

## ORIGINAL RESEARCH

## Pediatrics

# Trends and variation in repeat neuroimaging for children with traumatic intracranial hemorrhage

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## Abstract

**Objectives:** We aimed to determine trends and institutional variation in repeat neuroimaging in children with traumatic intracranial hemorrhage and to identify factors associated with neuroimaging modality (subsequent magnetic resonance imaging [MRI] vs computed tomography [CT]).

**Methods:** We conducted a retrospective cross-sectional study of 35 hospitals in the Pediatric Health Information System database. We included children <18 years of age hospitalized from 2010–2019 with intracranial hemorrhage and who underwent a brain CT. We calculated repeat neuroimaging rates by modality and used regression analyses to examine temporal trends. We used hierarchical logistic regression to identify factors associated with subsequent MRI versus repeat CT, controlling for hospital.

**Results:** We identified 12,714 children with intracranial hemorrhage, of which 5072 with repeat neuroimaging were studied. Of the 5072 children with repeat neuroimaging, repeat CT was performed in 67.6% (n = 3429) and subsequent MRI in 32.4% (n = 1643). Overall repeat neuroimaging with either a CT or MRI remained similar from 2010–2019 (P = 0.431); however, repeat CT scans significantly decreased (P = 0.001); whereas, MRIs significantly increased (P < 0.001). Repeat neuroimaging by hospital ranged from 20%–80%. After controlling for institution, subsequent MRI was more likely to be used in younger children and children who did not receive hyperosmotic agents, neurosurgical interventions, or intensive care unit admission (all P-values < 0.001).

**Conclusions:** We found that repeat neuroimaging rates for children with intracranial hemorrhage vary substantially by institution. We also found that although MRI was increasingly used to re-image these children, overall repeat neuroimaging rates (CT or MRI) have not decreased over the past decade. Future work to implement optimal utilization of neuroimaging in these children is needed.

## KEYWORDS

brain injuries, diagnostic imaging, hospitals, intracranial hemorrhages, neuroimaging, pediatric emergency medicine, pediatrics, traumatic, wounds and injuries

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## 1 | INTRODUCTION

### 1.1 | Background

Traumatic brain injuries account for over 6000 pediatric deaths, 60,000 hospitalizations, and 800,000 emergency department (ED) visits in the United States annually.<sup>1</sup> Much of the morbidity from traumatic brain injury occurs in children with intracranial hemorrhage, and clinicians closely monitor patients for hemorrhage progression with neuro-imaging techniques.<sup>2-9</sup> Computed tomography (CT) scans are the standard acute neuroimaging modality to both identify intracranial hemorrhage and monitor for hemorrhage progression because of its diagnostic accuracy, availability, and rapidity of results.<sup>2-9</sup> Children with intracranial hemorrhage undergo an average of 1-3 repeat CT scans during acute hospitalization, with 40%-88% of children undergoing at least 1 repeat CT scan.<sup>2-9</sup> However, CT scans have inherent risks, particularly if they are used repeatedly.<sup>10</sup> Furthermore, radiation from CT scans increases the risk of future cancer, with the lifetime risk for fatal cancer for a child undergoing 1 brain CT estimated to be 1 in 5000.<sup>10,11</sup> Serial CT scans compound this risk incrementally.<sup>10</sup>

Magnetic resonance imaging (MRI) does not expose children to radiation, but until recently it was not widely used in the acute evaluation of intracranial injury in children with traumatic brain injury due to lack of widespread emergent availability, the length required to complete scans, frequent need for procedural sedation, and uncertain diagnostic accuracy for bony injuries. Building off protocols for rapid brain MRI developed to assess for potential ventriculoperitoneal shunt malfunctions, some institutions now use rapid MRIs for repeat neuroimaging in pediatric trauma, and recent literature supports feasibility and accuracy compared to CT scans even as an initial neuroimaging modality.<sup>12-16</sup>

### 1.2 | Importance

However, the frequency of subsequent MRI use in this population and the factors associated with the use of subsequent MRI versus repeat CT scan is not well described. A better understanding of temporal trends and institutional variation in use of repeat neuroimaging would inform future clinical effectiveness work to standardize the optimal utilization of neuroimaging in these children.

