Utility of a pediatric fast magnetic resonance imaging protocol as surveillance scanning for traumatic brain injury

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OBJECTIVE Traumatic brain injury (TBI) is a prevalent pediatric pathology in the modern emergency department. Computed tomography (CT) is utilized for detection of TBI and can result in cumulatively high radiation exposure. Recently, a fast brain magnetic resonance imaging (fbMRI) protocol has been employed for rapid imaging of hydrocephalus in pediatric patients. The authors investigate the utility of a modified trauma-focused fbMRI (t-fbMRI) protocol as an alternative to surveillance CT in the setting of acute TBI in pediatric patients, thus reducing radiation exposure while improving diagnostic yield.

METHODS A retrospective review was performed at the authors' institution for all pediatric patients who had undergone t-fbMRI within 72 hours of an initial CT scan, using a 1.5- or 3-T MR scanner for trauma indications. Forty patients met the study inclusion criteria. The authors performed a comparison of findings on the reads of CT and fbMRI, and a board-certified neuroradiologist conducted an independent review of both modalities.

RESULTS T-fbMRI outperformed CT in specificity, sensitivity, and negative predictive value for all injury pathologies measured, except for skull fractures. T-fbMRI demonstrated a sensitivity of 100% in the detection of extraaxial bleed, intraventricular hemorrhage, and subarachnoid hemorrhage and had a sensitivity of 78% or greater for epidural hematoma, subdural hematoma, and intraparenchymal hemorrhage. T-fbMRI yielded a specificity of 100% for all types of intracranial hemorrhages, with a corresponding negative predictive value that exceeded that for CT.

CONCLUSIONS In pediatric populations, the t-fbMRI protocol provides a valid alternative to CT in the surveillance of TBI and intracranial hemorrhage. Although not as sensitive in the detection of isolated skull fractures, t-fbMRI can be used to monitor pathologies implicated in TBI patients while minimizing radiation exposure from traditional surveillance imaging.

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KEYWORDS traumatic brain injury; pediatric trauma; magnetic resonance imaging; computed tomography; radiation; intracranial hemorrhage; surveillance imaging

EVERY year, nearly 630,000 emergency department visits are attributed to children under 18 years of age suffering from traumatic brain injury (TBI).^{1–3} Prompt accurate evaluation of these patients is paramount to triage those with urgent surgical needs versus those requiring conservative observation.^{4,5} Over the last 30 years, computed tomography (CT) has been a rapid, presumably accurate source of imaging when a child requires head and/or brain evaluation because of its speed, availability, and diagnostic ability to rule out severe acute intracranial

injury.⁶ Although the modality is clinically useful, the emission of ionizing radiation increases the risk of brain neoplasm and leukemia, especially in children and adolescents who are more radiosensitive.⁷ Brenner et al.⁸ found that each noncontrast head CT is estimated to contribute a lifetime cancer mortality risk of 0.7% in a 1-year-old child, which is an order of magnitude higher than in an adult. Moreover, children with TBI may undergo multiple CT scans, creating an additive effect.^{9,10}

Magnetic resonance imaging (MRI) utilization in pe-

ABBREVIATIONS ADC = apparent diffusion coefficient; CT = computed tomography; DWI = diffusion-weighted imaging; EDH = epidural hematoma; GCS = Glasgow Coma Scale; GRE = gradient echo; HASTE = half-Fourier acquisition single-shot turbo spin echo; IPH = intraparenchymal hemorrhage; IVH = intraventricular hemorrhage; MRI = magnetic resonance imaging; NPV = negative predictive value; PPV = positive predictive value; SAH = subarachnoid hemorrhage; SDH = subdural hematoma; TBI = traumatic brain injury; t-fbMRI = trauma-focused fast brain MRI.

