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CONCEPTS

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Emergency department implementation of abbreviated magnetic resonance imaging for pediatric traumatic brain injury

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Abstract

Pediatric head injury is a common presenting complaint in the emergency department (ED), often requiring neuroimaging or ED observation for diagnosis. However, the traditional diagnostic neuroimaging modality, head computed tomography (CT), is associated with radiation exposure while prolonged ED observation impacts patient flow and resource utilization. Recent scientific literature supports abbreviated, or focused and shorter, brain magnetic resonance imaging (MRI) as a feasible and accurate diagnostic alternative to CT for traumatic brain injury. However, this is a relatively new application and its use is not widespread. The aims of this review are to describe the science and applications of abbreviated brain MRI and report a model protocol's development and ED implementation in the evaluation of children with head injury for replication in other institutions.

KEYWORDS

head injury, pediatrics, traumatic brain injury, trauma

1 | INTRODUCTION

1.1 | Background

Abbreviated magnetic resonance imaging (MRI), often termed "fast MRI" or "quick MRI," represents a focused and shortened MRI protocol used to image an area of the body, often in less than 10 min. MRIs use magnetic fields to align the body's molecules resulting in signal emission when stimulated by radio waves. These signals result in radiologic images.[1] Different tissues emit varying energies and have different times of re-alignment, presenting contrasting types of images for interpretation. A specific series of these image-types, or sequences, comprise a protocol examining an area of the body.

Advances in MRI image acquisition, reconstruction, and denoising have allowed for the development and refinement of imaging sequences. Historically, these refined sequences were added to a traditional protocol, creating lengthy imaging. However, trends in patient-centered radiology, quality improvement, and patient satisfaction support culling extraneous sequence clips to focus on the area and pathology of interest resulting in the abbreviated MRI.[2]

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Abbreviated MRIs reduce table-time, image acquisition time, and image interpretation times by eliminating redundant or irrelevant sequences in specific disease processes.[3] Abbreviated MRIs are more and more commonly used to image the abdomen including the appendix, prostate, breast, shoulder, brain, and lungs over the last 2 decades.[3–6]

The Bottom Line
Abbreviated MRI may be feasibly implemented in emergency departments to aid in the evaluation of children with head trauma.

1.2 | Abbreviated brain MRI and pediatric traumatic brain injury

Radiologic initiatives to "image gently" aim to improve safe and effective imaging care of children by providing as low as reasonably achievable radiation doses and advance the applications of alternative non-ionizing imaging modalities.[7–10] The duration of traditional brain MRI (30 min or more) (1) is too lengthy to dictate emergent management, and (2) is challenging for children to tolerate due to requirements for prolonged immobility, confined space, and loud mechanical noises. Brain MRI is, however, commonly used in non-emergent settings and is an accurate and sensitive imaging modality to identify brain injury as compared to head computed tomography (CT).[11–13]

Variations of abbreviated brain MRI have been successfully implemented in emergency departments nationwide in the assessment of ventriculo-peritoneal shunt malfunction, stroke, and, very recently, traumatic brain injury.[14,15] Abbreviated brain MRI is comparative to head CT in detecting intracranial injury, particularly when employing gradient recall echo and susceptibility weighted imaging, though it is not as good as CT at detecting simple skull fracture and possibly subarachnoid hemorrhage.[16–18] A 2019 study conducted in a pediatric emergency department (ED) reported that abbreviated brain MRI is a feasible and accurate diagnostic alternative to CT in children <6 years of age with traumatic brain injury.[18] This study reported a sensitivity of abbreviated brain MRI as 92.8% and 96.2% specificity. Another small study reported that abbreviated MRI detected trauma-related abnormalities in 47% of suspected mild traumatic brain injury patients with a prior negative CT.[14]