### 1.3 | Goals of this investigation

We aimed to determine trends and institutional variation in the use of MRI versus CT as neuroimaging techniques for re-imaging in a multi-institutional cohort of children with intracranial hemorrhage. We also aimed to identify factors independently associated with the use of subsequent MRI compared to repeat CT among children who underwent repeat neuroimaging. We hypothesized that, although there is substantial institutional variability, the rates of repeat CT scans are decreasing over time, MRI is increasing, and there will be factors independent of institution associated with use of subsequent MRI over repeat CT.

#### The Bottom Line

This study included 5072 children with traumatic intracranial hemorrhage who underwent repeat neuroimaging to evaluate trends and institutional variation in repeat neuroimaging. The authors found that 68% had a repeat CT scan, while 32% had an MRI. Although there were substantial variations between hospitals, the use of repeat CT has been decreasing with time as MRI has become more widely used.

## 2 | METHODS

### 2.1 | Study design and data source

Data for this study were obtained from the Pediatric Health Information System (PHIS), an administrative database that contains inpatient, ED, ambulatory surgery, and observation encounter-level data from tertiary care pediatric hospitals in the United States. These hospitals are affiliated with the Children's Hospital Association (Lenexa, KS). Data quality and reliability are assured through a joint effort between the Children's Hospital Association and participating hospitals. Portions of the data submission and data quality processes for the PHIS database are managed by Truven Health Analytics (Ann Arbor, MI). For the purposes of external benchmarking, participating hospitals provide discharge or encounter data including demographics, diagnoses, and procedures. Hospitals also submit resource utilization data (eg, pharmaceuticals, imaging, and laboratory) into PHIS. Timing of resource utilization data is limited to the day of service performed. Data are de-identified at the time of submission and are subjected to reliability and validity checks before being included in the database. Hospitals with unreliable data were excluded from the study using standard PHIS reliability checks. As tertiary care medical centers, PHIS hospitals have both CT and MRI available.

All statistical analyses were performed using Stata/SE version 16.0 (Stata Corp, College Station, TX). The study was determined to be exempt by our Institutional Review Board. The study was approved by the administrators of the PHIS database. In accordance with PHIS policies, the identities of the institutions were not reported.

### 2.2 | Selection of participants, definitions, and assumptions

All children <18 years of age with an ED encounter from January 1, 2010 through June 30, 2019 who were hospitalized for a principal diagnosis of intracranial hemorrhage and had at least 1 brain CT scan performed on the day of their index ED visit were eligible for inclusion. We used principal hospital discharge diagnosis codes to define intracranial hemorrhage. We included only children hospitalized during the ED encounter and who had a brain CT scan performed on the

day of their index ED visit to capture the target sample of children with acute intracranial hemorrhage because hospitalization and CT as the initial neuroimaging modality remains standard practice.

The unit of analysis was the ED encounter, which was classified as a case with intracranial hemorrhage if any *International Classification of Diseases (ICD) Ninth Revision (ICD-9)* or *Tenth Revision (ICD-10)* codes for intracranial hemorrhage were assigned as the principal diagnosis from the index ED visit. We defined hospitalization by inpatient or observation codes. Hospital days were defined midnight to midnight, starting first at midnight of the day of ED presentation. We excluded children with any complex chronic conditions, including those with malignancy and hematologic disorders, based on ICD-9 and ICD-10 codes defined by Feudtner et al,<sup>17</sup> because these children may have comorbidities that adjust their risk of hemorrhage progression and need for repeat neuroimaging. For patients with multiple ED encounters, we included only the first ED visit for intracranial hemorrhage during the study period to best capture the care provided during acute hospitalization.

### 2.3 | Exposures and outcomes

We limited outcomes to acute hospitalization from the index ED visit, defined as the first 4 days of the encounter. We defined repeat neuroimaging as either a brain CT scan or MRI in addition to the initial brain CT scan. We additionally defined the encounter based on the type of second (repeat) imaging performed. We defined an encounter as having a repeat CT scan if a CT scan was the second image obtained after the initial CT scan. If the second image was an MRI, we defined the encounter as having a subsequent MRI. We recorded demographic factors, trauma center designation, free-standing versus non-free-standing children's hospital, hospital length of stay, ICU admission, hyperosmotic agent (hypertonic saline or mannitol) administration, non-operative endotracheal intubation, neurosurgical procedures (operations, external ventricular drains, or intracranial monitors), and hemorrhage subtype. We identified hemorrhage subtypes by billing codes and grouped them into 7 categories: intraparenchymal, cerebellar or brainstem, other, mixed intracranial hemorrhage (subarachnoid and/or subdural and/or epidural), isolated subdural, isolated subarachnoid, and isolated epidural.

