

Feasibility and Accuracy of Fast MRI Versus CT for Traumatic Brain Injury in Young Children

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abstract

BACKGROUND: Computed tomography (CT) is commonly used for children when there is concern for traumatic brain injury (TBI) and is a significant source of ionizing radiation. Our objective was to determine the feasibility and accuracy of fast MRI (motion-tolerant MRI sequences performed without sedation) in young children.

METHODS: In this prospective cohort study, we attempted fast MRI in children <6 years old who had head CT performed and were seen in the emergency department of a single, level 1 pediatric trauma center. Fast MRI sequences included 3T axial and sagittal T2 single-shot turbo spin echo, axial T1 turbo field echo, axial fluid-attenuated inversion recovery, axial gradient echo, and axial diffusion-weighted single-shot turbo spin echo planar imaging. Feasibility was assessed by completion rate and imaging time. Fast MRI accuracy was measured against CT findings of TBI, including skull fracture, intracranial hemorrhage, or parenchymal injury.

RESULTS: Among 299 participants, fast MRI was available and attempted in 225 (75%) and completed in 223 (99%). Median imaging time was 59 seconds (interquartile range 52–78) for CT and 365 seconds (interquartile range 340–392) for fast MRI. TBI was identified by CT in 111 (50%) participants, including 81 skull fractures, 27 subdural hematomas, 24 subarachnoid hemorrhages, and 35 other injuries. Fast MRI identified TBI in 103 of these (sensitivity 92.8%; 95% confidence interval 86.3–96.8), missing 6 participants with isolated skull fractures and 2 with subarachnoid hemorrhage.

CONCLUSIONS: Fast MRI is feasible and accurate relative to CT in clinically stable children with concern for TBI.



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WHAT'S KNOWN ON THIS SUBJECT: Computed tomography is an important source of ionizing radiation exposure for children when there is concern for traumatic brain injury.

WHAT THIS STUDY ADDS: Fast MRI without sedation is a feasible alternative to computed tomography, with 99% imaging success and median imaging times of ~6 minutes. Sensitivity for radiographic traumatic brain injury was 93%; missed injuries included 6 isolated skull fractures and 2 isolated subarachnoid hemorrhages.

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Traumatic brain injury (TBI) is a common reason for children to seek emergency care, resulting in ~600 000 to 1 600 000 emergency department (ED) visits in the United States annually.^{1,2} Despite a relatively low incidence of clinically significant injury in these children, 20% to 70% undergo computed tomography (CT), exposing them to ionizing radiation and increased risk of cancer.^{3–6} Clinical decision rules can identify some children in whom CT can be avoided, with 1 well-validated decision rule having the potential to decrease CT use by 24%.⁷ However, this decision rule has not significantly decreased CT use.⁶ Even with perfect implementation, the rule would not prevent imaging for the majority of children, and it cannot be used for children with concern for abusive head trauma in whom clinical history may be limited, and where imaging may identify abusive injuries that are not otherwise clinically significant.⁸

Although MRI does not expose children to ionizing radiation, conventional MRI requires the child to remain motionless for several minutes and usually requires sedation. Sedation limits clinical feasibility and may be associated with mild cognitive injury.^{9,10} Fast MRI uses abbreviated, motion-tolerant sequences to complete neuroimaging without sedation and has been used to eliminate radiation exposure in children with shunted hydrocephalus.¹¹ Some guidelines suggest that fast MRI could be used in young children with TBI, but it has not been shown to be as feasible or accurate as the current criterion standard of CT.¹² Although small, retrospective comparisons of CT and fast MRI have reported limited sensitivity for fast MRI, most did not routinely use sequences that are most sensitive for blood products (eg, gradient recall echo [GRE] and susceptibility weighted imaging).^{13–18} Our objective was to prospectively determine the feasibility and accuracy

of fast MRI with GRE to identify radiographically apparent TBI in children <6 years old.