Pediatric traumatic brain injury is a common and life-threatening condition. In 2013, there were 2.5 million traumatic brain injury-related ED visits in the United States with the majority occurring in children and young adults aged 0–4 and 15–24 years.[19] The timely diagnosis of traumatic brain injury in pediatric populations is critical for treatment. Validated clinical prediction rules stratify children with a higher risk of clinically important traumatic brain injury, guiding clinical decision making for head CT use; however, these prediction tools did not examine brain MRI alternatives.[20] A significant portion of children with acute head injury are directed to a clinical decision category to "[CT] image versus observe," based on specific predictors.[21] Studies have reported that children in this category represent up to a third of pediatric head injuries and may have a 0.8%–0.9% increased risk of clinically important traumatic brain injury.[21] In assessing best patient outcomes, emergency physicians previously considered (1) clinical observation impacting patient care, and (2) CT radiation exposure and its potential sequalae including possible additional sedation for image procurement.[22–25] A third option of abbreviated brain MRI, supported by scientific evidence for its feasibility and diagnostic accuracy in pediatric head injury even in very young children, is poised to change the way we care for head injury.[26]

1.3 | Institutional example of abbreviated brain MRI implementation

Pediatric emergency physicians, neurosurgeons, and neuroradiologists have described our institutional experience with a 10-month clinical implementation project and present a model MRI protocol for a "how-to" approach applicable to the evaluation of pediatric head injury in other EDs.[26–28]

At the time of the abbreviated brain MRI protocol implementation, our ED was a suburban Level I Pediatric Trauma Center and Level 1 Adult Trauma Center caring for 70,000 patients annually. The dedicated pediatric ED cared for 19,000 of those pediatric patients annually, with ∼4–5 visits per day for head injury. The majority of children presenting with head injury were treated by board-certified pediatric emergency physicians with 24-hour per day consultation as needed from pediatric neurosurgery, neuroradiology, and trauma. The department had 3 dedicated MRI machines available to its total patient population 24 hours per day. The abbreviated brain MRI clinical implementation project was divided into 3 phases: (1) project development, (2) protocol design, and (3) ED implementation, depicted in Figure 1.[26] For this particular project, a multidisciplinary team decided that children falling into the "image versus observe" category of the PECARN clinical decision tool were eligible for the abbreviated brain MRI.[21]

Abbreviated brain MRI project development required conceptual collaboration between key stakeholders in (1) Emergency Medicine, (2) Neurosurgery, and (3) Neuroradiology regarding projected use in the ED. Clinicians and staff, including emergency physicians, pediatric neurosurgeons, radiologists, trainees, ED and radiology technicians, child life specialists, and nurses, were engaged and educated for project adoption at various monthly staff meetings. Stakeholders identified facilitators and barriers to the clinical application of the abbreviated brain MRI in the ED and clinical application questions identified are detailed in Table 1. In the second phase of protocol implementation, design and trial of the abbreviated brain MRI protocol were championed by a physician lead in Neuroradiology, further advocating for departmental final approval and adoption. Aspects of brain MRI protocol considerations are discussed below in "Abbreviated brain MRI protocol description," with a primary goal of efficiently detecting traumatic intracranial injury including hemorrhage, axonal