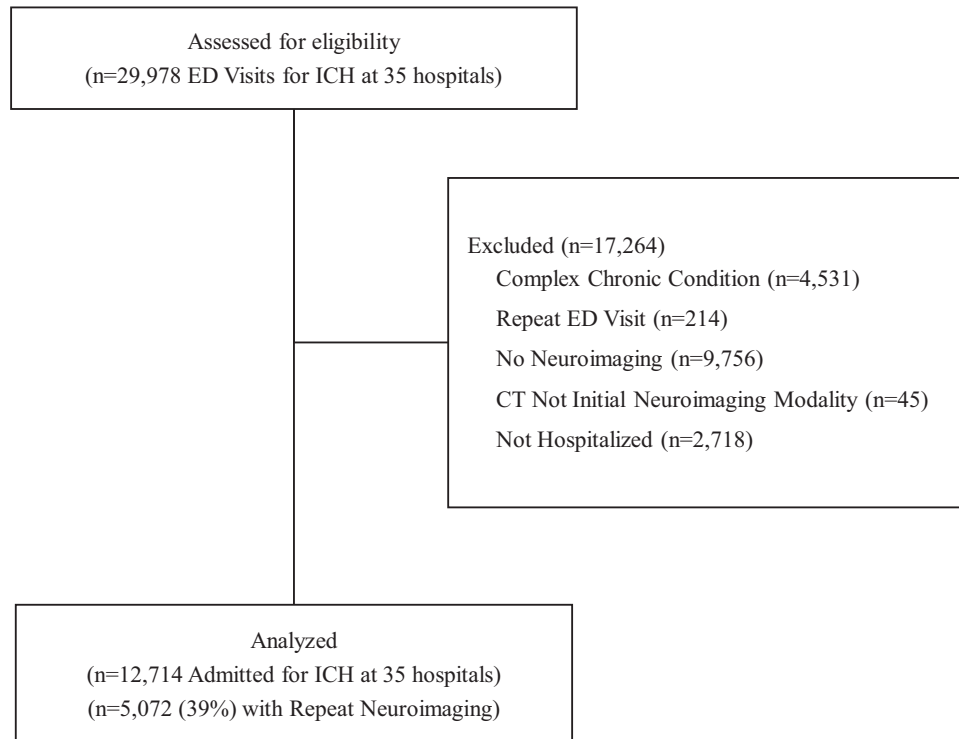
### 2.4 | Analysis

Our primary goal was to determine temporal trends and institutional variation in the use of MRI versus CT as neuroimaging techniques for re-imaging in children with intracranial hemorrhage. Our primary hypothesis was that, although there will be substantial institutional variability, the rates of repeat CT scans are decreasing over time, while MRI is increasing. Our secondary goal was to identify factors associated with the use of subsequent MRI compared to repeat CT. Our secondary hypothesis was that, after controlling for institution, there will be encounter-level factors independently associated with the use of subsequent MRI compared to repeat CT.

We calculated frequencies and proportions for categorical variables and analyzed with  $\chi^2$  tests of homogeneity. We described continuous variables as medians with interquartile ranges (IQR) and analyzed them with the Mann-Whitney *U* test. We calculated encounter-level and hospital-level rates of repeat neuroimaging, repeat CT scans, and subsequent MRIs. To test the primary hypothesis that the rates of subsequent MRI have increased while repeat CT scans have decreased, we created a set of logistic regression models to test for linear temporal trends in rates of repeat neuroimaging, repeat CT scans, and subsequent MRI, with time (measured in calendar years) as the independent variable. The dependent variable for each logistic regression model was assigned as the outcome of interest (repeat neuroimaging, repeat CT scan, and subsequent MRI). A robust variance estimator was used to accommodate the correlation resulting from the clustering of patients within hospitals. We examined linear temporal trends in repeat neuroimaging, repeat CT scans, and subsequent MRI as a proportion of annual cases of intracranial hemorrhage. The proportion of annual cases was used rather than absolute rates to account for any variability in the denominators due to coding differences. Statistical significance for all models was assigned at  $P < 0.05$ .

