Published in final edited form as:

J Neurosurg Pediatr. 2023 July 01; 32(1): 26–34. doi:10.3171/2023.2.PEDS22393.

Toward rational use of repeat imaging in children with mild traumatic brain injuries and intracranial injuries

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Disclosures

Dr. Kuppermann reported grants from NIH, HRSA, and PCORI, outside the submitted work. Dr. Limbrick reported grants from Medtronic, Inc. and Microbot Medical, Inc., outside the submitted work.

Previous Presentations

This work was presented in part at the 2021 AANS/CNS Section on Pediatric Neurological Surgery Annual Meeting, Salt Lake City, Utah, December 7–10, 2021.

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Abstract

OBJECTIVE: Limited evidence exists on the utility of repeat neuroimaging in children with mild traumatic brain injuries (mTBIs) and intracranial injuries (ICIs). Here, the authors identified factors associated with repeat neuroimaging and predictors of hemorrhage progression and/or neurosurgical intervention.

METHODS: The authors performed a multicenter, retrospective cohort study of children at four centers of the Pediatric TBI Research Consortium. All patients were ≤ 18 years and presented within 24 hours of injury with a Glasgow Coma Scale score of 13–15 and evidence of ICI on neuroimaging. The outcomes of interest were 1) whether patients underwent repeat neuroimaging during index admission, and 2) a composite outcome of progression of previously identified hemorrhage ≥ 25% and/or repeat imaging as an indication for subsequent neurosurgical intervention. The authors performed multivariable logistic regression and report odds ratios and 95% confidence intervals.

RESULTS: A total of 1324 patients met inclusion criteria; 41.3% of patients underwent repeat imaging. Repeat imaging was associated with clinical change in 4.8% of patients; the remainder of the imaging tests were for routine surveillance (90.9%) or of unclear prompting (4.4%). In 2.6% of patients, repeat imaging findings were reported as an indication for neurosurgical intervention. While many factors were associated with repeat neuroimaging, only epidural hematoma (OR 3.99, 95% CI 2.22–7.15), posttraumatic seizures (OR 2.95, 95% CI 1.22–7.41), and age ≥ 2 years (OR 2.25, 95% CI 1.16–4.36) were significant predictors of hemorrhage progression and/or neurosurgery. Of patients without any of these risk factors, none underwent neurosurgical intervention.

CONCLUSIONS: Repeat neuroimaging was commonly used but uncommonly associated with clinical deterioration. Although several factors were associated with repeat neuroimaging, only posttraumatic seizures, age ≥ 2 years, and epidural hematoma were significant predictors of hemorrhage progression and/or neurosurgery. These results provide the foundation for evidence-based repeat neuroimaging practices in children with mTBI and ICI.

Keywords

mild traumatic brain injury; repeat imaging; imaging overuse; emergency medicine; trauma

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Pediatric mild traumatic brain injury (mTBI; Glasgow Coma Scale [GCS] scores 13–15) is common and costly, with annual inpatient charges totaling more than $1 billion.[1–3] While surveillance neuroimaging is common in children with mTBI and intracranial injuries (ICIs), it infrequently leads to changes in clinical management.[4,5] There is ample literature and clinical decision support tools to guide decision-making on whether to obtain an initial neuroimaging study in children with minor head trauma;[6–9] however, there is little evidence regarding the utility of routine surveillance neuroimaging.[5,10–13]

Routine repeat surveillance imaging in children with minor traumatic brain injury (TBI) has both benefits and costs. While appropriate use of repeat imaging may allow early detection of patients at risk of neurological decline or those who might benefit from neurosurgical intervention, pediatric head CT has been shown to increase the lifetime risk of future malignancies,[14,15] leading to efforts to reduce radiation exposure in children with head trauma.[16] Furthermore, both head CT and MRI are associated with increased hospital length of stay and increased costs of care.[17] Effective risk stratification may focus repeat imaging decisions on patients most likely to benefit, thereby decreasing hospital resource use, alleviating caretaker financial burdens, and reducing preventable radiation-induced harm.[18–24]

In adults, there is evidence suggesting that surveillance neuroimaging in mTBI is overused and may not be indicated in many circumstances.[4,25,26] This overuse of advanced imaging techniques is likely influenced by a variety of factors, including lack of knowledge of, or confidence in, validated clinical decision tools, physician risk tolerance, legal reform, and patient expectations.[27,28] In children, the role of repeat neuroimaging among those with mTBI and ICI remains controversial, and nearly all published evidence is based on small, single-center series.[5,11,13,29] Given this evidence gap, the objectives of this study were 1) to identify factors associated with repeat imaging in children with mTBI and ICI, and 2) to identify predictors of hemorrhage progression ≥ 25% and/or neurosurgical intervention. We hypothesized that these data might be used to provide better evidence for repeat neuroimaging in these children.

Methods

Study Population and Inclusion Criteria

We used the retrospectively collected Pediatric TBI Research Consortium (PTRC) data set, which included patients evaluated at four academic medical centers from 2006 to 2019.[30] Inclusion criteria for this study were 1) patients aged ≤ 18 years presenting to the emergency department within 24 hours of nonpenetrating blunt cranial trauma, 2) with a GCS score of 13–15 on initial presentation, and 3) ICI on initial cranial imaging. As reported previously, ICI was defined as intracranial hemorrhage, cerebral edema, midline shift, pneumocephalus, skull fracture depressed by at least the skull width, traumatic infarction, herniation, or venous sinus thrombosis.[30] Patients with more than one type of ICI were classified once within each ICI pathology. Patients with subacute or chronic ICI, brain tumors, developmental delay impacting neurological assessments, or the presence of permanent CSF diversion were excluded. Central imaging review was performed within each institution by site investigators via review of radiology reports in conjunction with review of primary CT and MR images.[31] Because of the restrictions of the data collected in the PTRC registry, outpatient follow-up, imaging, and subsequent interventions are not reported. Waivers of informed consent and institutional review board approval were obtained at each participating site. An operations manual was used to standardize the definitions of variables collected. Data are reported in accordance with the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) guidelines for cohort studies.[32]