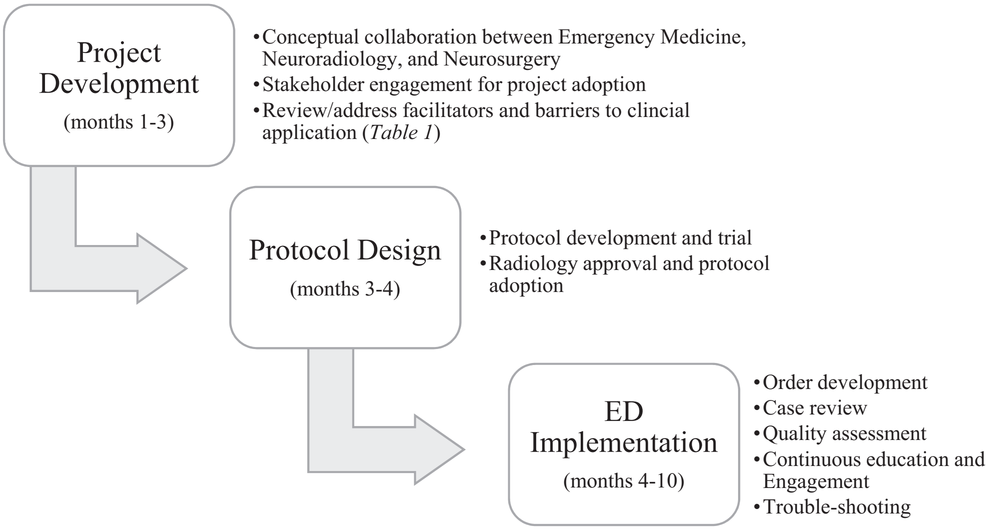

FIGURE 1 Abbreviated brain MRI implementation phases. Three phases of emergency department clinical implementation of an abbreviated brain MRI to assess for traumatic brain injury in select children presenting with head injury are described: (1) project development, (2) protocol design, and (3) emergency department implementation

TABLE 1 Facilitators and barriers to the clinical application of abbreviated brain MRI for pediatric head injury

Clinical application questions	Facilitators	Barriers
How many patients per day do we anticipate would utilize the abbreviated MRI and does our ED MRI workflow have capacity for this increase?	Electronic health record query of pediatric patient encounters for head injury-related visits	Overestimates of (1) patient use and (2) in-suite imaging acquisition times
Which patients are excluded from the abbreviated MRI?	Development and agreement of a documented list of patient exclusions available to all relevant parties	Inadequate review or adjudication of potential controversies such as: decompensating traumatic brain injury, non-accidental trauma, sub-acute head injury, suspected skull fracture
What other ED clinicians and staff can support successful abbreviated MRI implementation?	Appointing project champions in nursing, child life, patient transport, and technicians Initiating a campaign to educate ED and radiology personnel on the new diagnostic	Failing to garner insight and support from ED and radiology personnel involved in the care of patients with head injury Failing to inform ED and radiology personnel of the new diagnostic test
What is the flow and timing of neuroradiologic review and reporting of abbreviated MRI results?	Dedicated neuroradiologists available 24/7 with radiology reports provided within 1 h	Appropriately trained radiologists either lacking or not covering 24/7
What are the next steps in patient care following a negative abbreviated MRI?	Development of a site-specific clinical care algorithm directing patient management and disposition of children presenting to the ED with head injury	Lack of clinical consensus
What are the next steps in patient care following a positive abbreviated MRI?	Development of a site-specific clinical care algorithm direction patient management and disposition of children with head injury	Lack of clinical consensus
How will neuroimaging "over-reads" be managed?	24/7 final radiology reports	Potential over-reads if appropriately trained radiologists not available 24/7
What are the current patient charges for abbreviated brain MRI ordering as compared to other pathologies and as compared to head CT?	Review of ED imaging charges may inform factors related to site-specific use; charge differences between non-contrast abbreviated brain MRI and non-contrast CT may be small	Depending on the institution, charge for a non-contrast abbreviated brain MRI may be significantly higher than charge for a non-contrast head CT

ED, emergency department; MRI, magnetic resonance imaging; CT, computed tomography.
Questions pertinent to the clinical application of abbreviated brain MRI for diagnosis of traumatic brain injury in children presenting with head injury are described in relationship to facilitators and barriers to process implementation.

