyzed the study population by demographic characteristics, insurance status, injury characteristics and severity, inflicted injury, and cardiac arrest (**Table 1**). We dichotomized the admission date variable as before or after July 31, 2003, when the first guidelines for the care of severe pediatric TBI (which endorsed ICP monitor use in children) were published, to test the hypothesis that the guidelines would decrease care variation.²⁰ These guidelines have recently been updated and continue to endorse ICP monitor use.²¹ We also analyzed patients by the admission hospital's ACS pediatric trauma designation.²²

The primary outcome was ICP monitoring, defined using Clinical Transaction Classification codes or ICD-9-CM procedure codes (see the footnotes to **Table 2**). Clinical Transaction Classification codes reflect hospital billing and can be used to identify services received by patients.^{15,16,23}

We defined poor outcome as hospital mortality or placement of a new tracheostomy tube (ICD-9-CM procedure codes 31.1, 31.2x, or 31.74) and a new gastrostomy tube (ICD-9-CM procedure codes 43.1x, 46.32, or 46.39) during the hospitalization. Children receiving tracheostomy and gastrostomy after TBI are likely severely disabled when discharged.

The patient-level factors in the multivariate models were specified a priori: patient age at hospital admission (years, continuous), head AIS score (categorical), ISS (continuous), inflicted injury, cardiac arrest, and craniotomy or craniectomy. We included age because children younger than 1 year with TBI receive ICP monitoring less often than do older children^{9,24}; AIS score as the best measure of head injury severity in this data set and as a factor associated with ICP monitoring²⁵; ISS as a measure of global injury severity and likelihood of patient viability,²⁶ which is also associated with ICP monitoring²⁵; inflicted injury to separate that effect from any age effect; cardiac arrest because it has been inversely associated with ICP monitoring²⁴; and craniotomy/craniectomy because it may be associated with ICP monitor placement as part of a single operating room course and because it is recommended in children with intracranial mass lesions.²⁷

PRIMARY DATA ANALYSES

We used the χ^2 test for categorical variables and the Wilcoxon rank sum test for continuous variables (patients per hospital). To understand how much of the observed variation in ICP monitor use between hospitals could be attributed to patient factors (case mix at each hospital) vs hospital factors, we first standardized hospital-level rates of ICP monitoring using a population-averaged logistic model with the prespecified covariates described previously. From this model, we estimated a predicted probability of ICP monitoring for each patient and then used these probabili-

Table 1. Select Demographic and Clinical Features of the Pediatric Traumatic Brain Injury Cohort by Outcome

Feature	Participants, No. (%)	
	Death or Tracheostomy and Gastrostomy (n = 2114)	Survival Without Tracheostomy and Gastrostomy (n = 2553)
Age		
0 to 364 d	512 (24)	723 (28)
1 to <5 y	662 (31)	595 (23)
5 to <13 y	565 (27)	761 (30)
13 to <18 y	375 (18)	474 (19)
Sex		
Male	1322 (63)	1606 (63)
Missing	2 (<1)	8 (<1)
Insurance status		
Government	1166 (55)	1416 (55)
Private	520 (25)	699 (27)
Other	404 (19)	407 (16)
Missing	24 (1)	31 (1)
Hospital admission date		
10/2000-7/2003	482 (23)	590 (22)
8/2003-6/2011	1632 (77)	1993 (78)
Cardiac arrest, any ^a	404 (19)	36 (1)
Inflicted injury ^b	658 (31)	715 (28)
EDH, no fracture ^c	24 (1)	50 (2)
SAH, no fracture ^d	317 (15)	253 (10)
SDH, no fracture ^e	575 (27)	617 (24)
Craniotomy/craniectomy ^f	122 (6)	288 (11)
Head AIS score ^g		
3 ("serious")	278 (13)	1249 (49)
4 ("severe")	277 (13)	914 (36)
5 ("critical")	1559 (74)	390 (15)
ICD/ISS		
<15	184 (9)	855 (33)
≥15	1930 (91)	1698 (67)
ACS trauma level		
I (15 hospitals)	1023 (48)	1318 (52)
II (2 hospitals)	138 (7)	128 (5)
None (4 hospitals)	953 (45)	1107 (43)
Patients per hospital		
<100 (8 hospitals)	248 (12)	308 (12)
100-200 (15 hospitals)	1018 (48)	1067 (42)
>200 (8 hospitals)	848 (40)	1178 (46)

Abbreviations: ACS, American College of Surgeons; AIS, Abbreviated Injury Scale; EDH, epidural hematoma; ICD/ISS, Injury Severity Score derived using ICDMAP-90 software; SAH, subarachnoid hemorrhage; SDH, subdural hemorrhage.