Predictor and Outcome Variables

Our first outcome was whether patients underwent repeat neuroimaging during their index admission. Our second outcome was a composite of progression of previously identified hemorrhage ≥ 25% and/or repeat imaging as an indication for subsequent neurosurgical intervention. In all cases of neurosurgical intervention, repeat imaging findings were reported in the operative note or electronic medical record as an indication for surgical intervention. Neurosurgical intervention was defined as craniotomy for hematoma evacuation, decompressive craniectomy, elevation of a depressed skull fracture, operative repair of dural laceration and/or CSF leak, or placement of intracranial pressure monitor or external ventricular drain. Scalp debridement and other minor procedures (e.g., lumbar drain placement for transient CSF leakage) were not included. Age was dichotomized as < 2 years versus ≥ 2 years given the strong clinical justification and extensive use of this cutoff in the literature.[9]

Statistical Analysis

We performed univariable logistic regression to identify candidate factors associated with the study outcomes, with subsequent backward stepwise multivariable logistic regression to identify significant predictors while controlling for the effect of other variables in the model. For our multivariable analysis, we included all variables that reached a threshold of $p < 0.15$ in univariable analysis. Predictor variables were retained in the final multivariable model if they met our a priori threshold of $p < 0.05$. The C-statistic, which represents the area under the receiver operating characteristic curve, was used to determine model discrimination. There were no missing data in this analysis. Data were analyzed using IBM SPSS version 27 (IBM Corp.)[33] and R (The R Language for Statistical Computing).[34] We report odds ratios and 95% confidence intervals for our predictors of interest.

Results

Cohort Description

Details of patient demographics and presentation can be found in Table 1. Most of our cohort was ≥ 2 years of age at the time of injury, male, and White, and presented with GCS scores of 15. The most common mechanism of injury was fall from elevation (38.8%), and the most common symptom was posttraumatic vomiting (30.7%). Radiographic findings on index neuroimaging can be found in Table 2. CT was the primary index imaging modality (99.9%). The most common initial ICI finding was subdural hematoma (SDH; 32.3%).

Overall, 547 patients (41.3%) underwent repeat neuroimaging at a median of 8 (IQR 10) hours after initial imaging. Repeat imaging findings are detailed in Table 3. Twenty-six repeat scans (4.8%) were obtained because of a clinical change, 24 (4.4%) were obtained for unclear reasons, and the remaining 497 (90.9%) were obtained for routine surveillance. Of those 497 patients undergoing routine surveillance imaging, only 12 (2.4%) underwent neurosurgical intervention. Forty-eight patients (9.7%) reached our composite outcome of hemorrhage progression ≥ 25% and/or neurosurgical intervention. On the other hand, of the 26 patients who underwent repeat imaging because of changes in clinical status, 3 (11.5%) developed the composite outcome, with 1 patient (3.8%) undergoing neurosurgical intervention. One patient who underwent neurosurgical intervention underwent repeat imaging for reasons of unclear prompting.

There was hemorrhage progression on 52 repeat imaging scans (9.5%) (Table 3). The most common index findings in patients with hemorrhage progression were epidural hematoma (EDH; 53.8%), SDH (32.7%), and cerebral contusion (19.2%). New traumatic findings were identified in 73 patients (13.3%) after repeat imaging, with the most common etiologies being cerebral contusion (32.9%) and SDH (30.1%). Of those who underwent repeat neuroimaging, 44 (8.0%) underwent neurosurgical intervention. Information on patient disposition and treatment can be found in Table 4.

Repeat imaging findings were reported as an indication for neurosurgical intervention in 14 (2.6%) of 547 patients. Of these 14 patients, the repeat neuroimaging scans were for routine surveillance in 12 (85.7%), associated with clinical change in 1 patient (7.1%), and of unclear prompting in 1 patient (7.1%). Twelve (85.7%) of these 14 patients had an EDH on initial imaging. Of the 2 patients without EDH on initial imaging, both developed new EDHs seen on delayed imaging.

Evaluating numbers needed to treat, we found that 11 patients with routine surveillance imaging would be needed to identify 1 patient with the composite outcome, but 42 would be needed to identify 1 patient who would undergo neurosurgery because of their repeat imaging findings. By comparison, 9 patients with clinical changes prompting repeat imaging would be needed to identify 1 patient with the composite outcome, and 26 repeat scans would be needed to identify 1 patient who would undergo subsequent neurosurgery.

Predictors of Repeat Imaging

The results of the univariable analysis to identify factors associated with repeat imaging are shown in Tables 1 and 2. The final multivariable model can be found in Table 5. While various clinical and radiological factors met our threshold for multivariable analysis, factors independently associated with repeat imaging included intraventricular hemorrhage (IVH; OR 18.4, 95% CI 2.1–165.1), EDH (OR 10.1, 95% CI 6.8–15.0), extra-axial hemorrhage (OR 5.5, 95% CI 3.6–8.5), SDH (OR 5.2, 95% CI 3.8–7.1), cerebral edema (OR 4.6, 95% CI 1.4–15.2), assault as the mechanism of injury (OR 2.2, 95% CI 1.1–4.4), concern for nonaccidental trauma (OR 1.8, 95% CI 1.1–2.8), posttraumatic vomiting (OR 1.8, 95% CI 1.4–2.3), and pneumocephalus (OR 0.7, 95% CI 0.5–1.0). We also found significant differences in repeat imaging utilization across institutions. This model’s C-statistic was 0.80, indicating good discrimination.

