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ORIGINAL RESEARCH

Pediatrics

Can QuickBrain MRI replace CT as first-line imaging for select pediatric head trauma?

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Abstract

Objective: The current standard of care for initial neuroimaging in injured pediatric patients suspected of having traumatic brain injury is computed tomography (CT) that carries risks associated with radiation exposure. The primary objective of this trial was to evaluate the ability of a QuickBrain MRI (qbMRI) protocol to detect clinically important traumatic brain injuries in the emergency department (ED). The secondary objective of this trial was to compare qbMRI to CT in identifying radiographic traumatic brain injury.

Methods: This was a prospective study of trauma patients less than 15 years of age with suspected traumatic brain injury at a level 1 pediatric trauma center in Portland, Oregon between August 2017 and March 2019. All patients in whom a head CT was deemed clinically necessary were approached for enrollment to also obtain a qbMRI in the acute setting. Clinically important traumatic brain injury was defined as the need for neurological surgery procedure, intubation, pediatric intensive care unit stay greater than 24 hours, a total hospital length of stay greater than 48 hours, or death.

Results: A total of 73 patients underwent both CT and qbMRI. The median age was 4 years (interquartile range [IQR] = 1–10 years). Twenty-two patients (30%) of patients had a clinically important traumatic brain injury, and of those, there were 2 deaths (9.1%). QbMRI acquisition time had a median of 4 minutes and 52 seconds (IQR = 3 minutes 49 seconds–5 minutes 47 seconds). QbMRI had sensitivity for detecting clinically important traumatic brain injury of 95% (95% confidence interval [CI] = 77%–99%). For any radiographic injury, qbMRI had a sensitivity of 89% (95% CI = 78%–94%).

Conclusion: Our results suggest that qbMRI has good sensitivity to detect clinically important traumatic brain injuries. Further multi-institutional, prospective trials are warranted to either support or refute these findings.

KEYWORDS
imaging, MRI, pediatric, trauma

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1 | INTRODUCTION

1.1 | Background

Pediatric traumatic brain injury is a common complaint in EDs in the United States, accounting for ~760,000 annual visits.[1] High-quality research has been conducted to derive and validate clinical decision rules for neuroimaging in pediatric head trauma.[2,3] These clinical decision rules are now considered the standard of care and have withstood independent validation.[4] The majority of pediatric head trauma patients in the ED are clinically stable with a Glasgow Coma Scale (GCS) greater than 13.[5] However, even with these rigorously developed decision tools and clinically stable patients, computed tomography (CT) imaging is obtained in the ED in up to 20% of pediatric patients with suspected traumatic brain injury.[6]

The current imaging standard for detection of acute head trauma injuries in the ED is CT. However, cranial CT imaging requires patient exposure to ionizing radiation that has been shown to carry an increased risk of developing a radiation-induced malignancy in children. The estimated risk of radiation-induced malignancy attributable to pediatric head CT is 1:1000–1:5000 scans.[7] In response, multiple medical professional societies have published recommendations designed to limit radiation exposure related to CT imaging in pediatric patients, and extensive research is now focused on reducing radiation exposure.[8] This raises the question of whether an alternative head imaging modality exists for patients who meet the clinical decision rule criteria for neuroimaging.

Unlike CT, magnetic resonance imaging (MRI) does not use ionizing radiation. However, MRI is used less frequently in the ED setting due to its limited availability and longer duration of scan time when compared to CT, as well as the potential need for sedation in pediatric patients. To address these issues, some centers have developed a QuickBrain MRI (qbMRI) protocol that includes fast acquisition of T_2-weighted imaging sequences in 3 planes, generally completed within minutes. This protocol has gained acceptance in many centers as the current standard of care for evaluating children with shunted hydrocephalus.[9–11] Whether qbMRI could be used to evaluate children for clinically important traumatic brain injuries in the acute setting, as defined in prior research, remains unclear.[2]

1.2 | Goals of this investigation

The primary objective of this trial was to evaluate the ability of a qbMRI protocol to detect clinically important traumatic brain injuries. The secondary objective of this trial was to evaluate qbMRI in identifying radiographic traumatic brain injury.

The Bottom Line

Rapid MRI protocols offer a potential imaging modality for pediatric traumatic brain injury without the radiation exposure of traditional CT scanning. In this article, rapid MRI had a high sensitivity for detecting clinically important injuries but was limited by the small sample size and loss of follow-up.