METHODS

We conducted a prospective cohort trial in which all participants received both CT and fast MRI. The study was approved by the Colorado Multi-Institutional Review Board. Methods comply with the Standards for Reporting Diagnostic Accuracy statement.¹⁹

Participants and Setting

Participants were recruited between June 2, 2015, and June 4, 2018, from the ED of a level 1 pediatric trauma center with an annual census of 75 000 visits, including ~3000 interfacility transfers. Research assistants staffed the ED 7 days per week from 7 AM to midnight and confirmed inclusion criteria with the child's attending physician before approaching the family for consent. Children were eligible to participate if they were <6 years (72 months) old and underwent head CT during their emergency care, including at another institution. Children were excluded if they had the following: contraindication to MRI (eg, pacemaker or implanted metal); known previous diagnosis of TBI, structural brain lesion, or previous brain surgery; previous study participation; or the attending physician deemed them clinically unstable.

Enrolled participants received fast MRI as soon as possible on the basis of clinical availability with a goal to obtain imaging within 24 hours of the CT scan.

CT and Fast MRI Imaging

CT technique varied for children who underwent CT before being transferred. At our center, CTs were performed by using a Siemens Somatom Definition Flash CT scanner with routine three-dimensional reconstruction of the

skull and were interpreted by pediatric radiologists without access to fast MRI results. We used the attending radiologist's clinical interpretation of the CT scan. A pediatric radiologist (N.V.S., D.M.M., or A.L.M.) reviewed and provided the final interpretation of CT scans from referring institutions.

Fast MRI was performed between 7 AM and 9 PM by using 1 of 2 Philips Ingenia 3T scanners. Sequences included the following: axial and sagittal T2 single-shot turbo spin echo, axial T1 turbo field echo, axial fluid-attenuated inversion recovery (FLAIR) single-shot turbo spin echo, axial gradient echo, and axial diffusion-weighted single-shot turbo spin echo planar imaging (Supplemental Table 3). Feeding, swaddling, or standard restraint methods (vacuum beanbag positioners, foam sound shields, or parental reassurance) were used for fast MRI; no additional sedation was given. Children who had undergone sedation for other clinical purposes were excluded from feasibility analyses but were included in accuracy analyses. MRI sequences were repeated as needed for motion according to normal clinical practice. Fast MRI was aborted and coded as an imaging failure if imaging could not be completed within 30 minutes or at the request of the patient's family or any care team provider. For clinical care, fast MRIs were interpreted at the time the study was performed by pediatric radiologists with access to CT images and all clinical data.

For research purposes, fast MRIs were independently interpreted by 2 of 3 pediatric radiologists (N.V.S., D.M.M., or A.L.M.) masked to all other clinical and imaging results and the initial clinical interpretations. Interrater reliability was compared by using Cohen's κ , and disagreements were resolved by consensus of all 3 radiologists.

Data Analysis

Feasibility was determined by using 2 main outcomes, completion rate (defined as the proportion of studies that were successfully completed) and imaging time (defined as the time from first image of first sequence to last image of last sequence, including any repeated sequences), and was reported by CT and MRI scanners. To determine accuracy, our main outcome measure was the presence of radiographically apparent TBI (yes, no, or unsure) using the CT as the criterion standard. TBI was defined to include any intracranial hemorrhage (subdural, subarachnoid, epidural, parenchymal, or intraventricular), parenchymal contusion, pneumocephalus, shear or diffuse axonal injury, or skull fracture. Despite their infrequent clinical significance, we included isolated skull fractures in our definition of radiographically apparent TBI because identifying skull fractures may have significance for recognition of abusive head trauma and because skull fractures have been reported to be less easily visualized by MRI than CT.²⁰ Isolated scalp or soft tissue swelling was not considered radiographically apparent TBI.

We report descriptive data, including proportions, sensitivity, and specificity, as well as the median and interquartile range (IQR) of imaging time for CT and MRI. Selected images from cases in which CT and MRI were discordant are reported in detail.

Power and Sample Size

Because the risks from sedation or ionizing radiation are outweighed by the risk from missed TBI, a clinically useful fast MRI requires high (>95%) sensitivity. We planned to enroll 110 participants with radiographic TBI on CT such that the 95% confidence interval (CI) for sensitivity would be 96.7% to 100.0% if fast MRI identified all radiographic TBI.