Predictors of Hemorrhage Progression and/or Neurosurgical Intervention

The results of the univariable analysis to identify factors associated with our composite outcome of hemorrhage progression and/or neurosurgical intervention are shown in Tables 1 and 2. On multivariable analysis, we identified EDH (OR 4.0, 95% CI 2.2–7.2), posttraumatic seizures (OR 3.0, 95% CI 1.2–7.4), and age ≥ 2 years (OR 2.3, 95% CI 1.2–

4.4) as statistically significant predictors of the composite outcome (Table 5). The C-statistic for this model was 0.71, also indicating moderate discrimination. When considering age as a continuous variable instead of a dichotomous variable, we found that EDH (OR 3.91, 95% CI 2.167–7.03), posttraumatic seizures (OR 2.64, 95% CI 1.10–6.36), and age in years (OR 1.08, 95% CI 1.03–1.14) remained statistically significant predictors of the composite outcome (Supplementary Table 1).

Of those who developed the composite outcome (n = 55), 50 (90.9%) had at least one of the risk factors identified. Only 5 (3.2%) of 155 patients without any of the identified risk factors developed either finding of the composite outcome, and none underwent neurosurgical intervention as a result of repeat imaging findings.

Supplementary Analyses

Subset analysis was done to determine predictors of neurosurgical intervention and hemorrhage progression, separately. Univariable analysis can be found in Supplementary Table 2 (cohort demographics and clinical presentation) and Supplementary Table 3 (initial radiographic presentation). Subsequent multivariable analysis regression models can be found in Supplementary Table 4. Briefly, we found that on subgroup analysis, EDH remained a significant predictor of neurosurgical intervention (OR 19.4, 95% CI 4.3–88.1), while EDH (OR 3.9, 95% CI 2.2–7.1) and age in years (OR 1.07, 95% CI 1.01–1.13) were predictive of hemorrhage progression.

Additionally, we performed a supplementary analysis adding patients with new traumatic findings on repeat imaging to our composite outcome. On multivariable analysis, we found that vomiting (OR 2.04, 95% CI 1.34–3.11; $p < 0.001$), treatment at institution A (OR 2.04, 95% CI 1.20–3.47; $p = 0.009$), and assault (OR 3.09, 95% CI 1.47–6.50; $p = 0.003$) were predictive of this broader composite outcome. While this more expansive outcome may have clinical relevance, it was used only as an exploratory analysis due to unclear clinical significance.

Discussion

The role of repeat neuroimaging in children with mTBI and ICI is contested in the literature,[5,10–13] as it infrequently leads to changes in clinical management.[4,5,35] In certain situations, however, it is warranted.[10,11,29,36] While there is ample evidence-based guidance to determine which children benefit from initial neuroimaging after head trauma,[6,8,9,37] there is a lack of data guiding the use of surveillance imaging after the injury is diagnosed.[30,38,39] In this study, we aimed to identify risk factors for repeat imaging, hemorrhage progression ≥ 25%, and neurosurgical intervention. While we noted a variety of risk factors associated with surveillance imaging, only EDH, posttraumatic seizures, and age were significant predictors of hemorrhage progression and/or neurosurgical intervention.

Previous studies of children with mTBI have suggested that surveillance imaging may not be necessary in the absence of neurological decline or previously identified risk factors.[5,10–13] To our knowledge, our cohort represents the largest, multi-institutional cohort of children with mTBI and ICI undergoing repeat head imaging studied to date. In our study, almost half of the cohort underwent repeat neuroimaging, but repeat imaging was performed because of a change in clinical status in only a small portion of patients. In line with prior studies,[26] we found that, based on numbers needed to treat, imaging prompted by clinical change was marginally more likely to be actionable than surveillance imaging. Notably, however, clinical deterioration was not associated with the composite outcome in our cohort. We acknowledge, however, that the severity of clinical change also likely plays a role[5,10–13] and that the association may be weak enough that it could not be detected even in this relatively large population. Heterogeneity among practitioners regarding the definition of "clinical deterioration" may have also precluded identifying a significant association in this retrospective study.[5,10, 11,2 9,36]

Medical decision-making is complex, and many factors contribute to the decision to order surveillance neuroimaging in children with mTBI. A prior study surveying healthcare providers about treatment of pediatric mTBI and ICI found that almost half of respondents would order surveillance neuroimaging despite a low concern for risk of neurological decline and low expectations of the utility of the repeat scan.[40] While that study elucidated provider-related characteristics contributing to high rates of surveillance imaging, it did not address what patient-specific characteristics may play a role in the clinical decision-making process. Here, we aimed to identify factors associated with repeat neuroimaging after mTBI and ICI while focusing on patient characteristics.

In our cohort, patients who underwent repeat neuroimaging differed from those who did not. Patients with a variety of characteristics, including concern for nonaccidental trauma, vomiting, and the presence of various intracranial pathologies, were more likely to undergo repeat imaging. Interestingly, we also found significant interinstitutional variation in the treatment of these patients. While clinicians may associate several of these factors as predictive of repeat imaging utility, on further analyses we found that only EDH, posttraumatic seizures, and age $\geq$ 2 years were significant predictors of hemorrhage progression and/or neurosurgical intervention.

Many studies have identified radiographic and clinical risk factors for delayed neurosurgical intervention after repeat imaging in children.[10,11,29,36] In our cohort, EDH was the only significant radiographic predictor of the composite outcome. This is a risk factor that has been widely cited in the pediatric literature.[10,11,29,36] Prior studies have also identified SDH,[36] cerebral edema,[36] and intraparenchymal hemorrhage[36] as radiographic risk factors for imaging progression and/or delayed neurosurgical intervention in pediatric patients. However, we did not find significant associations between these factors with our composite outcome, suggesting that these findings may lack generalizability.[26]

Older age has been previously noted to be associated with imaging progression and/or neurosurgical intervention.[17,29] We initially dichotomized age to assist clinicians in more easily applying this factor in clinical practice, using the cutoff used by the PECARN (Pediatric Emergency Care Applied Research Network) study for risk stratification of children with minor head trauma at risk for TBI.[9] The authors of that study analyzed preverbal (age < 2 years) and verbal (age $\geq$ 2 years) patients separately for various reasons, including the ability to communicate, risks for TBI, and mechanisms leading to TBI.[9] We found that older age (both dichotomized and as a continuous variable) was associated with increased risk of the composite outcome. Possible explanations for this finding include more severe mechanisms of injury, increased ability to detect more subtle examination findings and complaints, or other changes related to the developing skull, brain, or spine.