TABLE 2 Abbreviated brain MRI protocol specifics

Series (DWI, FLAIR, etc)	Pulse sequence (SE, EPI, etc)	TE (ms)	TR (ms)	Flip angle	FOV (mm)	Plane	Slice thickness (mm)	Interslice gap (mm)	NEX	Phase encoding direction	Matrix	Comments
1.5T												
Ax T1	BRAVO or SPGR	3–5	2000	15	140–240	Ax	0.5–1	0 (3D)	1	A/P	256 × 200	
Ax DWI	EPI, ETL 128, b = 0 and 1000	>70	>3500	90	140–240	Ax	4–5	0	1–3	A/P	128 × 128–192 × 192	BW ≥1200
Ax T2 FLAIR	EPI or FSE, ETL ∼30	>100	>6000	90	140–240	Ax	4–5	0	1–2	R/L	320 × 256	TI 2100–2500
Ax GRE	2D gradient echo	>20	>500	20	140–240	Ax	4–5	0	1–2	R/L	256 × 192	flow comp to slice, BW 80
Ax SWI	3D SWI	Min	25–50	10–15	140–240	Ax	0.8–2	0	1	A/P	320 × 224	flow comp to slice, BW 80–100
Ax pCASL	pCASL (PASL if pCASL not available)	10	5000	90	140–240	Ax	5–8	1	1	A/P	512 × 6	
3T												
Ax T1	BRAVO or SPGR	3–5	2000	15	140–240	Ax	0.5–1	0 (3D)	1	A/P	256 × 200	
Ax DWI	EPI,ETL 128, b = 0 and 1,000	>50	>3500	90	140–240	Ax	4–5	0	1–3	A/P	128 × 128–192 × 192	BW ≥ 1200
Ax T2 FLAIR	EPI or FSE, ETL ∼30	>100	>6000	90	140–240	Ax	4–5	0	1–2	R/L	320 × 256	TI 2100–2500
Ax GRE	2D gradient echo	>20	>500	20	140–240	Ax	4–5	0	1–2	R/L	256 × 192	flow comp to slice, BW 80
Ax SWI	3D SWI	Min	15–30	10–15	140–240	Ax	0.8–2	0	1	A/P	320 × 224	flow comp to slice, BW 80–100
Ax pCASL	pCASL (PASL if pCASL not available)	10	6500	90	140–240	Ax	5–8	1	1	A/P	512 × 6	

DWI, diffusion-weighted imaging; GRE, gradient echo; SWI, susceptibility-weighted imaging
Specific sequence formats are provided for application to 1.5T and 3T MRI machines.

injury, and fracture. Frequent radiology in-service presentations to neuroradiologists, fellows, resident, and technologists supported protocol awareness and education. Implementation of the abbreviated brain MRI for clinical use required: (1) development of a new electronic health record order for the abbreviated brain MRI for clinicians to use signaling the order to radiology, (2) case-based review for tracking patient care flows with collaborative teams, (3) quality assessment and structure for outcome-measure monitoring and review, (4) on-call physicians available for trouble-shooting during trial and implementation periods, and (5) further education and engagement of ED clinicians and staff via monthly meetings and postings in relevant newsletters/email announcements.

1.4 | Abbreviated brain MRI protocol description

The abbreviated, non-contrast brain MRI protocol specific for traumatic brain injury is designed to detect (1) bleeding, (2) signs of axonal injury, and (3) skull fracture. The protocol includes the following sequences: 3-plane localizer, axial diffusion-weighted imaging, axial T_2 FLAIR, axial gradient echo or susceptibility-weighted imaging, axial 3D BRAVO, and axial arterial spin labeling. These sequences are available on state-of-the art MRI scanners, and the detailed parameters for these sequences are offered in Table 2. The gradient echo and susceptibility-weighted imaging sequences are meant to detect any intracranial hemorrhage, including hemorrhagic traumatic axonal injury, as punctate foci of susceptibility or "microbleeds," typically located at the gray–white matter junction, in the corpus callosum and in the dorsolateral midbrain. The diffusion-weighted imaging sequence is meant to detect non-hemorrhagic traumatic axonal injury, which would show in the acute period as focal areas of restricted diffusion for instance located in the corpus callosum. The T_2 FLAIR is meant to detect contusions and subarachnoid hemorrhage, which would appear as areas of non-suppression in the cerebrospinal fluid. The axial 3D BRAVO sequence assesses the skull and can detect significant fractures, but its sensitivity to subtle skull fractures is limited, and a head CT should be obtained when there is a strong suspicion of clinically significant skull fracture. The arterial spin labeling sequence is meant to detect brain perfusion changes that precede visible contusions or result from extra-axial hemorrhages and to assess possible fistulas. The total duration of these sequences back to back is ∼6 minutes. When adding the time to position the patient on the MRI table, to interact with and monitor the patient during imaging acquisition, and to return the patient to the gurney, the total duration spent in the MRI suite averages 15 minutes.

