Rapid-sequence MRI for evaluation of pediatric traumatic brain injury: a systematic review

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OBJECTIVE Rapid-sequence MRI (RSMRI) of the brain is a limited-sequence MRI protocol that eliminates ionizing radiation exposure and reduces imaging time. This systematic review sought to examine studies of clinical RSMRI use for pediatric traumatic brain injury (TBI) and to evaluate various RSMRI protocols used, including their reported accuracy as well as clinical and systems-based limitations to implementation.

METHODS PubMed, EMBASE, and Web of Science databases were searched, and clinical articles reporting the use of a limited brain MRI protocol in the setting of pediatric head trauma were identified.

RESULTS Of the 1639 articles initially identified and reviewed, 13 studies were included. An additional article that was in press at the time was provided by its authors. The average RSMRI study completion time was variable, spanning from 1 minute to 16 minutes. RSMRI with “blood-sensitive” sequences was more sensitive for detection of hemorrhage compared with head CT (HCT), but less sensitive for detection of skull fractures. Compared with standard MRI, RSMRI had decreased sensitivity for all evidence of trauma.

CONCLUSIONS Protocols and uses of RSMRI for pediatric TBI were variable among the included studies. While traumatic pathology missed by RSMRI, such as small hemorrhages and linear, nondisplaced skull fractures, was frequently described as clinically insignificant, in some cases these findings may be prognostically and/or forensically significant. Institutions should integrate RSMRI into pediatric TBI management judiciously, relying on clinical context and institutional capabilities.

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KEYWORDS rapid-sequence MRI; pediatric head imaging; head trauma; traumatic brain injury

RAPID-SEQUENCE MRI (RSMRI) of the brain is a limited-sequence MRI protocol. RSMRI is a radiation-free alternative to head CT (HCT) imaging, which is the gold-standard axial imaging modality for cranial trauma.1,3 Reported RSMRI brain protocols include variations in terminology (such as “fast-brain” or “quick-brain” MRI), exact imaging sequences included, and clinical indication.4,5 Early RSMRI utilization included triplanar (axial, coronal, sagittal) T2-based orthogonal sections of the brain and focused on evaluation of ventricular size in the longitudinal evaluation of treated hydrocephalus patients.6,7 Additional sequences can be added in specific clinical context, such as susceptibility-weighted imaging (SWI) and gradient-echo (GRE) imaging for evaluation of blood products, or diffusion-weighted imaging (DWI) for evaluation of ischemia.

Although the use of RSMRI is not limited to pediatric patients, the advantages of short scan times and the
absence of ionizing radiation exposure are amplified in children. The effective radiation dosage associated with HCT is proportionally higher in younger children. Furthermore, the lifetime cancer mortality risk attributable to a single HCT in a 1-year-old child is 0.07%.\textsuperscript{8,9} The length of time required to perform standard brain MRI studies and their sensitivity to patient motion require most pediatric patients to undergo some form of sedation or general anesthesia, which raises concerns about possible neurotoxic effects of sedation and general anesthesia on the developing brain.\textsuperscript{10,11} Sedation also presents both practical and cost barriers to implementation in the context of acute neurotrauma evaluation in children. RSMRI can be done in minutes, reducing the need for sedation. Accordingly, utilization of RSMRI of the brain appears to be increasing for pediatric applications within the United States and Canada.\textsuperscript{3}

Evaluation of pediatric traumatic brain injury (TBI) is becoming an increasingly prevalent indication for RSMRI.\textsuperscript{12,13} However, RSMRI must be utilized judiciously, as the reduced number of sequences included in these protocols may limit diagnostic accuracy compared with standard MRI brain protocols or HCT. Currently, the American College of Radiology does not include RSMRI within their appropriateness criteria, and there is not a standard RSMRI sequence protocol.\textsuperscript{14} This lack of consensus raises concerns regarding liability in utilizing and charging for a limited study.\textsuperscript{4} Additionally, radiation reduction in children with hydrocephalus via low-dose HCT or utilizing MRI as an alternative to HCT is a diagnostic imaging quality measure listed by the American College of Radiology,\textsuperscript{15} raising the possibility that such a measure could be extended to other pediatric populations or adopted by third-party payers.