Posttraumatic seizures in children with mTBI are uncommon.[41] To our knowledge, studies to date have not identified posttraumatic seizures as a risk factor for hemorrhage progression and/or delayed neurosurgical intervention. However, seizures are a risk factor for extended inpatient stay,[37] ICU-level interventions,[42] and intracranial hemorrhage[43] in children with mTBI, as well as unfavorable outcomes in children with TBI overall.[44] In our cohort, we found that posttraumatic seizures were associated with 3 times the odds of our composite outcome.

We also performed subset analyses to analyze predictors of each outcome of neurosurgical intervention and hemorrhage progression. We found that EDH remained a significant predictor of neurosurgical intervention, while age in years and EDH were significant predictors of hemorrhage progression. Given the loss of statistical power because of a decrease in sample size when performing subgroup analysis, this suggests that EDH and age likely have the strongest association with our composite outcome, whereas the association of seizure may be more modest and should thus be verified in future analyses.

Of the patients in our cohort who developed the composite outcome, 91% had at least one of the risk factors identified. Thus, our data suggest that repeat neuroimaging may be used most frequently in children presenting with EDH or posttraumatic seizures, particularly those ≥ 2 years. Future work directed toward evidence-based guidelines and shared clinical decision-making[45] could potentially limit imaging overuse and its associated risks to children with mTBI and ICI.

This study has several limitations. Importantly, the data are specific to children with mTBI and ICI and are thus not generalizable to patients with severe TBI or patients with mTBI without ICI. We acknowledge that the PTRC data set supported the analysis of only center-level data, and future studies will need to look at the influence of provider-level differences on decision-making, as results are impacted by individual variability in decision-making regarding repeat imaging and surgical intervention among physicians.[40] Second, although our composite outcome included neurosurgical intervention triggered by repeat imaging findings, we acknowledge that we are unable to account for all factors that influenced surgical decision-making. Third, we did not assess the association between the volume of the initial ICIs and the composite outcome, as ICI measurement data were not widely available for patients in our cohort. However, recent evidence suggests that quantitative ICI measurements do not necessarily improve outcome predictions compared with categorical imaging findings in children with mTBI and ICI.[31] Because of limitations in the data set documentation, we were unable to exclude possible rare cases in which patients had repeat imaging performed after neurosurgical intervention, although we acknowledge that decision-making in such patients may differ. Finally, while we report readmission within 30 days, we acknowledge that we do not report imaging or subsequent interventions beyond this time frame.

Conclusions

In this large, multicenter population of children with mTBI and ICI, repeat head imaging was commonly used, but was uncommonly associated with clinical change or neurosurgical intervention. Furthermore, the proportion of children who experienced adverse outcomes, regardless of repeat imaging status, was relatively low. Many factors were associated with repeat neuroimaging. However, we found that only posttraumatic seizures, age ≥ 2 years, and presence of EDH on initial imaging were significantly associated with the composite outcome. While these findings should be validated in future studies, the present results may assist physicians in focusing their indications for repeat imaging on the small subset of children with mTBI and ICI most likely to benefit.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

This study was funded by grants from the Agency for Healthcare Research and Quality (1F32HS027075-01A1) and the Thrasher Research Fund (15024). Research reported in this publication was supported by the National Center for Advancing Translational Sciences of the National Institutes of Health under award no. TL1TR002344. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

ABBREVIATIONS

EDH	epidural hematoma
GCS	Glasgow Coma Scale
ICI	intracranial injury
IVH	intraventricular hemorrhage
mTBI	mild TBI
PTRC	Pediatric TBI Research Consortium
SDH	subdural hematoma
TBI	traumatic brain injury

References

1. Schneier AJ, Shields BJ, Hostetler SG, Xiang H, Smith GA. Incidence of pediatric traumatic brain injury and associated hospital resource utilization in the United States. Pediatrics. 2006;118(2):483–492. [PubMed: 16882799]
2. Bowman SM, Bird TM, Aitken ME, Tilford JM. Trends in hospitalizations associated with pediatric traumatic brain injuries. Pediatrics. 2008;122(5):988–993. [PubMed: 18977977]
3. Brain Injury Association of America. Incidence of Brain Injury in Children. Accessed March 2, 2023. https://www.biausa.org/brain-injury/about-brain-injury/children-what-to-expect/incidence-of-brain-injury-in-children