To further investigate if substantial hospital-level variability in repeat neuroimaging technique exists, we examined hospital-level rates of repeat neuroimaging, repeat CT scans, and subsequent MRI to measure variation at the hospital level. Because repeat neuroimaging is often performed more frequently in more severely injured children, we performed a sensitivity analysis of hospital-level rates of repeat neuroimaging, repeat CT scans, and subsequent MRI in a subgroup of children who did not receive hyperosmotic agents or undergo non-operative intubation or a neurosurgical procedure.

To test our secondary hypothesis that encounter-level factors associated with use of subsequent MRI compared to repeat CT will be identified, we created logistic regression models to determine whether each factor retained an independent association with undergoing a subsequent MRI, our primary outcome, among the subset of children who underwent repeat neuroimaging. To account for potential non-independence among encounters at each hospital due to institutional similarities in ordering patterns for repeat neuroimaging, we used hierarchical multivariable logistic regression models with the institution as the random effect.<sup>18–20</sup> We first constructed a baseline, encounter-level model without predictors using the institution as the grouping variable. We chose factors a priori based on published literature, our hypothesis, and after examining both the clinical and the statistical significance from the univariate analysis. The initial set of predictors entered into the model was 2 hospital-level factors: Level 1 Trauma Center designation and whether the hospital was a free-standing children's hospital. We then sequentially entered encounter-level predictors that were significantly associated ( $P < 0.1$ ) with subsequent MRI in univariable analysis and retained those that remained associated with subsequent MRI in multivariable modelling ( $P < 0.05$ ) or were confounders ( $> 10\%$  change in association between risk factors and subsequent MRI regardless of *P* value) in the final model. Finally, we calculated the final model area under the curve



**FIGURE 1** Study flowchart

(AUC) of the receiver operating characteristic (ROC) plot with 95% confidence intervals (CI) against subsequent MRI.

### 3 | RESULTS

#### 3.1 | Characteristics of study subjects

The study flowchart is depicted in Figure 1. For this study, we included data from the 35 hospitals that had complete demographic and billing information during the entire study period, January 1st, 2010 through June 30th, 2019. During the study period, 29,978 ED visits for intracranial hemorrhage were identified from these 35 pediatric hospitals. After eliminating cases based on a priori exclusions, 12,714 encounters of children admitted through the ED with intracranial hemorrhage constituted the study sample, with repeat neuroimaging performed in 39.9% ( $n = 5072$ ) of encounters. Of the 5072 children with repeat neuroimaging, repeat CT was performed in 67.6% ( $n = 3429$ ) and subsequent MRI in 32.4% ( $n = 1643$ ). Of the 3429 repeat CTs performed, 85.5% ( $n = 2942$ ) were performed by hospital day 1, and of the 1643 subsequent MRIs performed, 78.9% were performed by hospital day 1. Hospital-level and encounter-level characteristics of those children who underwent repeat neuroimaging are displayed in Table 1. The sample was predominantly male (63%) with a median (IQR) age of 5.3 (0.9, 11.8) years. Median (IQR) length of stay was 2 (1, 3) days. Sixty percent ( $n = 3061$ ) were admitted to the ICU during the study period.

#### 3.2 | Temporal trends

Temporal trends in rates of repeat neuroimaging, repeat CT scans, and subsequent MRI, in addition to rates of admission and discharge over the study period are displayed in Figure 2. Repeat neuroimaging rates did not decline over the study period (test for linear trend: odds ratio [OR] = 0.99; 95% CI = 0.96–1.02) (Table 2). However, use of repeat CT scans significantly decreased (difference 2010 vs 2019:  $-9.3\%$ ; 95% CI =  $-14.0\%$  to  $-4.6\%$ ) over the study period (OR = 0.94; 95% CI = 0.90–0.97); whereas, use of subsequent MRIs significantly increased (difference 2010 vs 2019:  $+8.1\%$ ; 95% CI = 4.3% to 11.9%) (OR = 1.09; 95% CI = 1.04–1.13).