RESULTS

Participant Characteristics

During the study period, 1179 ED patients <72 months old had a head CT performed or uploaded from a referring hospital. Of these, 299 (25%) consented to participate, and fast MRI was attempted in 225 (75%; Fig 1). In the large majority of cases in which fast MRI was not attempted in consenting participants (88%), this was because fast MRI was not available before the patient was discharged. In 5 cases, caregivers withdrew consent because the patient was sleeping or crying, the patient would have needed their earrings removed, or because they changed their minds (2 cases).

Participant characteristics are shown in Table 1. The median age of participants was 12.6 months (IQR 4.7–32.6), with slight majorities being of male sex and transferred from another institution. Just over one-quarter were evaluated by the child protection team for concerns of physical abuse, and one-sixth were

ultimately reported to child protective services. Clinically significant TBI was identified in 31 participants (14%) using the Pediatric Emergency Care Applied Research Network (PECARN) standard for clinical significance (death, neurosurgical intervention, intubation >24 hours, or admission for TBI for >2 midnights).⁷

For participants with completed fast MRI, median interval between performing CT and fast MRI was 243 minutes (IQR 59–664). Twelve participants underwent fast MRI 6 to 106 minutes before CT.

Feasibility

Of 225 participants for whom fast MRI was attempted, it was completed in 223 (99%). In 1 case, the fast MRI could not be completed because the child was moving, and in the other, parents requested that the study be stopped because the child was crying.

Although no participants had undergone sedation to facilitate the fast MRI, 8 participants were sedated for other clinical reasons (usually

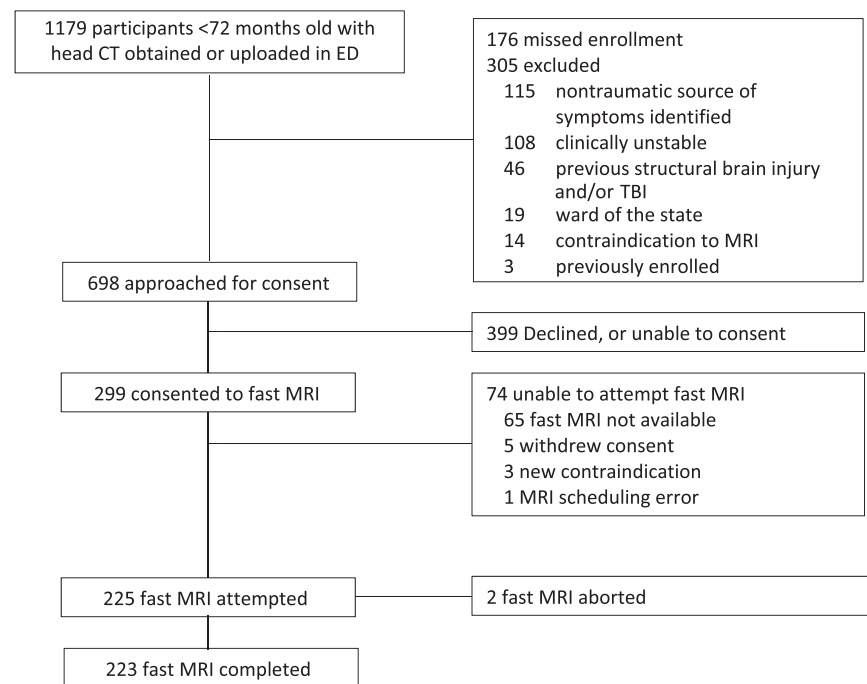


FIGURE 1
Patient flow.