4. Almenawer SA, Bogza I, Yarascavitch B, et al. The value of scheduled repeat cranial computed tomography after mild head injury: single-center series and meta-analysis. Neurosurgery. 2013;72(1):56–64. [PubMed: 23254767]
5. Aziz H, Rhee P, Pandit V, et al. Mild and moderate pediatric traumatic brain injury: replace routine repeat head computed tomography with neurologic examination. J Trauma Acute Care Surg. 2013;75(4):550–554. [PubMed: 24064865]
6. Babl FE, Borland ML, Phillips N, et al. Accuracy of PECARN, CATCH, and CHALICE head injury decision rules in children: a prospective cohort study. Lancet. 2017;389(10087):2393–2402. [PubMed: 28410792]
7. Dunning J, Daly JP, Lomas JP, Lecky F, Batchelor J, Mackway-Jones K. Derivation of the children's head injury algorithm for the prediction of important clinical events decision rule for head injury in children. Arch Dis Child. 2006;91(11):885–891. [PubMed: 17056862]
8. Osmond MH, Klassen TP, Wells GA, et al. CATCH: a clinical decision rule for the use of computed tomography in children with minor head injury. CMAJ. 2010;182(4):341–348. [PubMed: 20142371]
9. Kuppermann N, Holmes JF, Dayan PS, et al. Identification of children at very low risk of clinically-important brain injuries after head trauma: a prospective cohort study. Lancet. 2009;374(9696):1160–1170. [PubMed: 19758692]
10. Howe J, Fitzpatrick CM, Lakam DR, Gleisner A, Vane DW. Routine repeat brain computed tomography in all children with mild traumatic brain injury may result in unnecessary radiation exposure. J Trauma Acute Care Surg. 2014;76(2):292–296. [PubMed: 24458036]
11. Patel SK, Gozal YM, Krueger BM, et al. Routine surveillance imaging following mild traumatic brain injury with intracranial hemorrhage may not be necessary. J Pediatr Surg. 2018;53(10):2048–2054. [PubMed: 29784284]
12. da Silva PSL, Reis ME, Aguiar VE. Value of repeat cranial computed tomography in pediatric patients sustaining moderate to severe traumatic brain injury. J Trauma. 2008;65(6):1293–1297. [PubMed: 19077616]
13. Hill EP, Stiles PJ, Reyes J, Nold RJ, Helmer SD, Haan JM. Repeat head imaging in blunt pediatric trauma patients: is it necessary? J Trauma Acute Care Surg. 2017;82(5):896–900. [PubMed: 28248802]
14. Donnelly LF, Frush DP. Fallout from recent articles on radiation dose and pediatric CT. Pediatr Radiol. 2001;31(6):388–391. [PubMed: 11436883]
15. Hauptmann M, Byrnes G, Cardis E, et al. Brain cancer after radiation exposure from CT examinations of children and young adults: results from the EPI-CT cohort study. Lancet Oncol. 2023;24(1):45–53. [PubMed: 36493793]
16. Appelbaum R, Hoover T, Azari S, et al. Development and implementation of a pilot radiation reduction protocol for pediatric head injury. J Surg Res. 2020;255:111–117. [PubMed: 32543375]
17. Hollingworth W, Vavilala MS, Jarvik JG, et al. The use of repeated head computed tomography in pediatric blunt head trauma: factors predicting new and worsening brain injury. Pediatr Crit Care Med. 2007;8(4):348–357. [PubMed: 17545925]
18. Halpern NA, Pastores SM, Greenstein RJ. Critical care medicine in the United States 1985–2000: an analysis of bed numbers, use, and costs. Crit Care Med. 2004;32(6):1254–1259. [PubMed: 15187502]
19. Norris C, Jacobs P, Rapoport J, Hamilton S. ICU and non-ICU cost per day. Can J Anaesth. 1995;42(3):192–196. [PubMed: 7743567]
20. Hazinski MF. Nursing Care of the Critically Ill Child. 3rd ed. Mosby; 2012.
21. Berenbaum J, Hatcher J. Emotional distress of mothers of hospitalized children. J Pediatr Psychol. 1992;17(3):359–372. [PubMed: 1640318]
22. Board R, Ryan-Wenger N. Stressors and stress symptoms of mothers with children in the PICU. J Pediatr Nurs. 2003;18(3):195–202. [PubMed: 12796862]
23. Eberly TW, Miles MS, Carter MC, Hennessey J, Riddle I. Parental stress after the unexpected admission of a child to the intensive care unit. CCQ. 1985;8(1):57–65. [PubMed: 10271317]

24. Nelson LP, Gold JI. Posttraumatic stress disorder in children and their parents following admission to the pediatric intensive care unit: a review. Pediatr Crit Care Med. 2012;13(3):338–347. [PubMed: 21499173]
25. Velmahos GC, Gervasini A, Petrovick L, et al. Routine repeat head CT for minimal head injury is unnecessary. J Trauma. 2006;60(3):494–501. [PubMed: 16531845]
26. Stippler M, Smith C, McLean AR, et al. Utility of routine follow-up head CT scanning after mild traumatic brain injury: a systematic review of the literature. Emerg Med J. 2012;29(7):528–532. [PubMed: 22307924]
27. Carpenter CR, Raja AS, Brown MD. Overtesting and the downstream consequences of overtreatment: Implications of “preventing overdiagnosis” for emergency medicine. Acad Emerg Med. 2015;22(12):1484–1492. [PubMed: 26568269]
28. Marin JR, Mills AM. Developing a research agenda to optimize diagnostic imaging in the emergency department: an executive summary of the 2015 Academic Emergency Medicine consensus conference. Pediatr Emerg Care. 2015;31(12):876–882. [PubMed: 26626899]
29. Kim WH, Lim DJ, Kim SH, Ha SK, Choi JI, Kim SD. Is routine repeated head CT necessary for all pediatric traumatic brain injury? J Korean Neurosurg Soc. 2015;58(2):125–130. [PubMed: 26361528]
30. Greenberg JK, Ahluwalia R, Hill M, et al. Development and external validation of the KIIDS-TBI tool for managing children with mild traumatic brain injury and intracranial injuries. Acad Emerg Med. 2021;28(12):1409–1420. [PubMed: 34245632]
31. Greenberg JK, Olsen MA, Johnson GW, et al. Quantitative imaging measurements marginally improve risk prediction for children with mild traumatic brain injuries and intracranial injuries. Neurosurgery. 2022;68(suppl 1):38–39.
32. von Elm E, Altman DG, Egger M, Pocock SJ, Gøtzsche PC, Vandenbroucke JP. The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: guidelines for reporting observational studies. J Clin Epidemiol. 2008;61(4):344–349. [PubMed: 18313558]
33. IBM SPSS Statistics for Macintosh, Version 27.0. IBM Corp. Accessed March 2, 2023. https://www.ibm.com/support/pages/downloading-ibm-spss-statistics-27
34. R: A language and environment for statistical computing. R Core Team. Accessed March 2, 2023. https://www.R-project.org/
35. Brown CVR, Weng J, Oh D, et al. Does routine serial computed tomography of the head influence management of traumatic brain injury? A prospective evaluation. J Trauma. 2004;57(5):939–943. [PubMed: 15580014]
36. Durham SR, Liu KC, Selden NR. Utility of serial computed tomography imaging in pediatric patients with head trauma. J Neurosurg. 2006;105(5 suppl):365–369. [PubMed: 17328259]
37. Greenberg JK, Yan Y, Carpenter CR, et al. Development of the CIDSS2 score for children with mild head trauma without intracranial injury. J Neurotrauma. 2018;35(22):2699–2707. [PubMed: 29882466]
38. Greenberg JK, Yan Y, Carpenter CR, et al. Development and internal validation of a clinical risk score for treating children with mild head trauma and intracranial injury. JAMA Pediatr. 2017;171(4):342–349. [PubMed: 28192567]
39. Greenberg JK, Stoev IT, Park TS, et al. Management of children with mild traumatic brain injury and intracranial hemorrhage. J Trauma Acute Care Surg. 2014;76(4):1089–1095. [PubMed: 24662876]
40. Greenberg JK, Jeffe DB, Carpenter CR, et al. North American survey on the post-neuroimaging management of children with mild head injuries. J Neurosurg Pediatr. 2018;23(2):227–235. [PubMed: 30485194]
41. Huguenard AL, Miller BA, Sarda S, Capasse M, Reisner A, Chern JJ. Mild traumatic brain injury in children is associated with a low risk for posttraumatic seizures. J Neurosurg Pediatr. 2016;17(4):476–482. [PubMed: 26613272]
42. Noje C, Jackson EM, Nasr IW, et al. Trauma bay disposition of infants and young children with mild traumatic brain injury and positive head imaging. Pediatr Crit Care Med. 2019;20(11):1061–1068. [PubMed: 31232854]