2 | METHODS

2.1 | Study design and setting

This was a prospective study of patients less than 15 years of age at a single level 1 trauma center in Portland, Oregon from August 2017 to March 2019. This trial was registered with clinicaltrials.gov (*NCT03291964*) and approved by the institutional review board at the study site. The state of Oregon has 2 level 1 pediatric trauma centers, including the study center, that evenly divide patients based on geographic distribution within the Portland metropolitan area.

2.2 | Selection of participants

All pediatric trauma patients less than 15 years of age and their families were approached for enrollment if they had an initial ED chief complaint of head injury. Patients were then included if the clinical team obtained a head CT or if a head CT was obtained at an outside hospital prior to transfer. Patients were excluded if the head CT was obtained greater than 6 hours prior to enrollment, if our study team was unable to review outside CT imaging, if the patient had a history of intracranial surgery prior to enrollment or history of metallic implants, or if the patient was deemed to be too unstable for qbMRI by the attending physician. Patients were screened and enrolled by the ED clinical research team 7 days a week from 7 am to 11 pm. If the family elected not to undergo the qbMRI directly in the ED but were open to discussing later in the course, they were followed by the study team. Any eligible patient and family who were approached but did not consent in the ED and subsequently underwent a qbMRI for clinical care were approached for consent at the later time.

2.3 | Methods and measurements

After eligible subjects and families were consented, the attending physician ordered the study qbMRI to be done after the head CT. QbMRIs are available to the pediatric ED at all hours at our institution. The emergency physician was blinded to the radiology read of the qbMRI as it was not intended to be used for clinical care. A copy of the images was de-identified and placed in a separate review folder in the hospital's picture archiving and communication system (PACS). All images were then reviewed by a blinded, board-certified neuroradiologist. All study CT images were reviewed sequentially prior to any review of study MRIs. In addition, the images were reviewed by the neuroradiologist in a separate folder and at a different occasion from the MRI studies to limit bias. We abstracted clinical data from the electronic medical record, including: sex, age, whether patient was

transferred or presented to the study institution for initial evaluation, GCS on arrival, PICU length of stay, total hospital length of stay, endotracheal intubation (including duration in days), whether a neurosurgical procedure was performed, in-hospital mortality, the time interval (in hours) between head CT and qbMRI, time interval between qbMRI order and obtaining the MRI, and the need for anxiolysis for the study. The qbMRI protocol consisted of single-shot T_2-weighted turbo spin echo sequences acquired in axial, sagittal, and coronal planes and an axial T_2^* sequence. T_2 sequences were acquired at 4 or 5 mm thickness with 1 mm gap, echo time (TE) of 90 ms (3T) or 120 ms (1.5T), and pulse repetition time (TR) of maximum. T_2^* images were acquired at 4-mm slice thickness with 1 mm gap, TE of 13–16 ms, TR of 665–885 ms, and flip angle of 18°. All exams were performed on either Philips Achieva or Ingenia platforms at 1.5T or 3T. No intravenous contrast was administered. It was not anticipated that any sedation or anti-anxiety drugs would be needed for the imaging, but was left to the discretion of the attending physician; only medications ordered and administered within 30 minutes prior or at the time of imaging were considered anxiolysis for imaging. After a subject completed imaging in the MRI suite, their further disposition was selected by the attending physician including admission to the hospital, observation or discharge. Traumatic brain injury on neuroimaging (either CT or MRI) was defined as previously published to include:[2]

- Intracranial hemorrhage or cerebral contusion;
- Cerebral edema;
- Traumatic infarction;
- Diffuse axonal injury;
- Shear injury;
- Midline shift of intracranial contents of signs of brain herniation;
- Skull fracture depressed by at least the width of the table of the skull;
- Pneumocephalus;
- Diastasis of the skull; and
- Sinus thrombosis.

2.4 | Outcomes

The primary objective of this trial was to evaluate the ability of qbMRI to detect clinically important traumatic brain injuries. Clinically important traumatic brain injury was defined as previously described to include intubation greater than 24 hours, total hospital length of stay greater than 48 hours, undergoing a neurosurgical procedure or death.[2]

The secondary outcomes included the sensitivity of qbMRI to detect any radiographic traumatic brain injury compared to CT as the gold standard, the sensitivity and specificity of qbMRI to detect midline shift, altered ventricular size including but not limited to decreased size or distorted likely from pressure, signs of herniation and characterize the traumatic lesions as intra-axial versus extra-axial.