TABLE 1 Patient Characteristics

	All Participants (<i>N</i> = 299), <i>n</i> (%)	Fast MRI Attempted (<i>n</i> = 225), <i>n</i> (%)	Fast MRI Not Attempted (<i>n</i> = 74), <i>n</i> (%)
Male sex	188 (63)	137 (61)	51 (69)
Age, mo			
0–6	89 (30)	72 (32)	17 (23)
6–12	59 (20)	46 (20)	13 (18)
12–24	43 (14)	29 (13)	14 (19)
24–36	40 (13)	27 (12)	13 (18)
36–48	17 (6)	11 (5)	6 (8)
48–60	33 (11)	25 (11)	8 (11)
60–72	18 (6)	15 (7)	3 (4)
Race			
White	212 (71)	157 (70)	55 (74)
African American	17 (6)	15 (7)	2 (3)
Hawaiian and/or Pacific Islander	1 (0)	1 (0)	0 (0)
American Indian and/or Alaskan native	2 (1)	1 (0)	1 (1)
Unknown	38 (13)	25 (11)	13 (18)
>1 race	29 (10)	26 (12)	3 (4)
Hispanic ethnicity	82 (27)	58 (26)	24 (32)
Unknown or not reported	16 (5)	12 (5)	4 (5)
Insurance type			
Public	180 (60)	134 (60)	46 (62)
Private	100 (33)	76 (34)	24 (32)
None or self-pay	19 (6)	15 (7)	4 (5)
Initial GCS score			
15	266 (89)	201 (89)	65 (88)
14	12 (4)	8 (4)	4 (5)
13	8 (3)	5 (2)	3 (4)
3–12	13 (4)	11 (5)	2 (3)
Transferred	169 (57)	127 (56)	42 (57)
CPT consult	74 (25)	59 (26)	15 (20)
CPS report filed	47 (16)	36 (16)	11 (15)
Injuries identified by CT	137 (46)	111 (49)	26 (35)
Skull fracture	102 (34)	81 (36)	21 (28)
Isolated	56 (19)	42 (19)	14 (19)
Nonisolated	47 (16)	40 (18)	7 (9)
Subdural hematoma	31 (10)	27 (12)	4 (5)
Subarachnoid hemorrhage	30 (10)	24 (11)	6 (8)
Extraaxial hemorrhage	21 (7)	17 (8)	4 (5)
Epidural hematoma	6 (2)	6 (3)	0 (0)
Other	12 (4)	12 (5)	0 (0)

Extraaxial hemorrhage refers to hemorrhages that could not clearly be defined as subdural, subarachnoid, or epidural on CT. Other injuries included pneumocephalus (*n* = 6), cerebral contusions (*n* = 3), intraventricular hemorrhage (*n* = 2), and 1 case of cerebral edema. Injuries do not sum to 111 because some children had multiple injuries. GCS, Glasgow Coma Scale; CPS, Child Protective Services; CPT, Child Protection Team.

because a conventional MRI was ordered to coincide with the fast MRI), and these participants were excluded from feasibility outcomes. Among 215 unsedated participants, median time to complete imaging was 6 minutes and 5 seconds (IQR 5 minutes and 40 seconds to 6 minutes and 32 seconds), which was longer than the median for CT of 59 seconds (IQR 52–78).

Accuracy

Interrater reliability for radiologists determining the presence of radiographic traumatic injury was good (96% agreement; $\kappa = 0.93$). Among the 223 participants who completed fast MRI, CT identified radiographic TBI in 111 (50%), with the most common injuries being skull fracture, subdural hematoma, and subarachnoid hemorrhage (Table 1).

Using CT as the criterion standard, fast MRI had 92.8% sensitivity (95% CI 86.3%–96.8%) and 96.2% specificity (95% CI 90.5%–99.0%; Table 2). Of the 8 cases for which radiographic TBI visible on CT was missed by fast MRI, 6 cases had isolated, linear, nondepressed skull fractures, and 2 had isolated subarachnoid hemorrhage (Fig 2).

Ultimately, 5 cases in which TBI was identified by fast MRI and not by CT were determined to represent real injuries identified by fast MRI and missed by CT (Fig 3). Injuries missed by CT included subdural hematomas (*n* = 3), parenchymal contusions (*n* = 2), and 1 subarachnoid hemorrhage (1 child had both subdural hematoma and contusion).

In 4 cases, CT raised concern for hypodense subdural hematomas but could not distinguish these from enlarged subarachnoid spaces. In all these cases, fast MRI was felt to definitively exclude subdural hematoma. In 1 case, CT was interpreted as indeterminate for subarachnoid hemorrhage, and fast MRI was unable to definitively identify or exclude TBI. Selected images from all discordant cases are shown in Supplemental Figs 4 through 21.

None of the participants whose CT and fast MRI results were discordant required neurosurgical intervention. One case (in which subarachnoid hemorrhage was identified by CT but not by fast MRI) met PECARN criteria for clinically significant TBI because the child was admitted to the hospital for >2 midnights. Fast MRI decreased the perceived likelihood of abuse in some cases when CT was unable to distinguish enlarged subarachnoid spaces from subdural hematomas.