43. Kim HJ, Eun S, Yoon SH, Kim MK, Chung HS, Koo C. Paediatric Trauma Score as a non-imaging tool for predicting intracranial haemorrhage in patients with traumatic brain injury. Sci Rep. 2021;11(1):20911. [PubMed: 34686729]

44. Slovis JC, Gupta N, Li NY, Kernie SG, Miles DK. Assessment of recovery following pediatric traumatic brain injury. Pediatr Crit Care Med. 2018;19(4):353–360. [PubMed: 29419604]

45. Hess EP, Grudzen CR, Thomson R, Raja AS, Carpenter CR. Shared decision-making in the emergency department: respecting patient autonomy when seconds count. Acad Emerg Med. 2015;22(7):856–864. [PubMed: 26112797]

TABLE 1.

Cohort demographics and clinical presentation

	All Patients	Repeat Imaging	No Repeat Imaging	Univariable p Value	No Composite Outcome*	Composite Outcome*	Univariable p Value
No. of patients	1,324	547	777		492	55	
Median age (IQR), yrs	4 (10.4)	4 (10.5)	5 (10.4)	0.102	3.0 (9.5)	8.0 (12.7)	**<0.001**
Age ≥2 yrs	837 (63.2)	320 (58.5)	517 (66.5)	**0.003**	279 (56.7)	41 (74.5)	**0.013**
Sex							
Male	859 (64.9)	354 (64.7)	505 (65.0)	Ref	317 (64.4)	37 (67.3)	Ref
Female	465 (35.1)	193 (35.3)	272 (35.0)	0.917	175 (35.6)	18 (32.7)	0.676
Race							
White	1104 (83.4)	456 (83.4)	648 (83.4)	Ref	407 (82.7)	49 (89.1)	Ref
Black	173 (13.1)	71 (13.0)	102 (13.1)	0.948	67 (13.6)	4 (7.3)	0.191
Asian	20 (1.5)	8 (1.5)	12 (1.5)	0.907	6 (1.2)	2 (3.6)	0.220
American Indian	2 (0.2)	0 (0)	2 (0.3)	0.999	0 (0)	0 (0)	
Pacific Islander	1 (0.1)	0 (0)	1 (0.1)	>0.999	0 (0)	0 (0)	
Unknown	24 (1.8)	12 (2.2)	12 (1.5)	0.395	12 (2.4)	0 (0)	0.999
Mechanism of injury							
Fall down the stairs	43 (3.2)	16 (2.9)	27 (3.5)	0.579	16 (3.3)	0 (0)	0.998
Fall from elevation	514 (38.8)	223 (40.8)	291 (37.5)	0.223	201 (40.9)	22 (40.0)	0.903
Struck by moving object	88 (6.6)	32 (5.9)	56 (7.2)	0.330	31 (6.3)	1 (1.8)	0.209
MVC	155 (11.7)	47 (8.6)	108 (13.9)	**0.003**	43 (8.7)	4 (7.3)	0.713
Pedestrian struck by moving vehicle	30 (2.3)	10 (1.8)	20 (2.6)	0.371	9 (1.8)	1 (1.8)	0.995
Motorcycle/ATV/motorized scooter collision	77 (5.8)	27 (4.9)	50 (6.4)	0.252	22 (4.5)	5 (9.1)	0.142†
Ground-level fall/ran into stationary object	118 (8.9)	46 (8.4)	72 (9.3)	0.590	42 (8.5)	4 (7.3)	0.749
Bicyclist struck by moving vehicle/fall of bicycle	88 (6.6)	34 (6.2)	54 (6.9)	0.598	32 (6.5)	2 (3.6)	0.410
Assault	51 (3.9)	32 (5.9)	19 (2.4)	**0.002**	27 (5.5)	5 (9.1)	0.286
Sports collision	14 (1.1)	4 (0.7)	10 (1.3)	0.337	4 (0.8)	0 (0)	0.999