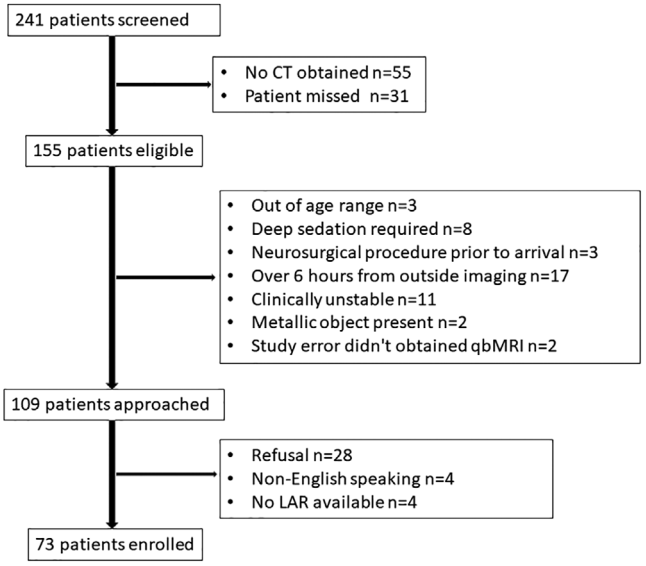

FIGURE 1 Enrollment flow diagram. CT, computed tomography; LAR, legally authorized representative; qbMRI, rapid brain magnetic resonance imaging

2.5 | Analysis

To evaluate the ability of qbMRI to detect clinically important traumatic brain injuries, we compared the diagnostic performance of qbMRI using sensitivity, and likelihood positive and negative ratios. We calculated 95% confidence intervals (CIs) for sensitivity and specificity using the Agresti-Coull method and the log method for likelihood ratios. We similarly compared the diagnostic performance of qbMRI to CT, both overall and within specific injuries. We compared the performance of qbMRI and CT both within patients with a clinically important traumatic brain injury and separately for all patients. In cases where sensitivity or specificity was 0.0% or 100.0%, we were unable to calculate the corresponding likelihood ratio. All analysis was performed in SAS 9.4 (Cary, NC), and an alpha of 0.05 was used for all calculations.

3 | RESULTS

3.1 | Characteristics of study subjects

A total of 241 patients were screened and 73 were successfully enrolled in the trial (Figure 1). Descriptive statistics are presented in Table 1. The median age was 4 years (interquartile range [IQR] = 1–10 years) and 56.2% of patients were male. The majority of patients (64.4%) had a mechanism of fall and had a mild traumatic brain injury. Approximately one-third (28.7%) of patients had a clinically important traumatic brain injuries as defined previously, and 2 patients died during their visit. The most common final diagnosis in patients with clinically important traumatic brain injuries was a subdural hematoma.

TABLE 1 Patient demographics, injury and care characteristics of included patients

	Overall, n = 73, 100%
Patient demographics, n (%)	
Gender identity at intake	
Male	41 (56.2%)
Female	32 (43.8%)
Age, median (p25–p75)	4 (1–10)
Injury characteristics, n (%)	
Mechanism	
MVC	4 (5.5%)
Fall	47 (64.4%)
Running into stationary object	2 (2.7%)
Sports related injury	3 (4.1%)
Auto versus pedestrian/bike	12 (16.4%)
Assault	1 (1.4%)
Other	4 (5.5%)
GCS	
Mild traumatic brain injury (13–15)	63 (86.3%)
Moderate traumatic brain injury (9–12)	4 (5.5%)
Severe traumatic brain injury (≤8)	6 (8.2%)
Characteristics of care, N (%)	
Total hospital length of stay (hours), median (p25–p75)	28.6 (16-50)
Pediatric ICU length of stay (hours), median (p25–p75)	0 (0–20)
Time patient was intubated (hours), median (p25–p75)	0 (0–0)
Clinically important traumatic brain injury: lesion found on CT or QB and 1 or more of the following	21 (28.7%)
Intubation greater than 24 hours	1 (1.4%)
Total length of stay greater than 48 hours	19 (26.0%)
Patient required a neurosurgical procedure	5 (5.8%)
Patient died during visit	2 (2.7%)
Facility was the first hospital this patient was seen at for this head injury	28 (38.4%)
Final diagnosis	
Epidural hematoma	5 (6.8%)
Subdural hematoma	19 (26.0%)
Brain contusion	5 (6.8%)
Subarachnoid hemorrhage	13 (17.8%)
Intraparenchymal hemorrhage/hematoma	3 (4.1%)
Depressed skull fracture	12 (16.4%)
Non-depressed skull fracture	17 (23.2%)
Concussion	9 (12.3%)
Details on the QuickBrain MRI, N(%)	
Image acquisition time (minutes: median, SD)	4.87 (1.97)
Anxiolytic used	1 (1.4%)
Time between initial head CT and QuickBrain MRI (hours), median (p25–p75)	5.6 (4–8)
Time from EPIC order entry to image acquisition (minutes), median (p25–p75)	75 (44–144)