#### 3.3 | Hospital-level variation

Hospital-level variation in rates of repeat CT versus subsequent MRI among children who underwent repeat neuroimaging is displayed in Figure 3. Repeat neuroimaging rates by hospital ranged from 20.4% to 79.9%, with a median (IQR) hospital-level repeat neuroimaging rate of 38.2% (32.7%, 46.5%). Median (IQR) hospital-level repeat CT scans and subsequent MRI rates were 27.0% (20.4%, 34.0%) and 7.6% (5.9%, 13.9%), respectively. For the sensitivity analysis of the subgroup of children who did not receive hyperosmotic agents or undergo non-operative intubation or a neurosurgical procedure, repeat neuroimaging rates by hospital ranged from 15.1% to 79.3%, with a median (IQR) hospital-level repeat neuroimaging rate of 34.2% (27.1%, 42.6%). In

**TABLE 1** Hospital-level and encounter-level characteristics, stratified by repeat neuroimaging modality, of children who underwent repeat neuroimaging for intracranial hemorrhage in United States pediatric hospitals from 2010–2019

Characteristics	Repeat CT (n = 3429)	Subsequent MRI (n = 1643)	All (n = 5072)	P value <sup>a</sup>
Hospital-level				
Level I trauma center designation	2991 (87.2)	1301 (79.2)	4292 (84.6)	<0.001
Free-standing children's hospital	3151 (91.9)	1432 (87.2)	4583 (90.4)	<0.001
Encounter-level				
Median age in years	7.1 (2.4, 12.6)	1.6 (0.4, 8.2)	5.3 (0.9, 11.8)	<0.001
Sex (female)	1256 (36.6)	647 (39.4)	1903 (37.5)	0.074
Race				
White	2245 (65.5)	1098 (66.8)	3343 (65.9)	0.340
Black	521 (15.2)	254 (15.5)	775 (15.3)	0.806
Asian	92 (2.7)	44 (2.7)	136 (2.7)	0.992
Other	380 (11.1)	193 (11.7)	573 (11.3)	0.484
Missing	191 (5.6)	54 (3.3)	245 (4.8)	<0.001
Ethnicity				
Non-Hispanic/Latino	2606 (76.0)	1133 (69.0)	3739 (73.7)	<0.001
Hispanic/Latino	532 (15.5)	438 (26.7)	970 (19.1)	<0.001
Other	291 (8.5)	72 (4.4)	363 (7.2)	<0.001
Source of payment				
Private	1441 (42.0)	626 (38.1)	2067 (40.8)	0.008
Public	1647 (48.0)	905 (55.1)	2552 (50.3)	<0.001
Other	341 (9.9)	112 (6.8)	453 (8.9)	<0.001
Median calendar year	2013 [2011, 2015]	2014 [2012, 2015]	2013 [2011, 2015]	<0.001
Median hospital length of stay	3 [2, 5]	3 [2, 4]	2 [1, 3]	<0.001
Intensive care unit admission	2152 (62.8)	909 (55.3)	3061 (60.4)	<0.001
Mortality	13 (0.4)	3 (0.2)	16 (0.3)	0.243
Critical medical or surgical intervention				
Hyperosmotic agent administration <sup>b</sup>	458 (13.4)	118 (7.2)	576 (11.4)	<0.001
Non-operative intubation	326 (9.5)	114 (6.9)	440 (8.7)	0.002
Neurosurgical intervention	254 (7.4)	38 (2.3)	292 (5.8)	<0.001
Hemorrhage subtype				
Intraparenchymal	371 (10.8)	161 (9.8)	532 (10.5)	0.267
Cerebellar or brainstem	13 (0.4)	15 (0.9)	28 (0.6)	0.016
Other	255 (7.4)	151 (9.2)	406 (8.0)	0.031
Mixed <sup>c</sup>	1585 (46.2)	525 (32.0)	2110 (41.6)	<0.001
Isolated subdural	509 (14.8)	476 (29.0)	985 (19.4)	<0.001
Isolated subarachnoid	226 (6.6)	180 (11.0)	406 (8.0)	<0.001
Isolated epidural	470 (13.7)	135 (8.2)	605 (11.9)	<0.001