	All Patients	Repeat Imaging	No Repeat Imaging	Univariable p Value	No Composite Outcome*	Composite Outcome*	Univariable p Value
Other‡	146 (11.0)	76 (13.9)	70 (9.0)	**0.006**	65 (13.2)	11 (20.0)	0.171
Severe mechanism of injury	466 (35.2)	186 (34.0)	280 (36.0)	0.446	171 (34.8)	15 (27.3)	0.268
Other significant injury	177 (13.4)	64 (11.7)	113 (14.5)	0.135†	59 (12.0)	5 (9.1)	0.527
Concern for nonaccidental trauma	123 (9.3)	85 (15.5)	38 (4.9)	**<0.001**	80 (16.3)	5 (9.1)	0.171
Median time from injury to ED (IQR), hrs	1 (3)	2 (3)	1 (2.9)	0.877	2.0 (3.0)	2.0 (3.0)	0.541
Clinical presentation							
Vomiting	407 (30.7)	215 (39.3)	192 (24.7)	**<0.001**	188 (38.2)	27 (49.1)	0.119†
History of loss of consciousness	359 (27.1)	158 (28.9)	201 (25.9)	0.224	139 (28.3)	19 (34.5)	0.330
Seizures	79 (6.0)	47 (8.6)	32 (4.1)	**<0.001**	39 (7.9)	8 (14.5)	0.102†
Presenting GCS score							
13	60 (4.5)	29 (5.3)	31 (4.0)	0.260	25 (5.1)	4 (7.3)	0.494
14	158 (11.9)	85 (15.5)	73 (9.4)	**<0.001**	78 (15.9)	7 (12.7)	0.545
15	1106 (83.5)	433 (79.2)	673 (86.6)	**<0.001**	389 (79.1)	44 (80.0)	0.871
Institution							
A	259 (19.6)	80 (14.6)	179 (23.0)	**<0.001**	67 (13.6)	13 (23.6)	0.050†
B	344 (26.0)	178 (32.5)	166 (21.4)	**<0.001**	165 (33.5)	13 (23.6)	0.140†
C	141 (10.6)	69 (12.6)	72 (9.3)	0.053†	63 (12.8)	6 (10.9)	0.688
D	580 (43.8)	220 (40.2)	360 (46.3)	**0.027**	197 (40.0)	23 (41.8)	0.799

ATV = all-terrain vehicle; MVC = motor vehicle crash.

Values are expressed as number (percentage) unless indicated otherwise. The p values were calculated using univariable logistic regression. Boldface type indicates statistical significance.

*Composite outcome was defined as hemorrhagic progression and/or neurosurgical intervention triggered by repeat imaging findings.

†The p value met our threshold for further inclusion in multivariable analyses ($p < 0.15$).

‡Other includes object falling on head, kicked by horse, jumped out of moving car/ATV, head collision with a person, fallen on by sibling, fall off skateboard, etc.

TABLE 2.

Cohort initial radiographic findings

	All Patients w/ ICI	Repeat Imaging	No Repeat Imaging	Univariable p Value	No Composite Outcome*	Composite Outcome*	Univariable p Value
Initial neuroimaging type							
MRI	1 (0.1)	0 (0)	1 (0.1)	NC	0 (0)	0 (0)	NC
CT	1323 (99.9)	547 (100)	776 (99.9)	NC	492 (100)	55 (100)	NC
Reason for repeat imaging							
Scheduled (surveillance)	NC	497 (90.9)	NC	NC	449 (91.3)	48 (87.3)	Ref
Clinical deterioration	NC	26 (4.8)	NC	NC	23 (4.7)	3 (5.5)	0.709
Unclear prompting	NC	24 (4.4)	NC	NC	20 (4.1)	4 (7.3)	0.243
Initial imaging findings							
SDH	427 (32.3)	240 (43.9)	187 (24.1)	**<0.001**	223 (45.3)	17 (30.9)	**0.043**
EDH	193 (14.6)	136 (24.9)	57 (7.3)	**<0.001**	107 (21.7)	29 (52.7)	**<0.001**
Extra-axial hemorrhage	133 (10.0)	80 (14.6)	53 (6.8)	**<0.001**	75 (15.2)	5 (9.1)	0.227
Cerebral contusion	184 (13.9)	81 (14.8)	103 (13.3)	0.422	70 (14.2)	11 (20.0)	0.256
Midline shift	79 (6.0)	53 (9.7)	26 (3.3)	**<0.001**	44 (8.9)	9 (16.4)	0.083†
Depressed skull fracture							
≥ width of skull	108 (8.2)	33 (6.0)	75 (9.7)	**0.019**	31 (6.3)	2 (3.6)	0.437
< width of skull	158 (11.9)	65 (11.9)	93 (12.0)	0.962	58 (11.8)	7 (12.7)	0.838
SAH	356 (26.9)	95 (17.4)	261 (33.6)	**<0.001**	90 (18.3)	5 (9.1)	0.095†
IVH	7 (0.5)	6 (1.1)	1 (0.1)	**0.047**	6 (1.2)	0 (0)	0.999
Cerebral edema	19 (1.4)	14 (2.6)	5 (0.6)	**0.008**	12 (2.4)	2 (3.6)	0.596
Traumatic infarction	14 (1.1)	2 (0.4)	12 (1.5)	0.058†	2 (0.4)	0 (0)	0.999
Herniation	1 (0.1)	0 (0)	1 (0.1)	>0.999	0 (0)	0 (0)	NC
Venous sinus thrombosis	2 (0.2)	0 (0)	2 (0.3)	0.999	0 (0)	0 (0)	NC
Pneumocephalus	289 (21.8)	68 (12.4)	221 (28.4)	**<0.001**	61 (12.4)	7 (12.7)	0.944
Linear, non–basilar skull fracture	482 (36.4)	222 (40.6)	260 (33.5)	**0.008**	202 (41.1)	20 (36.4)	0.502
Basilar skull fracture	91 (6.9)	39 (7.1)	52 (6.7)	0.757	36 (7.3)	3 (5.5)	0.612

NC = not calculated; SAH = subarachnoid hemorrhage.