p25–p75 = 25th percentile to 75th percentile. MVC, motor vehicle crash.

3.2 | Clinically important traumatic brain injury test characteristics

QbMRI had a sensitivity of 95.2% (95% CI = 77.3%–99.1%) and a specificity of 36.0% (95% CI = 24.1%–49.9%) to identify clinically important traumatic brain injuries, and the positive likelihood ratio was 1.5 (95% CI = 1.2–1.9) and the negative likelihood ratio was 0.1 (95% CI = 0.0–0.9) (Table 2). For identifying clinically important traumatic brain injuries, CT had a sensitivity of 100% (95% CI = 84.5%–100%) and a specificity of 32.0% (95% CI = 20.8%–45.8%) with a positive likelihood ratio of 1.5 (95% CI = 1.2–1.8) and a negative likelihood ratio of 0. Within patients with a clinically important traumatic brain injuries who had a depressed skull fracture identified by either qbMRI or CT, qbMRI had a sensitivity of 100% (95% CI = 67.6%–100%). QbMRI showed a higher sensitivity to identify intra-axial versus extra-axial injuries (100% vs 66.7%). Of all patients with a clinically important traumatic brain injuries and midline shift (identified by either CT or qbMRI), qbMRI had a sensitivity of 90% (95% CI = 48.7%–97.4%). QbMRI missed 1 patient who had a 2 mm subdural hematoma identified on CT that was questionable if present or artifact according to the clinical neurosurgery note.

3.3 | Any radiographic injury test characteristics

Lesions were found on either imaging test in 79.4% (n = 58) of all patients. Table 3 details the test characteristics of qbMRI compared to CT as the reference standard. QbMRI showed an overall sensitivity of 89.1% (95% CI = 78.2%–94.9%) and specificity of 83.3% (95% CI = 60.7%–94.1%). QbMRI had particular high sensitivity for epidural hematoma and cerebral edema/contusion while demonstrating poor sensitivity for subarachnoid hemorrhage. Table 4 details the differences in lesions seen on CT and qbMRI overall.

3.4 | MRI details

Anxiolysis was only required in 1 patient in this trial (1.4%). The median time to directly acquire the qbMRI images was 4 minutes and 52 seconds (IQR = 3 minutes 49 seconds–5 minutes 47 seconds) compared to CT image acquisition that took a median of 2 minutes and 28 seconds (IQR = 1 minute 47 seconds–4 minutes 15 seconds). The median time

TABLE 2 Sensitivity, specificity, positive, and negative likelihood ratios of qbMRI to detect clinically important traumatic brain injury