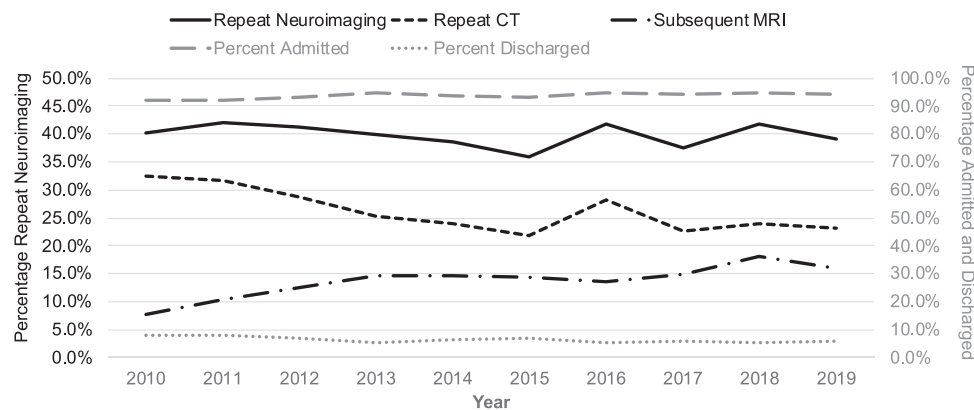
Values in table represent median [interquartile range] or frequency (column percent).

Proportions might not sum to 100% due to rounding.

<sup>a</sup>P values are  $\chi^2$  or Mann-Whitney U between repeat CT and subsequent MRI.

<sup>b</sup>Hyperosmotic agent administration includes mannitol or hypertonic saline.

<sup>c</sup>Subarachnoid and/or subdural and/or epidural.



**FIGURE 2** Temporal trends in rates of repeat neuroimaging, repeat CT, and subsequent MRI (left, y-axis) and rates of admission and discharge (right, y-axis) in children with intracranial hemorrhage, 2010–2019

**TABLE 2** Trends in hospital-level repeat neuroimaging, repeat CT, and subsequent MRI in children with intracranial hemorrhage, 2010–2019

Neuroimaging modality	Number n (%)	Absolute difference in rate of repeat imaging, 2010 versus 2019 (95% CI), %	Test for linear trend, OR (95% CI)
Repeat neuroimaging	5072 (39.9)	−1.2 (−6.5 to 4.1)	0.99 (0.96 to 1.02)
Repeat CT	3429 (27.0)	−9.3 (−14.0 to −4.6)	0.94 (0.90 to 0.97)
Subsequent MRI	1643 (12.9)	8.1 (4.3 to 11.9)	1.09 (1.04 to 1.13)

CI, confidence interval; CT, computed tomography; MRI, magnetic resonance imaging; OR, odds ratio.

this subgroup, median (IQR) hospital-level repeat CT scans and subsequent MRI rates were 23.0% (16.0%, 32.2%) and 7.1% (6.0%, 12.0%), respectively. Hospital-level variation in rates of repeat neuroimaging, repeat CT scans, and subsequent MRI in this subgroup of children were similar to primary analysis cohort of all children who underwent repeat neuroimaging.

### 3.4 | Encounter-level factors

Results of the final hierarchical multivariable logistic regression model are displayed in Table 3. In multivariable modeling, after controlling for institution, the other hospital-level factors of Level 1 Trauma Center designation ( $P = 0.780$ ) and free-standing children's hospital status ( $P = 0.093$ ) were not independently associated with use of subsequent MRI. Encounter-level factors that remained independently associated with a subsequent MRI included younger age ( $P < 0.001$ ), and more recent year ( $P < 0.001$ ) (Table 3). Encounters with ICU admission ( $P < 0.001$ ), hyperosmotic agent administration ( $P < 0.001$ ), and neurosurgical intervention ( $P < 0.001$ ) were associated with repeat CT compared to subsequent MRI. Among hemorrhage subtypes, cerebellar or brainstem hemorrhage ( $P = 0.017$ ) and subdural hemorrhage (0.027) were associated with subsequent MRI, while epidural hemorrhage ( $P < 0.001$ ) and mixed intracranial hemorrhage ( $P < 0.001$ ) were more likely to undergo repeat CT. The final random effects model for subsequent MRI as compared to repeat CT had an AUC of 0.71 (95% CI, 0.69, 0.72).