To our knowledge, a qualitative synthesis of RSMRI utilization in pediatric TBI has not been performed. The aim of this systematic review was to examine studies of clinical applications of RSMRI for pediatric head trauma across institutions. Our study evaluates various RSMRI protocols used, their reported advantages, and clinical and systems-based limitations to RSMRI implementation.

Methods

The published literature on RSMRI for TBI was systematically reviewed in accordance with Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Fig. 1). Using PubMed, EMBASE, and Web of Science databases, searches were conducted on March 11, 2020. Covidence systematic review software (Veritas Health Innovation Ltd.) was used to organize the systematic review. A combination of the following keywords was used with Boolean “AND” and “OR” phrases: “Rapid,” “Fast,” “Ultrafast,” “Quick,” “Brain,” and “MRI.” Studies were also added after reviewing reference lists from articles with relevant abstracts.

Our goal was to identify clinical articles reporting the use of a limited brain MRI protocol in the setting of pedi-
tractive TBI with the aim of reducing scan time or eliminating the need for radiation exposure (i.e., CT). Inclusion criteria included randomized trials, nonrandomized trials, retrospective reviews, and substantial case series. Studies were included if they reported 1) clinical utilization of an RSMRI protocol, either retrospective or prospective; 2) indications for the use of RSMRI that included TBI; and 3) patients who were younger than 18 years of age. The search was limited to English-language articles and articles published after 2000. Publications other than full-text original reports were excluded, as were technical or nonclinical studies (e.g., review articles and commentaries). For included publications, specific sequences used within the RSMRI protocol, the average scan time if reported, the average patient age, relative test characteristics if RSMRI was performed concurrently with standard scanning (either HCT or standard brain MRI), and any comments on limitations (clinical or system based) were recorded. Papers were graded in an evidentiary table using the revised Quality of Assessment of Diagnostic Accuracy (QUADAS-2) tool, a preferred tool for systematic reviews of diagnostic test accuracy. The QUADAS-2 tool comprises 4 domains (patient selection, index test, reference standard, and flow and timing), with domains assessed in terms of risk of bias and applicability.

The RSMRI protocols were summarized based on the MRI and acceleration techniques. Since variability exists in naming of MRI sequences among different techniques used in fast T2-weighted imaging, single-shot echo-planar imaging (EPI), or simple modifications of scan parameters, such as repetition time or echo time. Common additional sequences included were “blood-sensitive” sequences, including T2*GRE, T2*EPI, and SWI. Other additional sequences included T1-weighted imaging, FLAIR, and DWI. Reported average study completion times were variable and ranged from 1 minute to 16 minutes (Table 1). Traumatic pathology identified in the studies included intraparenchymal hemorrhage (IPH) or contusions, subarachnoid hemorrhage (SAH), subdural hemorrhage (SDH), epidural hematoma (EDH), midline shift, and skull fracture. Nine of the 13 studies compared relative test characteristics of an RSMRI protocol to a standard scan, either HCT or standard brain MRI. Four studies described clinical implementation and utilization of RSMRI studies without concurrent imaging by another modality.

**Test Characteristics of RSMRI With T2-Weighted Imaging Alone**

Of the 4 studies that utilized RSMRI with triplanar T2-weighted imaging alone, 3 used concurrent standard scans, either HCT or standard brain MRI studies, and reported relative test characteristics. In a study of 54 patients presenting with head trauma, Sheridan et al. reported a sensitivity and specificity of 85% and 100%, respectively, for detection of any radiographic evidence of head trauma relative to HCT. When identifying clinically important radiographic evidence of head trauma, the sensitivity and specificity were both 100%. The sensitivity and specificity of detection of a midline shift were reported as 75% and 90%, respectively, while test characteristics for detection of other specific pathology were not reported. The authors noted 2 skull fractures missed by RSMRI.

Kabakus et al. reported a series of 48 patients who underwent RSMRI within 15 days of either HCT or standard brain MRI for head trauma. The respective sensitivity and specificity of RSMRI were 100% and 97% for detection of IPH, 86% and 96% for extraaxial hemorrhage (EDH or SDH), 10% and 100% for SAH, 50% and 100% for IVH, and 47% and 97% for skull fractures. The authors noted that the mean thickness of missed extraaxial hemorrhage was 3.7 mm.