All patients	Present on CT (n)	Sensitivity (95% CI)	LR+ (95% CI)	Absent on CT (n)	Specificity (95% CI)	LR−(95% CI)
In patients with clinically significant traumatic brain injury by QB or CT						
Lesion found	21	0.952 (0.773–0.991)	NA	0	0.000 (0.000–0.730)	NA
Type						
Subdural hematoma	12	1.6 (0.5–2.6)	9	0.778 (0.453–0.937)	0.4 (−0.2–1.1)	1.6 (0.5–2.6)
Epidural hematoma	2	19.0 (2.8–128.0)	19	0.947 (0.753–0.991	0.1 (−0.1–0.2)	19.0 (2.8–128.0)
Intraparenchymal hematoma	5	0.800 (0.376–0.964)	4.4 (−3.5–12.2)	16	0.875 (0.64–0.965	0.2 (−0.1–0.4)
Subarachnoid hemorrhage	7	0.000 (0.000–0.279)	NA	14	0.857 (0.6–0.96)	1.2 (0.9–-1.4)
Skull fracture						
Non-depressed	6	0.500 (0.188–0.812)				
Depressed	8	1.000 (0.676–1.000)				
Cerebral edema/ contusion	5	1.000 (0.566–1.000)	2.7 (1.4–5.0)	16	0.625 (0.386–0.815)	NA
Subdural hygroma	1	0.000 (0.000–0.730)	NA	20	0.75 (0.531–0.888)	1.3 (1.0–1.7)
Intraventricular hemorrhage	1	1.000 (0.207–1.000)	10.0 (2.7–37.2)	20	0.9 (0.699–0.972)	NA
Diffuse axonal injury	0	NA	1.0 (0.9–1.2)	21	0.952 (0.773–0.991)	NA
Location						
Intra-axial	6	1.000 (0.610–1.000)	3.8 (1.6–8.7)	15	0.733 (0.48–0.891)	NA
Extra-axial	15	0.667 (0.417–0.848)	NA	6	1.000 (0.610–1.000)	0.3 (0.1–0.6)
Midline shift	7	0.857 (0.487–0.974)	3.7 (−0.2–7.6)	14	0.769 (0.507–0.915)	0.2 (−0.2–0.5)
Altered ventricles	1	0.000 (0.000–0.730)	NA	20	0.947 (0.760–0.990)	NA
Herniation	1	0.000 (0.000–0.730)	NA	20	1.000 (0.886–1.000)	NA

between initial head CT and qbMRI was 5.6 hours with an IQR of 4–8 hours. The median time from order placement to obtaining a qbMRI was 75 minutes (IQR = 44–144 minutes). All qbMRI tests were ordered with a T_2^* sequence (sensitive for detection of blood products); however, this sequence was obtained in only 56 subjects (76.7%). In the patients with the T_2^* sequence, 17 subjects (30.4%) had their traumatic lesion missed on standard T_2 imaging and only identified on the T_2^* sequence. It was unclear why the T_2^* sequence was not obtained in all patients that it was ordered on. It was most likely an oversight during the imaging acquisition. Figure 2 details a patient with a lesion missed on standard T_2 images but present on T_2^* sequence.

4 | LIMITATIONS

The largest limitation of this study was that qbMRI was judged in terms of ability to detect any radiographic injury against the current historical reference standard of CT imaging. However, there are instances where qbMRI may outperform CT imaging as detailed in Table 4 such as diffuse axonal injury, which may negatively affect reporting of qbMRI test characteristics. This study only had 1 radiologist review all study images, precluding assessment of inter-rater variability. Additionally, because the study radiologist was a subspecialty trained neuroradiologist practicing at an academic center, his findings may not be generalizable to other settings. CT and MRI were not performed at the same time in all patients, but instead had a median time difference of ~5 hours. We expect that any true decompensation would have manifested in patients who had growing lesions from the time of CT acquisition to qbMRI, but this was not seen. Therefore, we do not believe there were significant changes in lesion progression between the 2 imaging modalities. This study was a prospective clinical trial but did not enroll 24 hours a day and a portion of families approached declined which could have led the possibility of selection bias in this study. Last, this trial was done at a single institution with a modest sample size that precluded more narrow confidence intervals especially in older patients as the median age was 4 years. Our study population was predominately transfer patients which may inherently represent a higher acuity population than general community sites. Future studies across many centers will increase the generalizability of the results.

TABLE 3 Sensitivity, specificity, positive and negative likelihood ratios of qbMRI for detection of radiographic traumatic brain injury