^aInternational Classification of Diseases, Ninth Revision, Clinical Modification (ICD-9-CM) discharge diagnosis code 427.5 or 997.1.

^bAny of ICD-9-CM discharge diagnosis codes 995.5 and E960 to 968.²⁰

^cICD-9-CM diagnosis code 852.4 or 852.5.

^dICD-9-CM diagnosis code 852.0 or 852.1.

^eICD-9-CM diagnosis code 852.2 or 852.3.

^fICD-9-CM procedure code 01.24 or 01.25.

^gMaximum AIS score, head body region, derived using ICDMAP-90.

ties to calculate expected hospital ICP monitoring rates. We then calculated standardized ICP monitoring rates by comparing observed and expected ICP monitoring rates for each hospital in a manner similar to that of Weiss et al.¹⁵

We compared between-hospital variation by ACS trauma designation and hospital patient volume with the proportion of patients at each hospital with a poor outcome. Linear regression with robust standard errors was used to test the slopes of the poor outcome–time, ICP monitoring–time, outcome–

Table 2. Select Demographic and Clinical Features of the Pediatric Traumatic Brain Injury Cohort by ICP Monitoring^a

Features	Participants, No. (%)	
	ICP Monitor (n = 2586)	No ICP Monitor (n = 2081)
Age		
0 to 364 d	420 (16)	815 (39)
1 to <5 y	751 (29)	506 (24)
5 to <13 y	868 (34)	458 (22)
13 to <18 y	547 (21)	302 (15)
Sex		
Male	1623 (63)	1305 (63)
Missing	7 (<1)	3 (<1)
Insurance status		
Government	1341 (52)	1241 (60)
Private	782 (30)	437 (21)
Other	437 (17)	374 (18)
Missing	26 (1)	29 (1)
Admission date		
10/2000-7/2003	601 (23)	441 (21)
8/2003-6/2011	1985 (77)	1640 (79)
Cardiac arrest ^b	121 (5)	319 (15)
Inflicted injury ^c	571 (22)	802 (39)
EDH, no fracture ^{cd}	47 (2)	27 (1)
SAH, no fracture ^e	258 (10)	312 (15)
SDH, no fracture ^f	576 (22)	616 (30)
Craniotomy/craniectomy ^g	350 (14)	60 (3)
Head AIS score ^h		
3 ("serious")	961 (37)	566 (27)
4 ("severe")	680 (26)	511 (25)
5 ("critical")	945 (37)	1004 (48)
ICD/ISS		
<15	683 (26)	356 (17)
≥15	1903 (74)	1725 (83)
ACS trauma level		
I (15 hospitals)	1369 (53)	972 (47)
II (2 hospitals)	126 (5)	140 (7)
None (14 hospitals)	1091 (42)	969 (47)
Patients per hospital		
<100 (8 hospitals)	226 (9)	330 (16)
100-200 (15 hospitals)	1144 (44)	941 (45)
>200 (8 hospitals)	1216 (47)	810 (39)

Abbreviations: ACS, American College of Surgeons; AIS, Abbreviated Injury Scale; EDH, epidural hematoma; ICD/ISS, Injury Severity Score derived using ICDMAP-90 software; ICP, intracranial pressure; SAH, subarachnoid hemorrhage; SDH, subdural hemorrhage.

^aThe ICP monitors were coded using any of International Classification of Diseases, Ninth Revision, Clinical Modification (ICD-9-CM) procedure codes 01.18, 01.10, 02.2, and 02.39 or Clinical Transaction Classification codes for "ICP monitor supply" or "intracranial pressure monitoring."

^bICD-9-CM discharge diagnosis code 427.5 or 997.1.