Discordant cases were not significantly more likely among the 23 participants with initial Glasgow Coma Scale score <15. Twenty-one (91%) had concordant results (9 with radiographic TBI and 12 without).

TABLE 2 Radiographic TBI by CT and Fast MRI

Fast MRI	CT			Total
	Yes	Equivocal	No	
Yes	103	1	4	108
Equivocal	2	1	0	3
No	6	5	101	112
Total	111	7	105	223

The 2 participants with discordant results included 1 contusion identified by fast MRI but not CT (Supplemental Fig 14) and 1 CT that raised concern for thin subdural hematomas that were excluded by fast MRI (Supplemental Fig 18).

Of the MRI sequences used, the most likely to identify TBI were GRE and T2 single-shot turbo spin echo, which identified signs of TBI in 94 and 88 participants, respectively. The sequences least likely to identify injury were the diffusion-weighted and T1 sequences, which identified injury in only 22 and 39 participants, respectively.

Fast MRI also identified 7 cases with clinically significant nontraumatic

findings, including enlarged vestibular aqueducts related to hearing loss, Chiari malformations (2 participants), subdural empyema, retrocerebellar epidermoid cyst, and demyelinating lesions.

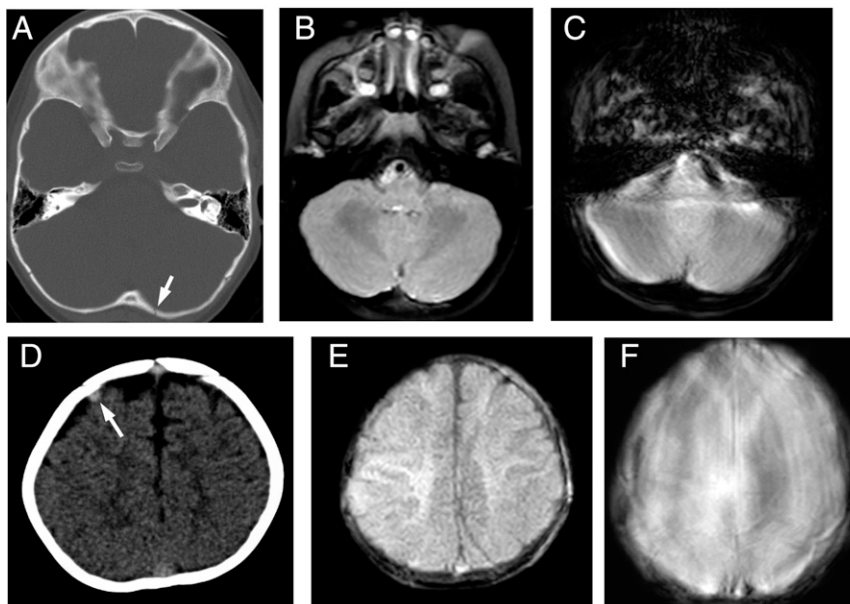
DISCUSSION

These results suggest that fast MRI is a reasonable alternative to CT with the potential to eliminate ionizing radiation exposure for thousands of children each year. The ability to complete imaging in ~6 minutes, without the need for anesthesia or sedation, suggests that fast MRI is appropriate even in acute settings, where patient throughput is a priority. The availability of

a low-risk imaging modality sensitive to changes in the brain parenchyma could advance brain injury research by allowing serial imaging for young children with minor TBI. This could improve understanding of the physiologic processes underlying “secondary brain injury,” wherein tissue damage continues after the initial trauma.