Ryan et al. retrospectively reviewed patients with head trauma who initially received HCT with follow-up RSMRI within 48 hours. The authors reported two cohorts of patients: those receiving triplanar T2-weighted imaging

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**Results**

The initial search yielded 1639 articles. Three additional articles were identified within reference lists of the other articles and 1 additional article by author referral. Following the removal of duplicates, 1328 article titles and abstracts were screened. A total of 30 articles were identified for full-text review, and 13 ultimately met the inclusion criteria. The selection process according to PRISMA guidelines is shown in Fig. 1. The extracted clinical data are reported in Table 1.

Many of the included studies were nonrandomized and retrospective in nature and compared either cohorts of patients who underwent different imaging modalities or separate imaging modalities performed in the same patient within a short time interval. Berger et al. prospectively evaluated the feasibility of an RSMRI protocol with variable comparative follow-up imaging, and Ramgopal et al. retrospectively evaluated RSMRI utilization after implementation of a protocol with variable follow-up imaging.
alone and those receiving triplanar T2-weighted imaging with T2*GRE. With triplanar T2-weighted imaging alone, the sensitivity for detection of any intracranial hemorrhage was 54% when readers were blinded to the HCT scan. The sensitivity for detection of specific pathology when blinded to the HCT was 90% for contusions, 80% for extradural hemorrhage (SDH or EDH), and 25% for SAH. When T2*GRE was added to triplanar T2-weighted imaging, the sensitivity for detection of any intracranial hemorrhage increased to 76% when blinded to the HCT.