^cAny of ICD-9-CM discharge diagnosis codes 995.5 and E960 to 968.²⁰

^dICD-9-CM diagnosis code 852.4 or 852.5.

^eICD-9-CM diagnosis code 852.0 or 852.1.

^fICD-9-CM diagnosis code 852.2 or 852.3.

^gICD-9-CM procedure code 01.24 or 01.25.

^hMaximum AIS score, head body region, derived using ICDMAP-90.

variation, and outcome-volume relationships. We then used a random-intercept logistic regression model including the same prespecified covariates^{15,16} and the intraclass correlation coefficient to estimate variation in ICP monitoring between hospitals not related to patient factors.

To determine variation by patient-level characteristics, we used a multivariate logistic regression model with clustering by hospital, an exchangeable correlation structure, and robust

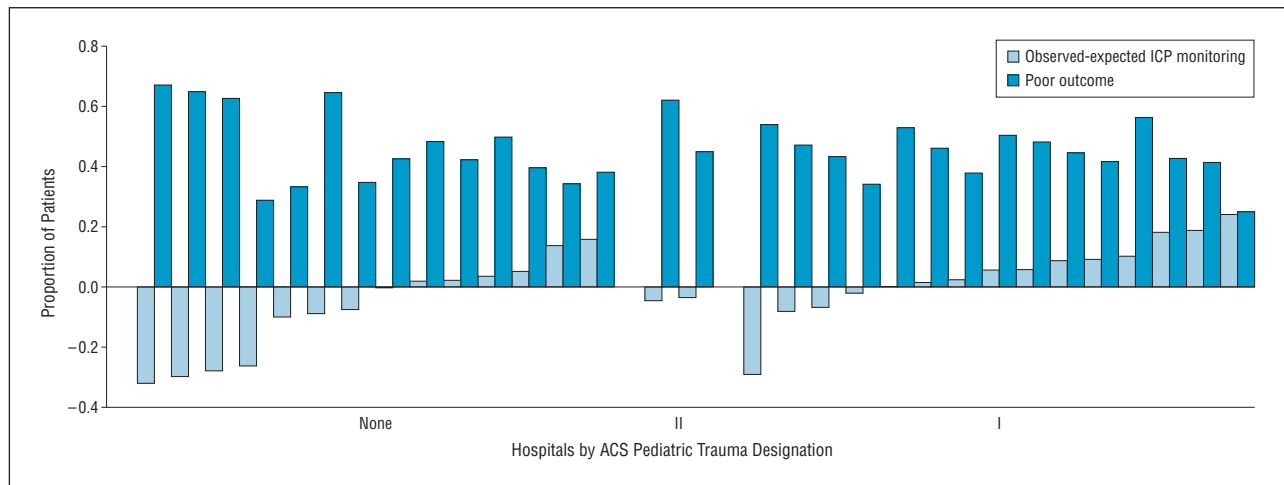


Figure 2. Observed and expected intracranial pressure (ICP) monitoring rates and poor outcome (death or tracheostomy and gastrostomy) by hospital trauma designation. ACS indicates American College of Surgeons.

standard errors calculated using generalized estimating equations. This model was populated with the same prespecified covariates described previously.

Statistical significance was defined as $P < .05$, and all the analyses were performed using a statistical software program (STATA, versions 10 and 11; StataCorp LP). This study was reviewed, and informed consent was not required by the University of Utah School of Medicine institutional review board.

RESULTS

PATIENTS AND HOSPITALS

We identified 6684 patients with TBI and early mortality or at least 96 hours of mechanical ventilation, and 4667 remained in the data set after exclusions (Figure 1). In each month, a median of 37 (interquartile range [IQR], 32-42) patients were discharged from 31 PHIS hospitals. In-hospital mortality was 41.1% (1919 of 4667). The combined poor outcome rate was 45.3% (Table 1), and it decreased slowly over time (being highest at 48.6% in 2002 and lowest at 42.1% in 2004; overall monthly decrease, 0.014%; 95% CI, 0.008%-0.021%; $P < .001$). The ACS level I hospitals (43.7%) had a similar poor outcome rate as hospitals without an ACS designation (46.3%; $\chi^2 P = .09$). Approximately 33% of patients (1555 of 4667) died in the first 4 days of admission, and the remaining patients (3112 of 4667) were candidates for the study because they were ventilated for at least 96 consecutive hours.