Although the sensitivity of fast MRI did not meet our prespecified threshold, we feel that the benefit of avoiding radiation exposure outweighs the concern for missed injury. No dose of radiation is completely safe, and median radiation exposure from head CT for children <5 years old is ~2.6 mSv, equivalent to several months of background radiation.^{4,21} The majority of injuries missed by fast MRI were isolated, linear, nondepressed skull fractures. In the absence of associated brain injury or intracranial bleeding, skull fractures are rarely treated and generally do not require hospital admission.^{20,22} Isolated, simple skull fractures can occur with relatively minor trauma, or from birth, and are uncommonly significant in abuse recognition.²³ Furthermore, skull fractures are likely to be identified by skull radiograph or skeletal survey, which is recommended in all young children when there is concern for abuse.^{23–26} In our sample, none of the cases with missed skull fractures had concern for abuse, and none had a skeletal survey. Complex skull fractures (ie, fractures with substantial depression, diastasis, or multiple fracture lines or those that cross sutures) that are more important in abuse recognition are less likely to be missed by fast MRI or skeletal survey. Although fast MRI missed 2 small subarachnoid hemorrhages, it did identify 5 children with TBI missed by CT (including 1 with subarachnoid hemorrhage) and improved evaluation of the extraaxial space.

Our results suggest that availability of fast MRI should be increased, perhaps

**FIGURE 2**

Injuries missed by fast MRI. A, Occipital skull fracture visible by CT. B, Occipital skull fracture not apparent by fast MRI. C, Occipital skull fracture not apparent by fast MRI. D, Right-parietal subarachnoid hemorrhage. E, Right-parietal subarachnoid hemorrhage not shown by fast MRI. F, Right-parietal subarachnoid hemorrhage not shown by fast MRI. Additional images and case summaries are available in the Supplemental Information.

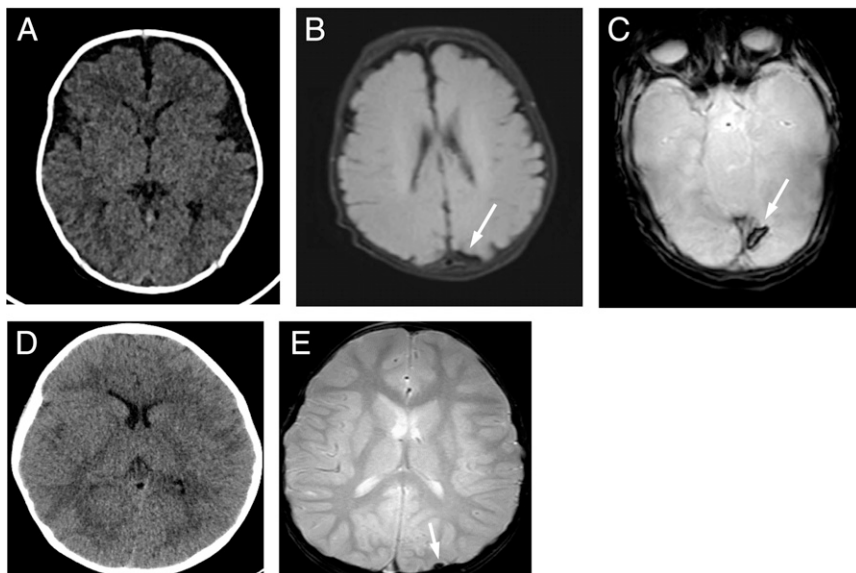


FIGURE 3

Injuries missed by CT. A, A 1-month-old who presented with a boggy scalp hematoma and no history of trauma. A, CT result was negative. B, Fast MRI identified a small occipital subdural hematoma. C, Fast MRI identified a contusion. D, A 4-year-old boy was transferred to our institution because of persistently altered mental status (grogginess) after a fall down stairs despite a negative head CT result. E, Fast MRI identified a small, posterior subarachnoid hemorrhage.

by increased staffing for existing scanners or by improving regional referral protocols. Even at our referral center, fast MRI was not available for approximately one-quarter of consenting participants because of a lack of overnight staffing. Adding significant numbers of patients with trauma to busy MRI scanners without increased capacity could result in significant imaging delays, obviating the benefits of short imaging times and high completion rates.

Imaging duration was significantly longer (~5 minutes) for fast MRI than for CT, and this did not include the time needed for MRI screening, transport, positioning, substitution of MRI-compatible equipment, and immobilization, each of which can affect MRI availability and the time a patient is away from medical supervision. We feel that all these delays will be most significant for patients with severe TBI, or polytrauma, who are more likely to require emergent interventions or complex medical equipment.