2 | DISCUSSION

Scientific evidence supports the use of abbreviated brain MRI in the evaluation of children with head injury in the ED. We report an abbreviated brain MRI protocol for replication in other institutions and model its implementation in the ED as a "how-to" in navigating stages from project development, to protocol design, to ED implementation, described in Figure 1. Practical pearls related to project success include strategic anticipation of facilitators and barriers to abbreviated brain MRI implementation, described in Table 1.

There are limited publications reporting abbreviated brain MRI protocols in the ED and none modeling step-wise implementation for the evaluation of children presenting with head injury.[18] Specifics of the abbreviated brain MRI protocol used in this implementation project are provided in Table 2 with reference to the reasoning for sequence selection. To our knowledge, a single prior brain MRI protocol has been published regarding pediatric head injury evaluation in the ED; however, this protocol does not detail the sequences to an extent that we can perform a side-by-side comparison.[18] However, abbreviated MRI implementation has been detailed in other settings and varying pathologies.[3,29–31]

Importantly, equipment, personnel, and financial resources for project implementation may vary by institution and ED, requiring modifications to the project's execution. Feasibility at other sites may be dependent upon adequate target patient volumes to support changes in clinical management, availability of MRI and radiology, and variations in hospital-based implementation costs.

Previously published head injury decision tools do not account for an abbreviated brain MRI option. Future studies are needed to advise pediatric head injury algorithms to include abbreviated brain MRI and to expand on its use in the diagnosis and prognosis of complicated mild traumatic brain injury.

3 | CONCLUSIONS

Abbreviated, non-contrast brain MRI is an important evaluation alternative to consider in children presenting to the ED with head injury.

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REFERENCES

1. National Institute of Biomedical Imaging and Bioengineering. Magnetic Resonance Imaging (MRI). https://www.nibib.nih.gov/science-education/science-topics/magnetic-resonance-imaging-mri. Accessed February 20, 2020.
2. Itri JN. Patient-centered radiology. *Radiographics*2015;35(6):1835-1846.
3. Canellas R, Rosenkrantz AB, Taouli B, et al. Abbreviated MRI protocols for the abdomen. *Radiographics*. 2019;39(3):744-758.
4. Imler D, Keller C, Sivasankar S, et al. Magnetic resonance imaging versus ultrasound as the initial imaging modality for pediatric and young adult patients with suspected appendicitis. *Acad Emerg Med*. 2017;24(5):569-577.
5. Subhas N, Benedick A, Obuchowski NA, et al. Comparison of a fast 5-minute shoulder MRI protocol with a standard shoulder MRI protocol: a multiinstitutional multireader study. *AJR Am J Roentgenol*. 2017;208(4):W146-W154.
6. Bakker MF, deLange SV, Pijnappel RM, et al. Supplemental MRI screening for women with extremely dense breast tissue. *N Eng J Med*. 2019;381(22):2091-2102.
7. Slovis TL. Children, computed tomography radiation dose, and the As Low As Reasonably Achievable (ALARA) concept. *Pediatrics*. 2003;112(4):971-972.
8. The Image Gently Alliance website. https://www.imagegently.org/. Accessed November 20, 2019.
9. Newman B, Callahan MJ. ALARA (as low as reasonably achievable) CT 2011–executive summary. *Pediatr Radiol*. 2011;41(suppl 2):453-455.
10. Frush DP, Frush KS. The ALARA concept in pediatric imaging: building bridges between radiology and emergency medicine: consensus conference on imaging safety and quality for children in the emergency setting, Feb. 23-24, 2008, Orlando, FL - Executive Summary. *Pediatr Radiol*. 2008;38(suppl 4):S629-S632.
11. Trifan G, Gattu R, Haacke EM, Kou Z, Benson RR. MR imaging findings in mild traumatic brain injury with persistent neurological impairment. *Magn Reson Imaging*. 2017;37:243-251.
12. Roguski M, Morel B, Sweeney M, et al. Magnetic resonance imaging as an alternative to computed tomography in select patients with traumatic brain injury: a retrospective comparison. *J Neurosurg Pediatr*. 2015;15(5):529-534.
13. Young JY, Duhaime A-C, Caruso PA, Rincon SP. Comparison of non-sedated brain MRI and CT for the detection of acute traumatic injury in children 6 years of age or less. *Emerg Radiol*. 2016;23(4):325-331.
14. Ricciardi MC, Bokkers RP, Butman JA, et al. Trauma-specific brain abnormalities in suspected mild traumatic brain injury patients identified in the first 48 hours after injury: a blinded magnetic resonance imaging comparative study including suspected acute minor stroke patients. *J Neurotrauma*. 2017;34(1):23-30.
15. Thompson EM, Baird LC, Selden NR. Results of a North American survey of rapid-sequence MRI utilization to evaluate cerebral ventricles in children. *J Neurosurg Pediatr*. 2014;13(6):636-640.
16. Mehta H, Acharya J, Mohan AL, Tobias ME, LeCompte L, Jeevan D. Minimizing radiation exposure in evaluation of pediatric head trauma: use of rapid MR imaging. *AJNR Am J Neuroradiol*. 2016;37(1):11-18.
17. Dremmen MHG, Wagner MW, Bosemani T, et al. Does the addition of a "Black Bone" sequence to a fast multisequence trauma MR protocol allow MRI to replace CT after traumatic brain injury in children?*AJNR Am J Neuroradiol*. 2017;38(11):2187-2192.
18. Lindberg DM, Stence NV, Grubenhoff JA, et al. Feasibility and accuracy of fast MRI versus CT for traumatic brain injury in young children. *Pediatrics*. 2019;144(4). https://doi.org/10.1542/peds.2019-0419
19. Taylor CA, Bell JM, Breiding MJ, Xu L. Traumatic brain injury–related emergency department visits, hospitalizations, and deaths—United States, 2007 and 2013. *MMWR Surveill Summ*. 2017;66(9):1-16.
20. 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.
21. 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. https://doi.org/10.1016/s0140-6736(09)61558-0