Approximately 26% of patients were younger than 1 year, and most were male (Table 1). Almost 10% of patients (440 of 4667) had a diagnosis of cardiac arrest, which was concentrated among infants (12.4%) and 1- to 5-year-olds (11.4%) vs older age groups (6.9% school-aged and 6.1% teenagers, $\chi^2 P < .001$ across age groups). Approximately 29% of all patients and 71% of infants had a diagnosis of inflicted injury. Cardiac arrest occurred in 12.9% of patients with inflicted injury vs 8.0% without inflicted injury ($\chi^2 P < .001$). Most patients (77%) had an intracranial hemorrhage, and 51% had a skull fracture (data not shown). Almost 9% had a craniotomy or

a craniectomy, with 78% of each patient's first such operation occurring on hospital day 0 (in the PHIS database, from admission until midnight that night) or hospital day 1 (the 24 hours after the first midnight of the hospitalization). Small percentages of those operations occurred on hospital days 2 (7%), 3 (2%), and 4 (2%), with 93% occurring by the end of hospital day 7.

The median ISS was 22 (IQR, 16-26). All 11 patients with the maximum ISS score of 75 ("unsurvivable") had the maximum spine AIS score of 6, and 10 of the 11 died. Most hospitals did not have an ACS pediatric trauma designation, and the overall median number of patients per hospital was 139 (range, 57-350; IQR, 85-201). The number of patients per hospital was not different between ACS level I hospitals (median, 140; IQR, 111-208) and hospitals without an ACS designation (median, 137; IQR, 72-149; Wilcoxon $P = .43$).

ICP MONITORING

Overall, 55% of patients (2586 of 4667) had documented ICP monitoring (Table 2). The ICP monitoring rate decreased slowly (monthly decrease, 0.014%; 95% CI, 0.007-0.021%; $P < .001$) during the 10.5 years of the study; annual ICP monitoring rates were lowest in 2011 (52.2%) and highest in 2002 (59.1%), with little change from guideline publication in 2003 (data not shown). Most ICP monitors (88%) were placed on hospital day 0 or 1, but small fractions were placed on hospital days 2 (4%), 3 (2%), and 4 (1%). Of patients with ICP monitoring, 62% (1597 of 2586) had an ICD-9-CM procedure code and a Clinical Transaction Classification code for a monitor, 25% (638 of 2586) had only a procedure code, and 14% (351 of 2586) had only a Clinical Transaction Classification code.

The relationships between patient demographic, injury, and treatment facility characteristics and ICP monitoring are given in Table 2. Infants were significantly less likely to have ICP monitoring than were older children ($\chi^2 P < .001$).

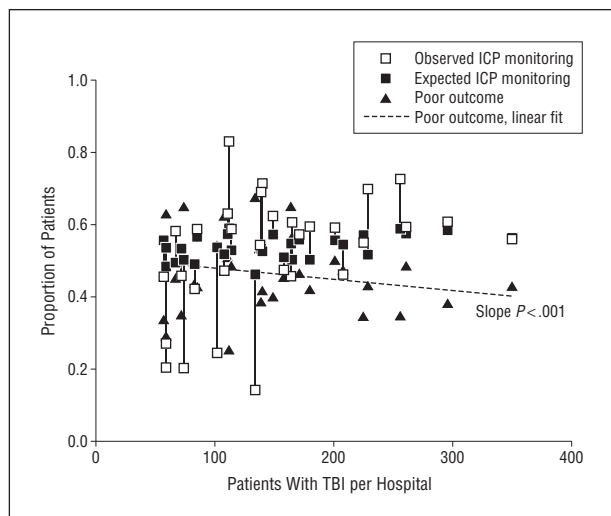


Figure 3. Observed and expected intracranial pressure (ICP) monitoring rates and poor outcome (death or tracheostomy and gastrostomy) by hospital volume. TBI indicates traumatic brain injury.