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FIG. 1. Selected sequences utilizing the t-fbMRI protocol. The seven sequences were as follows: T2-weighted HASTE in the axial (A), sagittal (B), and coronal (C) planes; T2-weighted FLAIR in the axial plane (D); DWI trace in the axial plane (E); ADC in the axial plane (F); and GRE in the axial plane (G).

diatric acute TBI has historically been avoided because of untimely access, the need for patients to be motionless, and the paucity of literature supporting its ability to rule out clinically significant intracranial injuries.^{11–13} Patient motion requiring sedation or intubation is likely the largest hurdle to MRI use, especially with very young patients, as anesthesia time in infants and toddlers is now being linked to adverse events and mild cognitive injury.^{14–17}

Recently, trauma-focused fast brain MRI (t-fbMRI) protocols have demonstrated validity for surveillance and follow-up imaging of TBI in patients with head trauma, including at our institution.^{18,19} Lindberg and colleagues²⁰ published a landmark paper in *Pediatrics* in 2019 in which they followed a cohort of almost 300 children, comparing the feasibility and accuracy of fast MRI with that of CT in the surveillance of TBI. Our study not only attempts to validate Lindberg and colleagues' findings but also reports on an independently designed t-fbMRI sequence, the breakdown of MRI accuracy for all intracranial hemorrhages independently, and the negative predictive values for CT versus MRI by using independent, blinded evaluations. The objective of this paper was to show that the accuracy of t-fbMRI as a surveillance tool for TBI is non-inferior to traditional CT scanning, making it a safe and effective alternative imaging modality.

Methods

Data Collection

An institutional review board–approved retrospective chart review was performed for all pediatric patients who had undergone t-fbMRI at the Medical University of South Carolina, a level I pediatric trauma center, between June 2018 and June 2019. Inclusion criteria were an age younger than 18 years, presentation with traumatic head injury requiring a head CT scan without contrast, and a

follow-up t-fbMRI within 72 hours. The time frame was determined using the start time on the initial CT and the start time on the initial t-fbMRI. Patients who had sustained nonaccidental trauma were excluded. Of the 172 patients identified, 40 met our inclusion criteria.

Data pertaining to demographics, mechanism of trauma, presenting Glasgow Coma Scale (GCS) score, time between CT and t-fbMRI, relevant time information related to t-fbMRI, radiological findings on CT and t-fbMRI, and required surgical interventions were collected. T-fbMRI was performed for further prognostication of TBI following acute trauma.

Imaging Protocol

At our institution, the t-fbMRI protocol includes seven sets of image sequences: T2-weighted half-Fourier acquisition single-shot turbo spin echo (HASTE) imaging in the axial, sagittal, and coronal planes; diffusion-weighted imaging (DWI); apparent diffusion coefficient (ADC) in the axial plane; T2-weighted FLAIR in the axial plane; and gradient echo (GRE) in the axial plane (Fig. 1). Imaging was performed on a 1.5- or 3-T MR scanner (Siemens Healthcare). The procedure takes 7 minutes to complete. No sedation or patient restraints were used for imaging.

Imaging Interpretation

Radiology reports from CT and t-fbMRI studies were reviewed for the presence or absence of the following terms: skull fracture, subarachnoid hemorrhage (SAH), epidural hematoma (EDH), subdural hematoma (SDH), extraaxial bleed (either SDH or EDH), and intraventricular or intraparenchymal hemorrhage (IVH or IPH). Each study was finalized by a board-certified neuroradiologist. Retrospective review of CT and t-fbMRI scans was performed by a separate board-certified neuroradiologist

(M.S.) using AGFA Impax. Images were assigned a score of either 0 or 1 based on image quality. A score of 1 was assigned to studies that were of acceptable image quality and answered the clinical question. Studies that did not meet these criteria were assigned a score of 0. CT and t-fbMRI studies were evaluated blindly and independent of one another.

Repeat Review for Rigor

In order to adequately assess the presence of skull fractures, t-fbMRI scans underwent two separate and independent reviews, without CT for comparison. A board-certified neuroradiologist performed an additional review of CT scans that had been read as positive for hemorrhage on initial presentation but were read as negative for hemorrhage with follow-up t-fbMRI. A subsequent review of all CT images was performed alongside the follow-up t-fbMRI for comparison to determine whether blood products were truly present on initial CT.

Statistical analysis was run in duplicate. Initial statistics used CT findings as the gold standard for true positive and negative when comparing t-fbMRI results. A second statistical analysis (corrected) allowed comparison of the t-fbMRI with CT to confirm true-positive and true-negative findings. Each analysis determined sensitivity, specificity, and positive and negative predictive values (PPV and NPV) for t-fbMRI findings compared with CT in each category of injury. A p value < 0.05 was considered significant.