22. Mathews JD, Forsythe AV, Brady Z, et al. Cancer risk in 680,000 people exposed to computed tomography scans in childhood or adolescence: data linkage study of 11 million Australians. *BMJ*. 2013;346:f2360
23. Miglioretti DL, Johnson E, Williams A, et al The use of computed tomography in pediatrics and the associated radiation exposure and estimated cancer risk. *JAMA Pediatr*. 2013;167(8):700-707.
24. Pearce MS, Salotti JA, Little MP, et al. Radiation exposure from CT scans in childhood and subsequent risk of leukaemia and brain tumours: a retrospective cohort study. *Lancet*. 2012;380(9840):499-505.
25. Ahmad R, Hu HH, Krishnamurthy R, Krishnamurthy R. Reducing sedation for pediatric body MRI using accelerated and abbreviated imaging protocols. *Pediatr Radiol*. 2018;48(1):37-49.
26. Hales S, Lesher-Trevino A, Ford N, Maher D, Ramsay A, Tran N. Reporting guidelines for implementation and operational research. *Bull World Health Organ*.2016;94(1):58-64. https://doi.org/10.2471/blt.15.167585
27. Powell BJ, Waltz TJ, Chinman MJ, et al. A refined compilation of implementation strategies: results from the Expert Recommendations for Implementing Change (ERIC) project. *Implement Sci*. 2015;10:21.
28. Proctor E, Silmere H, Raghavan R, et al. Outcomes for implementation research: conceptual distinctions, measurement challenges, and research agenda. *Adm Policy Ment Health*. 2011;38(2):65-76.
29. Trofimova A, Kadom N. Added value from abbreviated brain MRI in children with headache. *AJR Am J Roentgenol*. 2019;1-6.
30. Harvey SC, Di Carlo PA, Lee B, Obadina E, Sippo D, Mullen L. An abbreviated protocol for high-risk screening breast MRI saves time and resources. *J Am Coll Radiol*. 2016;13(11s):R74-r80.
31. Pooler BD, Hernando D, Reeder SB. Clinical implementation of a focused MRI protocol for hepatic fat and iron quantification. *AJR Am J Roentgenol*. 2019;1-6.

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