All patients	Present on CT (n)	Sensitivity (95% CI)	LR+ (95% CI)	Absent on CT (n)	Specificity (95% CI)	LR−(95% CI)
Lesion found	55	0.891 (0.782–0.949)	5.3 (−0.3–11.0)	18	0.833 (0.607–0.941)	0.1 (0.0–0.2)
Type						
Subdural hematoma	20	0.650 (0.433–0.819)	2.5 (1–4.1.0)	53	0.887 (0.774–0.947)	0.2 (0.0–0.3)
Epidural hematoma	2	1.000 (0.342–1.000)	71.0 (10.1–497.1)	71	0.986 (0.925–0.998)	0 (−0.1–0.1)
Intraparenchymal hematoma	7	0.571 (0.250–0.842)	2.1 (0.3–3.8)	66	0.879 (0.779–0.937)	0.2 (0.0–0.4)
Subarachnoid hemorrhage	14	0.286 (0.117–0.547)	1.2 (0.8–1.6)	59	0.864 (0.754–0.929)	0.5 (0.0–1.0)
Skull fracture						
Non-depressed	17	0.471 (0.262–0.691)				
Depressed	11	0.818 (0.523–0.949)				
Cerebral edema/ contusion	6	1.000 (0.610–1.000)	5.6 (3.3–9.3)	67	0.821 (0.713–0.895)	NA
Subdural hygroma	2	0.500 (0.095–0.905)	1.8 (−0.7–4.3)	71	0.887 (0.793–0.942)	0.2 (−0.1–0.6)
Intraventricular hemorrhage	2	0.500 (0.095–0.905)	1.9 (−0.8–4.6)	71	0.958 (0.883–0.986)	0.1 (−0.1–0.2)
Diffuse axonal injury	0	NA	NA	73	0.945 (0.867–0.978)	NA
Location						
Intra-axial	8	1.000 (0.676–1.000)	4.1 (1.9–6.3)	46	0.667 (0.523–0.786)	NA
Extra-axial	46	0.667 (0.523–0.786)	NA	8	1.000 (0.676–1.000)	0.4 (0.3–0.6)
Midline shift	8	0.875 (0.529–0.978)	7.2 (0.9–13.5)	47	0.878 (0.755–0.944)	0.1 (−0.1–0.4)
Altered ventricles	2	0.500 (0.095–0.905)	23.5 (−33.5–80.5)	53	0.979 (0.897–0.996)	0.5 (−0.2–1.2)
Herniation	1	0.000 (0.000–0.730)	NA	72	1.000 (0.963–1.000)	NA

5 | DISCUSSION

This clinical trial found that qbMRI has excellent test characteristics with a sensitivity of over 95% for detection of clinically important traumatic brain injuries in pediatric head trauma. This is of particular importance in the pediatric population where the risk of radiation-induced malignancy is higher than adults.[7] Therefore any test that has the ability to accurately identify intracranial injuries while eliminating radiation risk may be very useful for traumatic brain injury evaluation in the pediatric and general ED. This study shows qbMRI could serve as an alternative first-line imaging test in pediatric patients who are clinically stable.

One recent study of almost 400 children undergoing a qbMRI protocol found that all patients were able to complete the imaging in a median scan time of 4.4 minutes. QbMRI has also become the standard of care for interval imaging of pediatric head trauma patients housed in the pediatric intensive care unit at our center. A retrospective study performed at our institution found follow-up qbMRI to have a sensitivity of 100% in detecting clinically important traumatic brain injuries (clinically important traumatic brain injuries) evident on initial CT scanning.[12] The significance of the retrospective study for a decision to adopt qbMRI as the primary imaging modality in pediatric traumatic brain injury was limited by the inherent delay between the primary CT and secondary qbMRI imaging in that study. Due to temporal delay between initial CT and subsequent follow-up qbMRI, the ability to use MRI as the primary diagnostic test remains unclear.

One concern about the use of qbMRI for the initial evaluation of head trauma in the ED is the availability of qbMRI and impact on ED throughput. Recent studies have found that MRI use in the ED has increased over time and the majority of centers with a neurosurgeon on staff have the ability to obtain MRI in ED patients.[13,14] An additional consideration for practical use is the time it takes to get an MRI as well as the ability of a child to tolerate the test. Our study found that ~1% of patients needed some form of anxiolysis to complete the qbMRI. This rate is less than previous reports of anxiolysis use in qbMRI and head CT for pediatric patients.[11] This is most likely due to the fast acquisition of qbMRI compared to standard brain MRI. Recent studies of scan times for similar qbMRI protocols found that patients reach the MR scanner from the ED within 30 minutes or order placement.[12,15] Our study showed that most qbMRI studies were obtained within ~75 minutes of ordering, but many in less than 45 minutes.