Statistical Evaluation

All statistical analyses were performed using IBM SPSS (IBM Corp.) to compare CT and t-fbMRI radiological findings. We utilized Cohen's kappa coefficient (κ) for agreement between CT and t-fbMRI for the presence of skull fracture and all categories of intracranial hemorrhage (SAH, SDH, EDH, IVH, and IPH). Agreement measures were defined as follows: $\kappa \leq 0.20$, poor agreement; $\kappa = 0.21$ – 0.40 , fair agreement; $\kappa = 0.41$ – 0.60 , moderate agreement; $\kappa = 0.61$ – 0.80 , good agreement; $\kappa = 0.81$ – 1 , very good agreement.

Results

Participant Characteristics

During the study period, 40 patients met the inclusion criteria. Twenty-five patients were female and 15 were male. The average age was 6.7 years (range 14.6 days–17 years), and the average presenting GCS score was 12.5 (range 3–15). The most common mechanism of trauma was a fall, followed by high-speed-impact accidents such as motor vehicle collisions. Patients warranted admission because of either a moderate (GCS score 9–13) or a severe (GCS score 3–8) TBI or positive findings on CT (Table 1). The average time between initial CT and follow-up t-fbMRI was 7.64 hours (range 1.38–30.67 hours). Of the 40 study participants, 18 were transfers from outside hospitals where they had received their original CT scans. The average time from the t-fbMRI order to the neuroradiology report created was 1.73 hours (range 0.27–11.47 hours).

TABLE 1. Demographic and imaging characteristics in 40 patients with TBI

Variable	Value
Gender	
Female	25 (63)
Male	15 (38)
Age in yrs	6.7 $\pm$ 5.8
Mechanism of trauma	
Fall	22 (55)
High-speed impact	17 (43)
Crush injury	1 (3)
GCS score	12.5 $\pm$ 3.9
14–15, mild	28 (70)
9–13, moderate	6 (15)
3–8, severe	6 (15)
Time btwn CT & MRI in hrs	7.64 $\pm$ 6.3
Time from MRI completion to report created in hrs	1.73 $\pm$ 2.2
Neurosurgical intervention (n = 5)	5 (13)
SAH	5 (100)
EDH	3 (60)
SDH	2 (40)
IPH	4 (80)

Values are expressed as number (%) or mean $\pm$ standard deviation.

Comparative Radiological Findings

Cohen's kappa coefficient demonstrated good agreement between CT and t-fbMRI when comparing SAH ($\kappa = 0.63$) and skull fracture ($\kappa = 0.74$) identified on t-fbMRI. The same method demonstrated fair agreement between CT and t-fbMRI for SDH ($\kappa = 0.48$) and IVH ($\kappa = 0.48$). Cohen's kappa coefficient showed poor agreement between CT and t-fbMRI for EDH ($\kappa = 0.22$), extraaxial bleed ($\kappa = 0.33$), and IPH ($\kappa = 0.34$; Table 2).

Sensitivity

When CT and t-fbMRI were evaluated as stand-alone studies, t-fbMRI outperformed CT for all hemorrhage types. The sensitivity of t-fbMRI for detecting an extraaxial bleed, IVH, and SAH (100% for each category) was substantially better than the sensitivity of CT (38%, 33%, and 86%, respectively; Table 3). T-fbMRI detected SDH with a sensitivity of 93% versus CT with 57%, IPH with a sensitivity of 85% versus 54%, and EDH with a sensitivity of 78% versus 11%. Initial statistical analysis suggested a high sensitivity of t-fbMRI in skull fracture detection (81%). When these data were reevaluated using the blinded protocol detailed above without CT comparison available, the sensitivity of t-fbMRI in detecting skull fracture dropped to 56%, considerably lower than that of CT (100%).

Specificity

T-fbMRI also outperformed CT in each category for specificity, with six of the seven categories demonstrating a specificity of 100%: SAH (vs 81% with CT), SDH (vs 92%), IPH (vs 93%), EDH (vs 100%), IVH (vs 100%), and

TABLE 2. Radiological findings using CT as the gold standard

Radiological Finding	Positive Finding on CT (no.)	Positive Finding on fbMRI (no.)	Negative Finding on CT (no.)	Negative Finding on fbMRI (no.)	Correlation (κ)	p Value	Sensitivity of fbMRI	Specificity of fbMRI
SAH	17	14	23	26	0.63	<0.0001	71%	91%
Extraaxial bleed	7	10	33	30	0.33	<0.031	57%	82%
EDH	1	7	39	33	0.22	<0.028	100%	85%
SDH	11	14	29	26	0.48	<0.002	73%	79%
IVH	1	3	39	37	0.48	<0.0001	100%	95%
IPH	9	11	31	29	0.34	<0.032	56%	81%
Skull fracture (initial)	27	22	13	18	0.74	<0.0001	81%	100%
Skull fracture (blinded)	27	15	13	25	0.45	<0.0001	56%	100%