There is a risk that a feasible, low-risk imaging alternative may inappropriately increase imaging use. Even without the risks of radiation, avoidable imaging still results in unnecessary cost and may identify worrisome but clinically irrelevant incidental findings. We recommend using the PECARN rule, coupled in some cases with a reasonable period of observation, to identify children at low risk of clinically significant brain injury, for whom any imaging (CT or MRI) can safely be avoided.^{7,27}

Within our cohort, the GRE and T2 sequences were the most likely to identify radiographic TBI. Although diffusion-weighted imaging (DWI) identified relatively fewer findings, it could be more important in cohorts with higher rates of ischemia or cytotoxic edema, which often develops in the subacute phase of injury.²⁸

These data stand in distinction to 2 studies concluding that fast MRI was insensitive for TBI.^{17,18} We identified 3 potential reasons for the difference. First, our fast MRI protocol included GRE sequences, which are sensitive

for blood products.^{16,29} Young et al,¹³ who also used GRE sequences, found comparable sensitivity for CT and fast MRI for all injuries except skull fractures. Second, our study was performed at a busy children's hospital with technologists who are experienced in performing unsedated examinations in young patients. Finally, we exclusively used newer 3T scanners, with which susceptibility effects indicating hemorrhage are greater than with 1.5T devices.

One previous study of fast MRI feasibility suggested that fast MRI resulted in longer imaging delays and increased length of stay.²⁹ Given the short imaging time, we feel that these parameters are likely to be related to scanner availability and transport times. Because all participants underwent clinical CT before enrollment, we cannot directly test whether fast MRI increased ED length of stay.

Software enhancements can improve fast MRI speed and feasibility even further.³⁰ Decreased imaging time improves clinical feasibility and may improve image quality by decreasing opportunities for motion.

These data are subject to important limitations. All imaging was conducted at a busy center, by using newer 3T scanners, with experienced technicians and pediatric radiologists. Feasibility may be worse in centers with smaller volumes of pediatric patients, and accuracy may be decreased with 1.5T scanners or with less experienced radiologists, and these data should be validated in other settings before widespread uptake. Because different MRI manufacturers use different (sometimes proprietary) imaging sequences with different sensitivity and duration, feasibility and accuracy could be affected by using other MRI scanners.

Subjectively, radiologists felt that identification of skull fractures became easier over time with experience comparing CT with fast MRI. We recommend that fast MRI

implementation begin with children who require repeat imaging for TBI identified by CT to provide a training period in which traumatic injuries can be compared on the 2 modalities.

Image quality varied between scans, especially because more than half of CT scans were performed at various outside institutions, and only 28% of these had three-dimensional reformatting for skull films. This could have artificially increased the measured accuracy of fast MRI if CT motion produced false-negative CT scan results. Imaging time and accuracy will be affected by willingness to repeat MRI sequences affected by motion (Supplemental Figs 10 and 11).

We excluded patients with clinically unstable injuries to ensure patient safety and informed consent. The large proportion of participants with significant delays due to transfer from other institutions further biased toward clinical

stability. Therefore, our results cannot be generalized to clinically unstable injuries. Longer imaging time and the need for other CT imaging are also relative contraindications to using fast MRI in unstable patients, although clinically unstable injuries, especially those with mass effect, are more likely to be radiographically apparent.

Finally, it is possible that imaging findings changed in the interval between CT and fast MRI. Although our interval was relatively short, it is possible that some findings became more or less apparent if pathologic blood was redistributed between imaging studies.^{17,18}

CONCLUSIONS

Fast MRI is a reasonable alternative to CT to identify radiographically evident TBI in clinically stable children.

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ABBREVIATIONS

CI: confidence interval
CT: computed tomography
DWI: diffusion-weighted imaging
ED: emergency department
FLAIR: fluid-attenuated inversion recovery
GRE: gradient recall echo
IQR: interquartile range
PECARN: Pediatric Emergency Care Applied Research Network
TBI: traumatic brain injury

Deidentified individual participant data (including data dictionaries) will be made available in addition to study protocols, the statistical analysis plan, and the informed consent form. The data will be made available 12 months after publication to researchers who provide a methodologically sound proposal for use in achieving the goals of the approved proposal. Proposals should be submitted to daniel.lindberg@cuanschutz.edu.

This trial has been registered at www.clinicaltrials.gov (identifier NCT02392975).

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