## 4 | LIMITATIONS

Our investigation has several important limitations. We leveraged a large administrative database, which allows for a high-level examination of trends and variation in repeat neuroimaging in children with intracranial hemorrhage but does not allow patient-level review for clinical characteristics (such as traumatic brain injury severity) or the appropriateness of imaging decisions (such as MRI for neuroprognostication or CT for clinical change). We presume that because these are tertiary care children's hospitals, lower radiation doses are being used for pediatric head CT scans, unfortunately, we do not have these data available to examine any potential influence on clinical decision making. Timing of resource utilization data in PHIS is limited to the day of service performed, limiting conclusions about whether repeat neuroimaging resulted in a change in management. Additionally, the diagnosis of intracranial hemorrhage was based on diagnostic codes, rather than clinical data. Although differences in absolute rates were noted over time, we used the proportion of annual cases to describe trends rather than absolute rates to account for any variability in the denominators due to coding differences when ICD-9 codes transitioned to ICD-10. To better identify our target sample, we included those who were admitted with a principal diagnosis of intracranial hemorrhage and had at least 1 CT scan obtained, so those who died in the ED or had polytrauma were not included. Although it is likely that we included some encounters that were not our target sample, we focused on high-level outcomes to assess for overall trends and variation in repeat neuroimaging.



**FIGURE 3** Hospital-level variation in rates of repeat CT versus subsequent MRI in children with intracranial hemorrhage who underwent repeat neuroimaging

For generalizability, we aimed to identify an otherwise healthy population of children presenting with intracranial hemorrhage. Although we excluded patients with a chronic comorbid condition, we were unable to exclude all possible comorbidities that could influence neuroimaging decisions. However, with our exclusion criteria and large sample of patients, the trends observed likely reflect trends in our target sample. Our sample represents children at major US pediatric hospitals, and our results might not be generalizable to other settings. Because encounters are tracked longitudinally at a single institution, we do not know whether any children presented to a different institution for follow-up. Moreover, we cannot comment on other important clinical outcomes for this sample.

## 5 | DISCUSSION

In a large sample of children with intracranial hemorrhage evaluated at US pediatric hospitals, ~40% of children underwent repeat neu-

roimaging (either a CT scan or MRI), a rate which has remained stable from 2010–2019. However, repeat CT scans decreased over the study period while MRI increased. We found that substantial variation in repeat neuroimaging exists among these pediatric hospitals, even among the subgroup of less severely injured children. Independent of institution, we identified several encounter-level factors, including age, ethnicity, year, ICU admission, hyperosmotic agent administration, neurosurgical intervention, and hemorrhage subtype that were associated with the modality used for repeat neuroimaging.

Children with traumatic intracranial hemorrhage commonly undergo repeat CT scans to monitor for hemorrhage progression and potential need for additional interventions and monitoring.<sup>2–9</sup> However, radiation exposure from multiple CT scans is associated with an incrementally increasing risk of cancer.<sup>10</sup> Historically, when deciding on repeat neuroimaging, clinicians must weigh the risks of missing a child with progressive hemorrhage against radiation exposure from serial CT scans and potentially unnecessary resource utilization such as prolonged hospital length of stay and ICU admission, even in severe

**TABLE 3** Final random effects model for subsequent MRI in children with intracranial hemorrhage who undergo repeat neuroimaging

Covariates	Odds ratio (95% CI)	P value
Median age in years	1.00 (1.00, 1.00) <sup>a</sup>	<0.001
Ethnicity		
Non-Hispanic/Latino	Reference group	-
Hispanic/Latino	1.02 (0.84, 1.25)	0.834
Other	0.59 (0.41, 0.85)	0.004
Median calendar year	1.15 (1.11, 1.19)	<0.001
Intensive care unit admission	0.62 (0.52, 0.73)	<0.001
Interventions		
Hyperosmotic agent administration <sup>b</sup>	0.57 (0.43, 0.75)	<0.001
Neurosurgical intervention	0.38 (0.25, 0.58)	<0.001
Hemorrhage subtype		
Intraparenchymal	Reference group	-
Cerebellar or brainstem	1.79 (1.11, 2.88)	0.017
Other	1.03 (0.92, 1.16)	0.579
Mixed <sup>c</sup>	0.87 (0.81, 0.93)	<0.001
Isolated subdural	1.07 (1.01, 1.13)	0.027
Isolated subarachnoid	1.02 (0.96, 1.08)	0.467
Isolated epidural	0.87 (0.83, 0.92)	<0.001

<sup>a</sup>0.9996916 (0.9996511, 0.9997321).

<sup>b</sup>Hyperosmotic agent administration includes mannitol or hypertonic saline.