Values are expressed as number (percentage) unless indicated otherwise. The p values were calculated using univariable logistic regression. Boldface type indicates statistical significance.

*Composite outcome defined as hemorrhage progression and/or neurosurgical intervention as a result of repeat imaging findings.

†The p value met our threshold for further inclusion in multivariable analyses ($p < 0.15$).

TABLE 3.

Characterization of repeat imaging findings

	Value
Median time btwn initial & repeat imaging (IQR), hrs	8 (10)
Repeat neuroimaging type	
CT	421 (77.0)
MRI	126 (23.0)
Median no. of repeat scans (range)	1 (1–4)
Reason for repeat imaging	
Scheduled (surveillance)	497 (90.9)
Clinical change	26 (4.8)
Unknown	24 (4.4)
Neurosurgical intervention*	14 (2.6)
Progression of previous findings	52 (9.5)
Found on CT	45 (86.5)
Found on MRI	7 (13.5)
New traumatic findings†	73 (13.3)
SDH	22 (30.1)
EDH	5 (6.8)
Extra-axial hematoma	6 (8.2)
SAH	8 (11.0)
IVH	2 (2.7)
Cerebral contusion	24 (32.9)
Cerebral edema	1 (1.4)
Traumatic infarction	6 (8.2)
Midline shift	6 (8.2)
Herniation	0 (0)
Venous sinus thrombosis	4 (5.5)
Pneumocephalus	2 (2.7)
Linear, non–basilar skull fracture	4 (5.5)
Basilar skull fracture	0 (0)
Depressed skull fracture	
≥ width of the skull	0 (0)
< width of the skull	0 (0)

Values are expressed as number (percentage) unless indicated otherwise.

*In all patients included in this cohort, repeat imaging findings were cited as an indication for neurosurgical intervention.

†Percentages for new traumatic findings are reported as new findings divided by total new traumatic findings.

TABLE 4.

Patient interventions and disposition

	All Patients	Repeat Imaging	No Repeat Imaging	No Composite Outcome*	Composite Outcome*
Neurosurgical intervention	101 (7.6)	44 (8.0)	57 (7.3)	27 (5.5)	17 (30.9)
Hematoma evacuation	56 (4.2)	36 (6.6)	20 (2.6)	20 (4.1)	16 (29.1)
Skull fracture elevation	46 (3.5)	11 (2.0)	35 (4.5)	9 (1.8)	2 (3.6)
ICP monitor placement	3 (0.2)	2 (0.4)	1 (0.1)	2 (0.4)	0 (0)
Craniectomy	4 (0.3)	2 (0.4)	2 (0.3)	2 (0.4)	0 (0)
Ventriculostomy	2 (0.2)	1 (0.2)	1 (0.1)	0 (0)	1 (1.8)
Dura repair for CSF leak	14 (1.1)	3 (0.5)	11 (1.4)	3 (0.6)	0 (0)
Other	13 (1.0)	2 (0.4)	11 (1.4)	2 (0.4)	0 (0)
Prolonged intubation (>24 hrs)	9 (0.7)	5 (0.9)	4 (0.5)	5 (1.0)	0 (0)
Death due to TBI	1 (0.1)	0 (0)	1 (0.1)	0 (0)	0 (0)
Disposition from ED					
Home	14 (1.1)	0 (0)	14 (1.8)	0 (0)	0 (0)
General inpatient	511 (38.6)	134 (24.5)	377 (48.5)	124 (25.2)	10 (18.2)
Short stay (<24 hrs)	34 (2.6)	9 (1.6)	25 (3.2)	9 (1.8)	0 (0)
ICU	706 (53.3)	390 (71.3)	316 (40.7)	349 (70.9)	41 (74.5)
Operating room	59 (4.5)	14 (2.6)	45 (5.8)	10 (2.0)	4 (7.3)
Median hospital LOS (IQR), days	2 (2)	2 (2)	1 (1)	2 (2)	3 (2)
Median LOS in ICU (IQR), days	1 (2)	1 (2)	0 (1)	1 (2)	2 (1)
Readmission due to TBI	23 (1.7)	23 (4.2)	0 (0)	18 (3.7)	5 (9.1)

ICP = intracranial pressure.

Values are expressed as number (percentage) unless indicated otherwise.

*Composite outcome was defined as hemorrhagic progression and/or neurosurgical intervention triggered by repeat imaging findings.

TABLE 5.

Final regression models

Variable	Beta Estimate	OR (95% CI)	Adjusted p Value
Model 1: factors associated w/ repeat imaging*			
Intercept	−1.71		
Concern for nonaccidental trauma	0.57	1.76 (1.11–2.78)	0.016
Vomiting	0.57	1.77 (1.35–2.34)	<0.001
Presence of SDH	1.64	5.18 (3.79–7.06)	<0.001
Presence of EDH	2.31	10.11 (6.83–14.97)	<0.001
Presence of extra-axial hemorrhage	1.71	5.52 (3.59–8.50)	<0.001
Presence of IVH	2.91	18.42 (2.06–165.08)	0.009
Presence of edema	1.52	4.58 (1.38–15.19)	0.013
Presence of pneumocephalus	−0.39	0.68 (0.48–0.96)	0.028
Institution B	0.54	1.72 (1.26–2.35)	<0.001
Institution A	−0.67	0.51 (0.36–0.73)	<0.001
MOI: assault	0.77	2.15 (1.05–4.40)	0.036
Model 2: predictors of hemorrhagic progression &/or neurosurgical intervention†			
Constant	−3.35		
Age ≥2 yrs	0.81	2.25 (1.16–4.36)	0.016
Seizure	1.08	2.95 (1.22–7.14)	0.017
Presence of EDH	1.38	3.99 (2.22–7.15)	<0.001

MOI = mechanism of injury.

*C-statistic = 0.80.

†C-statistic = 0.71.