BETWEEN-HOSPITAL VARIATION

Expected rates of ICP monitoring by hospital after adjustment for age, cardiac arrest, inflicted injury, head AIS score, ISS, and craniotomy/craniectomy were 47% to 60%, whereas observed rates varied from 14% to 83%. Monitoring of ICP occurred significantly more often at ACS pediatric trauma level I hospitals and at hospitals with higher patient volumes ($\chi^2 P < .001$ for differences across ACS trauma levels and hospital volume categories). Hospitals with higher standardized ICP monitoring rates had better patient outcomes (slope $P < .001$ overall and in ACS level I and no designation, with too few ACS level II hospitals to test the within-level slope) (**Figure 2**). Hospitals without an ACS designation had the most variation in ICP monitoring, and 4 of the 5 hospitals with the lowest standardized ICP monitoring rates had no ACS designation.

Hospitals with higher patient volume had less variation in standardized rates of ICP monitoring and modestly better patient outcomes (estimated decrease in poor outcomes, 0.31% for each additional 10 patients; 95% CI, 0.28%-0.34%; $P < .001$) than did hospitals with lower patient volume (**Figure 3**). These relationships did not change when the analysis was restricted to 2004 to 2011 (data not shown), suggesting that the guidelines published in July 2003 were not associated with changes in ICP monitoring variation.

Using a random-intercept logistic model adjusted for the same prespecified covariates, we estimated from the intraclass correlation coefficient that 12.7% (95% CI, 7.7%-20.4%) of the total variance in ICP monitoring is between-hospital variance not explained by identified patient factors.

PATIENT-LEVEL VARIATION

Using generalized estimating equation models, we found that age 1 year and older, the absence of cardiac arrest, receipt of a craniotomy or a craniectomy, a head AIS score of 4 vs 3, and a lower ISS were independently associated

Table 3. Logistic Regression Model for Intracranial Pressure Monitoring Adjusted for Clustering by Hospital Using Generalized Estimating Equations

Feature	aOR (95% CI)
Age	
0 to 364 d	1 [Reference]
1 to <5 y	2.95 (2.38-3.66)
5 to <13 y	3.38 (2.72-4.21)
13 to <18 y	3.21 (2.50-4.13)
Cardiac arrest	
None	1 [Reference]
Any	0.36 (0.29-0.46)
Inflicted injury	
No	1 [Reference]
Yes	0.86 (0.71-1.04)
Craniotomy/craniectomy	
No	1 [Reference]
Yes	3.71 (2.65-5.19)
Head AIS score ^a	
3	1 [Reference]
4	1.37 (1.11-1.70)
5	0.91 (0.72-1.16)
ICD/ISS	
<15	1 [Reference]
≥15	0.54 (0.43-0.67)

Abbreviations: AIS, Abbreviated Injury Scale; aOR, adjusted odds ratio; ICD/ISS, Injury Severity Score derived using ICDMAP-90 software.
^aMaximum AIS score, head body region, derived using ICDMAP-90.

with ICP monitoring (**Table 3**). In an otherwise identical model with age dichotomized at 1 year, the adjusted odds ratio for ICP monitoring in children 1 year and older vs younger than 1 year was 3.1 (95% CI, 2.5-3.8).

COMMENT

In this large multicenter database, we found significant between-hospital variation in ICP monitoring in children with TBI. Hospitals with higher standardized ICP monitoring rates and hospitals with higher patient volumes had better outcomes. The ACS designation was not associated with better outcomes but was associated with less variation in monitoring. Infants (age <1 year) were less likely to have ICP monitoring than were older children.

After adjustment for patient factors, we estimated that 13% of the ICP monitoring variation was attributable to between-hospital variation. Publication of the 2003 pediatric TBI treatment guidelines did not seem to change ICP monitoring rates or variation in ICP monitoring, as we found little change over time. Similar to the present findings, Bulger et al²⁸ found broad between-hospital variation in ICP monitoring of adults with TBI in the United States and better outcomes at centers with greater ICP monitor use. Substantial between-hospital variation in ICP monitoring rates in children with TBI has also been reported in the United Kingdom; however, the variation-outcome relationship was not reported.⁹ Although the exact relationship between variation in hospital ICP monitoring rates and outcomes in children with TBI needs further study, it is likely that there are opportunities for improvement in the care of children with TBI.⁷