Quick brain MRI may not be the optimal imaging test for clinically unstable cranial trauma patients with low or declining GCS if CT imaging is more rapidly available in the clinical setting. The most common

TABLE 4 Difference in lesions seen on CT and QbMRI

	Present in either CT or QB imaging n (%)	Present on CT n (%)	Missed by CT, found by QB n (%)	Present on QB n (%)	Missed by QB, found by CT n (%)
All patients					
Lesion found	58	55 (94.8)	3 (5.2)	52 (89.7)	6 (10.3)
Type					
Subdural hematoma	26	20 (76.9)	6 (23.1)	19 (73.1)	7 (26.9)
Epidural hematoma	3	2 (66.7)	1 (33.3)	3 (100.0)	0 (0.0)
Intraparenchymal hematoma	15	7 (46.7)	8 (53.3)	12 (80.0)	3 (20.0)
Subarachnoid hemorrhage	22	14 (63.6)	8 (36.4)	12 (54.5)	10 (45.5)
Skull fracture					
Non-depressed	17 (85.0)	17 (85.0)	3 (15.0)	8 (40.0)	12 (60.0)
Depressed	12 (100.0)	11 (91.7)	1 (8.3)	10 (83.3)	2 (16.7)
Cerebral edema/contusion	18	6 (33.3)	12 (66.7)	18 (100.0)	0 (0.0)
Subdural hygroma	10	2 (20.0)	8 (80.0)	9 (90.0)	1 (10.0)
Intraventricular hemorrhage	5	2 (40.0)	3 (60.0)	4 (80.0)	1 (20.0)
Diffuse axonal injury	4	0 (0.0)	4 (100.0)	4 (100.0)	0 (0.0)
Location					
Intra-axial	21	7 (33.3)	14 (66.7)	21 (100)	0 (0.0)
Extra-axial	49	46 (93.9)	3 (6.1)	31 (63.3)	18 (36.7)
Midline shift	13	8 (61.5)	5 (38.5)	12 (92.3)	1 (7.7)
Altered ventricles	3	2 (66.7)	1 (33.3)	2 (66.7)	1 (33.3)
Herniation	1	1 (100.0)	0 (0.0)	0 (0.0)	1 (100.0)
In patients with clinically significant traumatic brain injury					
Lesion found	21	21 ((100.0)	0 (0.0)	20 (95.2)	1 (4.8)
Type					
Subdural hematoma	14	12 (85.7)	2 (14.3)	8 (57.1)	6 (42.9)
Epidural hematoma	3	2 (66.7)	1 (33.3)	3 (100.0)	0 (0.0)
Intraparenchymal hematoma	7	5 (71.4)	2 (28.6)	6 (85.7)	1 (14.3)
Subarachnoid hemorrhage	9	7 (77.8)	2 (22.2)	2 (22.2)	7 (77.8)
Skull fracture					
Non-depressed	6 (100.0)	6 (100.0)	0 (0.0)	3 (50.0)	3 (50.0)
Depressed	9 (100.0)	8 (88.9)	1 (11.1)	9 (100.0)	0 (0.0)
Cerebral edema/contusion	11	5 (45.5)	6 (54.5)	11 (100.0)	0 (0.0)
Subdural hygroma	6	1 (16.7)	5 (83.3)	5 (83.3)	1 (16.7)
Intraventricular hemorrhage	3	1 (33.3)	2 (66.7)	3 (100.0)	0 (0.0)
Diffuse axonal injury	1	0 (0.0)	1 (100.0)	1 (100.0)	0 (0.0)
Location					
Intra-axial	10	6 (60.0)	4 (40.0)	10 (100.0)	0 (0.0)
Extra-axial	15	15 (100.0)	0 (0.0)	10 (66.7)	5 (33.3)
Midline shift	10	7 (70.0)	3 (30.0)	9 (90.0)	1 (10.0)
Altered ventricles	2	1 (50.0)	1 (50.0)	1 (50.0)	1 (50.0)
Herniation	1	1 (100.0)	0 (0.0)	0 (0.0)	1 (100.0)

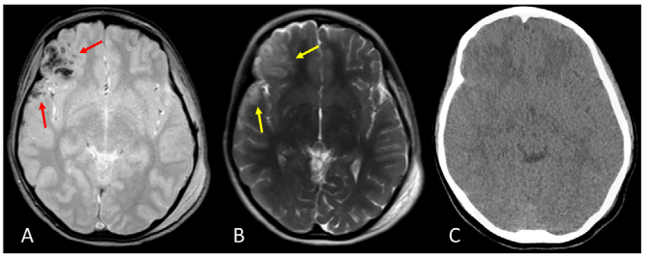

FIGURE 2 Cerebral hemorrhagic contusion on qbMRI. T_2^* image (A) depicts numerous foci of susceptibility in the inferolateral portion of the right frontal lobe and adjacent right temporal lobe (arrows), representing small foci of intraparenchymal hemorrhage. T_2 image (B) depicts hyperintense signal abnormality representing cerebral edema associated with the hemorrhagic contusions. Non-contrast axial CT image (A) through the same level of the brain appears normal.