<sup>c</sup>Subarachnoid and/or subdural and/or epidural.

traumatic brain injury.<sup>21,22</sup> More recently, because of the known risks associated with radiation exposure from CT scans and more widespread availability, MRI has become an increasingly used alternative modality for children with traumatic brain injury. Traditional MRI has long scanning times, frequently requiring sedation for young children, and is not as widely available as CT, which limits routine use. However, rapid MRI protocols have been developed to evaluate children with possible ventriculoperitoneal shunt malfunction, and these protocols are now being applied to children with traumatic brain injury.<sup>12,13</sup>

Although evidence is currently limited on the use of rapid MRI protocols for both the initial evaluation of children with traumatic brain injury and for monitoring for hemorrhage progression in children with intracranial hemorrhage,<sup>13-16</sup> it is clear that many institutions are adopting MRI. Between 2010 and 2019, we found that the rates of repeat CT scans decreased by 9% and subsequent MRIs increased by 8%, whereas overall rates of repeat neuroimaging remained stable. Additionally, we found that the majority of both repeat CTs and subsequent MRIs were performed by hospital day 1. Although we are unable to distinguish whether a rapid MRI protocol was used due to limitations of the dataset, these findings suggest that a proportion of repeat CT scans were replaced by subsequent MRI in these children.

Among these pediatric hospitals, we found substantial institutional variation in rates of repeat neuroimaging, repeat CT scans, and subsequent MRI, with rates of repeat neuroimaging ranging from 20%–80%. Although the study hospitals are major pediatric centers, differences in severity among institutions likely contributed to some of the observed variation. However, severity of illness was likely not the only contributor, as similar variation existed even among less severely injured children who did not receive hyperosmotic agents or undergo non-operative intubation or neurosurgical procedures. Although we are unable to comment on the clinical indications for repeat neuroimaging due to limitations of our dataset, after accounting for institutional differences in a random effect model, we identified several encounter-level factors that were independently associated with the modality used for repeat neuroimaging. Younger age and more recent year were associated with subsequent MRI compared to repeat CT, suggesting that clinicians may be attempting to decrease CT-associated radiation exposure for younger children, particularly as MRI has become more available recently. Encounter-level factors that were associated with more severe injuries, including children who were admitted to the ICU and underwent hyperosmotic agent administration or a neurosurgical intervention, were associated with use of repeat CT compared to MRI. These findings together suggest the likely practice of using subsequent MRI when possible in children with lower severity and/or non-operative head injuries.

Clinician practice patterns are a known contributing factor to variation in repeat neuroimaging rates among children with intracranial hemorrhage.<sup>23</sup> Our findings highlight the substantial variability in repeat neuroimaging in children with intracranial hemorrhage. Although MRI spares radiation exposure, its use can add time, costs, and additional resource utilization that may not be necessary in children with low-risk hemorrhage types without neurologic changes. Although we examined this variability at the encounter-level, further investigation that includes granular clinical data to determine indications for repeat neuroimaging is warranted. Additionally, the development and effective dissemination of evidence based clinical decision rules can decrease practice variation. Similar to the work of Greenberg et al<sup>24</sup> predicting need for ICU admission following mild traumatic brain injury, efforts to standardize management, including the indications, timing, and modality used for repeat neuroimaging should be implemented.

In conclusion, among children with intracranial hemorrhage evaluated at US pediatric hospitals, use of repeat CT scans decreased from 2010–2019; whereas, use of subsequent MRIs increased. We found substantial institutional variation in repeat neuroimaging for children with intracranial hemorrhage. Further exploration of patient-level factors in the use of repeat neuroimaging is needed to better standardize its optimal utilization for children with intracranial hemorrhage.

#### AUTHOR CONTRIBUTIONS

All authors qualify for authorship according to the journal's Authorship policy.



Dr. Chaudhari conceived of this study, had full access to the data, performed data analyses and interpretation of data, drafted the manuscript, and assumed final responsibility for the submitted manuscript. Dr. Bachur provided substantial guidance to the design, data analysis, and interpretation of data, provided critical review of the manuscript, and approved the final version. Dr. Pineda provided substantial guidance to the design and interpretation of data, provided critical review of the manuscript, and approved the final version. Dr. Khemani provided substantial guidance to the design, analysis, and interpretation of data, provided critical review of the manuscript, and approved the final version.

All authors have participated sufficiently in the work to take public responsibility for appropriate portions of the content and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

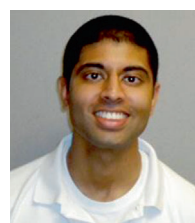
### CONFLICT OF INTEREST

The authors declare no conflict of interest.

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