Cohen's kappa (κ): ≤ 0.20, poor agreement; 0.21–0.40, fair agreement; 0.41–0.60, moderate agreement; 0.61–0.80, good agreement; 0.81–1, very good agreement.

skull fracture (vs 100%). When t-fbMRI was evaluated without CT comparison, the specificity for detecting skull fracture dropped to 85%.

Positive Predictive Value

t-fbMRI demonstrated higher PPV than CT across all hemorrhage categories, with a value of 80% or higher. The PPV of t-fbMRI was 100% for IPH (vs 87% with CT), SDH (vs 88%), EDH (vs 100%), and IVH (vs 100%). The initial t-fbMRI PPV for skull fracture was 100% (vs 100% with CT), but it was 93% when corrected. The PPV of t-fbMRI was 80% for SAH (vs 74% with CT; Table 4).

Negative Predictive Value

T-fbMRI demonstrated a higher NPV than CT across all hemorrhage categories, with a value of 93% or higher. Pathologies with an NPV of 100% included SAH (vs with 93% CT), IVH (vs 95% with CT), and extraaxial bleed (vs 86% with CT). The NPV of t-fbMRI was 96% for SDH (vs 81% with CT), 94% for EDH (vs 79%), and 93% for IPH (vs 82%). Again, CT had a higher NPV for the detection of skull fracture (100%) than t-fbMRI (72% initially, corrected to 52%; Table 4).

Discussion

TBI is a prevalent pathology in the modern pediatric

emergency department, most commonly detected using CT. Given accumulating evidence for the negative effects of ionizing radiation exposure in children attributed to CT, MRI has become a modality of interest for evaluation of TBI. In the present study, t-fbMRI was performed as the follow-up study after initial CT imaging in children with TBI. In our series, participants did not require intubation, sedation, or restraints for completion of t-fbMRI. The ability to accurately identify all intracranial hemorrhages was higher with t-fbMRI than with standard noncontrast head CT, but not in identifying skull fracture. Findings missed on follow up t-fbMRI were clinically nonsignificant in our study. Similarly, multiple prior studies have demonstrated linear, nondisplaced fractures to be clinically nonsignificant²¹ and, unless associated with additional underlying intracranial injury, to carry minimal risk for related complications.^{6,22–25}

In this study, we initially designated the original CT scan as the gold standard and thus used κ as a comparison evaluation for t-fbMRI against the CT scan, as reported in Lindberg and colleagues' 2019 *Pediatrics* landmark paper, which observed greater than 90% sensitivity and specificity for TBI using fbMRI.²⁰ Using their method of comparison, we found t-fbMRI to have a sensitivity of 100% for IVH and EDH and greater than 79% specificity for each category of hemorrhage (Table 2). This high specificity allows clinicians to rule in only those patients requiring admission, avoiding unnecessary hospitalizations.

TABLE 3. Comparison of sensitivity and specificity of MRI and CT following the revised gold-standard method

Variable	CT Sensitivity	t-fbMRI Sensitivity	CT Specificity	t-fbMRI Specificity
SAH	86%	100%	81%	100%
Extraaxial bleed	38%	100%	88%	94%
EDH	11%	78%	100%	100%
SDH	57%	93%	92%	100%
IVH	33%	100%	100%	100%
IPH	54%	85%	93%	100%
Skull fracture (initial)	100%	81%	100%	100%
Corrected skull fracture (blinded)	100%	56%	100%	85%

TABLE 4. Comparison of PPV and NPV of MRI and CT following the revised gold-standard method

Variable	CT PPV	t-fbMRI PPV	CT NPV	t-fbMRI NPV
SAH	74%	80%	93%	100%
Extraaxial bleed	67%	80%	86%	100%
EDH	100%	100%	79%	94%
SDH	88%	100%	81%	96%
IVH	100%	100%	95%	100%
IPH	87%	100%	82%	93%
Skull fracture (initial)	100%	100%	100%	72%
Corrected skull fracture (blinded)		93%		52%