reported use of qbMRI is for evaluation of potential CSF shunt failure in patients with hydrocephalus, who average 8.5 CT scans during childhood.[16] Because CT is the most common imaging modality to evaluate for potential traumatic brain injury, head trauma patients may also benefit from qbMRI rather than CT imaging. Although patients undergoing qbMRI rather than CT imaging may stay up to 41 minutes longer in the ED,[17] their imaging time with qbMRI image acquisition only took approximately 2.5 minutes longer than CT.[15] Such delays appear reasonable in patients with mild traumatic brain injury who constituted the majority of patients in our study.

This study supports a growing literature describing the use of qbMRI for pediatric trauma indications.[15,17,18] However, our study was unique in a number of ways including a higher population of patients with clinically important traumatic brain injuries which is critical to ensure this imaging modality is identifying the patients at highest risk for morbidity and mortality, a primary outcome focused on clinically important traumatic brain injuries, broader age inclusion than past studies, and being a separate research institute and geographically removed from prior studies. One previous study of qbMRI for head trauma in children less than 6 years of age reported a 92.8% sensitivity for traumatic brain injury.[15] MRI has been shown in various populations to be very sensitive at detecting intracranial hemorrhage.[19] The ability of various additional sequences to the standard MRI increases the ability to detect blood in particular.[20] T_2^* is a specific sequence called gradient recall echo that is affected by the oxygenation state of hemoglobin and whether red blood cell lysis has occurred. When red blood cells are lysed or a blood clot is forming, it affects the magnetic field resulting in signal change of the imaging.[21] In various studies, including at our institution, MR sequence choice was important to sensitivity.[15,22,23] In the present study, for example, addition of the T_2^* sequence disclosed intracranial lesions not identified by the standard qbMRI sequence in approximately one-third of patients. Even with this additional sequence, total scan time remained under 5 minutes in most patients.

This imaging modality has the potential to decrease the radiation risk that is often discussed with parents in the ED surrounding neuroimaging. This should not encourage providers to image more patients however. The rigorous clinical decisions rules developed by the Pediatric Emergency Care Applied Research Network (PECARN) should be used in the patient to first identify children at very low risk and relatively definitively not in need for neuroimaging.[2] Yet, studies have shown that even after their implementation CT use for pediatric head trauma remains higher than expected.[6] QbMRI has the potential to eliminate a significant risk for pediatric patients who fall outside the PECARN head injury rules.

In the present study, qbMRI has a 95.2% sensitivity to detect clinically important traumatic brain injuries in children presenting with head trauma. Table 2 details the clinically important traumatic brain injuries seen on qbMRI. CT imaging found all clinically important traumatic brain injuries, while qbMRI missed one. QbMRI missed a 2-mm subdural hematoma that was identified on CT. This patient was a 7-year-old involved in a high speed motor vehicle collision. She was noted to have a 2-mm subdural hematoma on CT that neurosurgery questioned if it was actually present. She had a prolonged hospital stay due to rib and pelvic fractures. She was discharged in normal neurologic condition. Both the present and previous studies have found decreased sensitivity using qbMRI for skull fractures and traumatic subarachnoid hemorrhage.[15] Neither of these conditions, however, commonly require any specific treatment or transfer to a higher level of care.[24] One concern of qbMRI may be the evaluation of bone. However, qbMRI showed a sensitivity of 100% in this study for identifying depressed skull fractures. Other clinically relevant findings driving specific clinical indications, such as brain edema, parenchymal hemorrhage, and mass effect, are exquisitely demonstrated on qbMRI.

These results are encouraging to the possibility of qbMRI to become a viable alternative to head CT as initial neuroimaging for pediatric head trauma in the ED. Larger, multi-institutional studies of qbMRI as a potential for the initial imaging of head trauma in children with GCS greater than 12 are needed to further support these findings.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

DCS, CDN, and MH conceived the study. DCS, SR, CDN, DP, MH, NRS, and MAJ designed the study. Data collection and analysis were performed by DCS, DP, and AL. DCS drafted the manuscript and critical review was provided by DP, CDN, NRS, SR, AL, MAJ, and MH with final approval of the manuscript. DCS takes responsibility for the paper as a whole.

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