We found less variation in ICP monitoring at ACS level I hospitals and better outcomes at hospitals with less variation. The ACS level, however, was not associated with better outcomes in a bivariate analysis. Similar to studies of adult TBI, we found better outcomes at hospitals with larger TBI patient volumes.^{12,13} Larger hospital volume is associated with better outcomes in children receiving critical care²⁹ and has been associated with adherence to some pediatric quality of care guidelines.³⁰ A recent British study³¹ did not find a significant relationship between hospital volume and outcome in pediatric TBI, although there was concerning variation in outcome according to pediatric neurosurgical availability. Pediatric neurosurgical availability was not present in this data set but is required for ACS level I designation.

In this analysis of patient-level variation, we found that ICP monitoring was used less often in infants than in older children, after adjustment for all other independent predictors and between-hospital variation. The 2003 guideline recommendation for ICP monitoring includes infants, as open fontanelles or sutures “[do] not preclude the development of intracranial hypertension or negate the utility of ICP monitoring.”^{6(p519)} The factors that contribute to lower use of ICP monitoring in infants are unknown. Technical feasibility may be a factor, as the infant skull may not be structurally able to support some monitoring devices. Providers may place monitoring devices less frequently because of a perceived poor prognosis, as many infants have experienced inflicted injury or a cardiac arrest, both associated with worse outcomes.^{24,32}

The present study has several limitations. Postresuscitation Glasgow Coma Scale scores, pupillary examination findings, and head computed tomographic results, the most predictive measures of TBI severity, are not present in the PHIS database. We restricted this analysis using AIS scores and mechanical ventilation for at least 96 hours as proxies for severity, but they may not completely represent Glasgow Coma Scale score–based severity of TBI; however, given the high mortality rate in this study cohort (41% vs 16%–24% in studies selected by Glasgow Coma Scale score), we were likely overly restrictive.^{33–36} The patients in the present study were severely injured, representing the type of patients potentially eligible for ICP monitoring. To ensure that between-hospital variation in ICP monitoring was not a result of patient factors related to poor prognosis, we adjusted for head injury severity, overall injury severity, inflicted injury, and cardiac arrest as known predictors of poor outcome.

ICDMAP-90, the software package used to calculate AIS scores and ISSs from ICD-9-CM diagnosis codes, has been validated in adults³⁷ and children³⁸ for its ability to determine injury severity, and it has been used in several pediatric TBI studies, including 2 from the PHIS database.^{11,39–41} Coates et al⁴² and Di Gennaro et al⁴³ also defined their study populations using head AIS scores of 3 or greater in analyses of children with severe TBI. Relatively low correlation coefficients of approximately ± 0.3 have been reported between AIS score, ISS, and Glasgow Coma Scale score in adults with TBI,^{44,45} but each add independently and significantly to functional outcome prediction.⁴⁵ Other limitations include that ICD-9-CM diagnosis codes for TBI do not allow ideal categorization

of intracranial hemorrhages¹⁸ and that changes in hospital ACS trauma designation are not shown in the publicly available trauma center list.²²

In conclusion, there is significant between-hospital variation in ICP monitoring that is unlikely to be due solely to differences in case mix. Hospitals that monitor ICP more often and hospitals with higher patient volumes had better patient outcomes, although a causal relationship between monitoring and improved outcome cannot be inferred from this analysis. Infants are less likely to receive ICP monitoring than are older children. The between-hospital variation suggests opportunities to improve the quality of pediatric TBI neurocritical care.

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Author Contributions: Dr Bennett had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis. *Study concept and design:* Bennett and Bratton. *Acquisition of data:* Bennett and Korgenski. *Analysis and interpretation of data:* Bennett, Riva-Cambrin, Keenan, and Bratton. *Drafting of the manuscript:* Bennett and Bratton. *Critical revision of the manuscript for important intellectual content:* Bennett, Riva-Cambrin, Keenan, Korgenski, and Bratton. *Statistical analysis:* Bennett. *Administrative, technical, and material support:* Riva-Cambrin and Korgenski. *Study supervision:* Keenan and Bratton.

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