FIG. 2. Example of intracranial hemorrhages identified on surveillance trauma MRI but not readily identifiable on an initial CT scan. Images (A, B) obtained in a 3-year-old female with TBI following crush injury. The CT (A) reveals SAH and skull fracture, prompting hospital admission and a surveillance scan. Surveillance MRI, an axial GRE sequence (B), reveals SAH, as well as EDH (short arrow) and IPH (long arrow) that had not been previously demonstrated on CT. Images (C–E) obtained in a 2-year-old female who presented with a severe TBI following a high-speed motor vehicle collision. The CT (C) reveals a scattered SAH with no other intracranial bleeds. Surveillance MRI, an axial FLAIR sequence (D), reveals areas of hyperintensity concerning for IPH (long white arrows, D and E) as well as small occipital SDHs (short arrows) not previously demonstrated on CT. IPH is confirmed on the accompanying GRE sequence (E).

However, CT imaging does have a propensity to miss intracranial pathology (Fig. 2). We would therefore challenge the current notion that CT may be the gold standard for identification of all intracranial hemorrhage pathologies from acute TBI. Given that CT is also a fallible tool, we obtained independent reviews of both CT and t-fbMRI by nonblinded neuroradiologists after all blinded evaluations were complete. This second round of statistical analysis helped to verify whether initial findings on CT were accurate or reflected artifact (bone, motion, or partial volume averaging). Following these secondary reviews, t-fbMRI had an even higher sensitivity and specificity for the detection of all types of hemorrhage measured.

The average time between CT and t-fbMRI for our study was only 7.64 ± 6.3 hours. Such a short interval provides a unique opportunity for a close comparison of t-fbMRI and CT, an advantage over a prior study with an average of 27.5 hours between scans.²⁶ The average time

between ordering t-fbMRI and the created neuroradiology report was 1.73 hours. We realize that if this modality is to be used as a primary imaging method, the time between ordering and the final report of the findings needs to be dramatically decreased. Given that our t-fbMRI was used as follow-up imaging for patients who are typically within the pediatric intensive care unit or the stepdown unit, the time between ordering and report is quite fast.

The goal of our t-fbMRI protocol is a nonradiating, nonsedating, and reliable surveillance tool following TBI. Three-plane T2-weighted images demonstrate gross pathology. FLAIR visualizes edema and inflammation, whereas GRE is useful for identifying blood products.²⁷ DWI and ADC are compared to evaluate for acute infarcts. Notably, previous studies have lacked sequences most sensitive for blood products, that is, GRE and SWI.^{28–32} In our study, the combination of FLAIR and GRE allowed for the detection of small microhemorrhages, whereas

GRE helped to visualize SDH and EDH, as have been observed in previous studies.^{10,33,34} The literature studies that included GRE and DWI showed higher MRI sensitivity rates than those that did not.^{20,35,36} Multisequence MRI performed as a fast scan is a relatively new technological advance that overcomes previous limitations of detecting blood products in sulci, cisterns, and ventricles and along the convexity where neighboring cerebrospinal fluid can mask its presence.

Conclusions

T-fbMRI compared to CT for children with TBI offers higher sensitivity, specificity, PPV, and NPV for all categories of intracranial hemorrhage. Our findings help validate and expand on prior studies while demonstrating the speed with which t-fbMRI studies can be obtained. Whether t-fbMRI can replace the initial trauma protocol head CT for children in the emergency department is still controversial.

We acknowledge that our study has several limitations, including a small sample size, non-immediate follow-up imaging, large variation in participant age, and inconsistent CT scans given the large proportion of patients transferring to our hospital given its status as a tertiary care level I pediatric trauma center. Yet, we are confident that our findings, along with those of others vying to improve imaging for children suffering from TBI, will collectively push the bar in a direction in which these limitations will become obsolete.

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Disclosures

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author Contributions

Conception and design: Alshareef, Shope, Eskandari. Acquisition of data: Alshareef, Shope, Bolling, Reagan, Yazdani, Spampinato. Analysis and interpretation of data: Alshareef, Shope, Bolling, Reagan, Yazdani, Spampinato. Drafting the article: Alshareef, Shope, Larrew, Eskandari. Critically revising the article: Alshareef, Shope, Larrew, Yazdani, Spampinato, Eskandari. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Alshareef. Statistical analysis: Alshareef. Study supervision: Alshareef, Eskandari.

Supplemental Information

Previous Presentations

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