### TABLE 1. Clinical data extracted from systematic review

<table>
<thead>
<tr>
<th>Authors &amp; Year</th>
<th>Study Design</th>
<th>MRI Tesla (1.5T, 3T, or both)</th>
<th>RSMRI Protocol</th>
<th>Average Reported Scan Time</th>
<th>Patient Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheridan et al., 2020</td>
<td>Prospective review of pediatric patients who underwent RSMRI for TBI</td>
<td>1.5T</td>
<td>Axial T2 SSFSE/TSE; coronal T2 SSFSE/TSE; sagittal T2 SSFSE/TSE; axial T2*GRE</td>
<td>Median 4 mins, 52 secs (IQR 3 mins, 49 secs to 5 mins, 47 secs)</td>
<td>Median 4 yrs (IQR 1–10 yrs)</td>
</tr>
<tr>
<td>Berger et al., 2020</td>
<td>Prospective feasibility study of an RSMRI protocol to screen for pediatric TBI</td>
<td>1.5T or 3T</td>
<td>Axial T2 conventional FSE; axial GRE; coronal T1 inversion recovery; axial DWI; axial T2 SSFSE</td>
<td>6 mins</td>
<td>Mean of 3.4 mos (SD 2.7 mos)</td>
</tr>
<tr>
<td>Ramgopal et al., 2020</td>
<td>Retrospective review of RSMRI use before &amp; after RSMRI protocol implementation, not exclusive to TBI indications</td>
<td>1.5T or 3T</td>
<td>Axial DWI; axial GRE; axial T2 propeller; coronal T1 FLAIR; axial 3D SWAN; axial fast FLAIR; axial T2 SSFSE</td>
<td>16 mins</td>
<td>&lt;12 yrs</td>
</tr>
<tr>
<td>Kabakus et al., 2019</td>
<td>Retrospective review of RSMRI use for nonhydrocephalus pediatric indications after HCT or full MRI in 15 days</td>
<td>1.5T or 3T</td>
<td>Axial HASTE; coronal HASTE; sagittal HASTE</td>
<td>Btwn 2 &amp; 3 mins</td>
<td>Median 10.8 mos (range 5 days to 16 yrs)</td>
</tr>
<tr>
<td>Lindberg et al., 2019</td>
<td>Prospective cohort study of pediatric patients w/ TBI who underwent RSMRI after initial HCT</td>
<td>3T</td>
<td>Axial T2 SSH; coronal T2 SSH; axial T1 SSH TFE; axial T2*FFE; axial SSH FLAIR; axial DWI; axial T2 EPI SSH</td>
<td>6 mins, 5 secs (IQR 5 mins, 40 secs to 6 mins, 32 secs)</td>
<td>Median 12.6 mos (IQR 4.7–32.6 mos)</td>
</tr>
<tr>
<td>Dremmen et al., 2017</td>
<td>Retrospective study of pediatric patients w/ TBI who underwent HCT &amp; RSMRI novel black bone sequence in 7 days</td>
<td>1.5T or 3T</td>
<td>Sagittal 3D T1; axial T2 HASTE; axial FLAIR; axial DTI; axial SWI; axial black bone sequence</td>
<td>Not reported</td>
<td>Mean of 4.89 yrs (range 6 days to 15.5 yrs)</td>
</tr>
<tr>
<td>Kralik et al., 2017</td>
<td>Prospective study of potential suspected pediatric patients w/ TBI who underwent HCT, RSMRI, &amp; standard MRI in sequence in 2 days</td>
<td>1.5T or 3T</td>
<td>Axial T2 HASTE; coronal T2 HASTE; axial DWI; axial T2*EPI</td>
<td>&lt;2 mins</td>
<td>Median 4 mos (range 9 days to 31 mos)</td>
</tr>
<tr>
<td>Sheridan et al., 2017</td>
<td>Retrospective study of pediatric patients w/ TBI who underwent RSMRI after initial HCT in 2 days</td>
<td>Not specified</td>
<td>Axial T2 FSE; coronal T2 FSE; sagittal T2 FSE</td>
<td>1–3 mins</td>
<td>Mean 3.24 yrs (range 0.03–12.3 yrs)</td>
</tr>
<tr>
<td>Mehta et al., 2016</td>
<td>Retrospective study of pediatric patients w/ TBI who underwent RSMRI after initial HCT in 2 days</td>
<td>1.5T or 3T</td>
<td>Axial SSH T2 FFE EPI; axial SSH DWI; axial SSH FLAIR; axial T2 FFE (T2*); coronal T2 TSE</td>
<td>2.5–3 mins</td>
<td>Mean 6 yrs (range 0–19 yrs)</td>
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<tr>
<td>Ryan et al., 2016</td>
<td>Retrospective study of pediatric patients w/ TBI who underwent RSMRI in 48 hrs of initial HCT</td>
<td>1.5T or 3T</td>
<td>Axial T2 SSFSE/HASTE; coronal T2 SSFSE/HASTE; sagittal T2 SSFSE/HASTE; w/ &amp; w/o axial GRE</td>
<td>2–3 mins (+1 min if GRE included)</td>
<td>Mean 2.4 yrs (range 1 day to 22 yrs)</td>
</tr>
<tr>
<td>Young et al., 2016</td>
<td>Retrospective study of pediatric patients w/ TBI who underwent RSMRI after HCT in 24 hrs</td>
<td>1.5T or 3T</td>
<td>Axial T2 HASTE/SSFSE; coronal T2 HASTE/SSFSE; sagittal T2 HASTE/SSFSE; axial EPI susceptibility</td>
<td>1.5–2 mins</td>
<td>Mean 23 mos (range 3 days to 6 yrs)</td>
</tr>
<tr>
<td>Cohen et al., 2015</td>
<td>Retrospective review of pediatric patients w/ TBI who underwent RSMRI compared w/ an age-matched HCT cohort</td>
<td>1.5T or 3T</td>
<td>Axial T2 HASTE/SSFSE; coronal T2 HASTE/SSFSE; sagittal T2 HASTE/SSFSE; axial EPI susceptibility</td>
<td>3–4 mins</td>
<td>Mean 2.7 yrs (SD 4 yrs)</td>
</tr>
<tr>
<td>Missios et al., 2008</td>
<td>Retrospective review of pediatric patients who underwent RSMRI for multiple indications inclusive of TBI</td>
<td>1.5T</td>
<td>Axial T2 SSFSE; coronal T2 SSFSE; sagittal T2 SSFSE</td>
<td>&lt;2.5 mins</td>
<td>Median 21.9 mos, mean 4.1 yrs</td>
</tr>
</tbody>
</table>

**Notes:**
- **DTI** = diffusion tensor imaging; **FFE** = fast field echo; **FSE** = fast spin echo; **SSFSE** = single shot; **SWAN** = susceptibility-weighted angiography; **TFE** = turbo field echo; **TSE** = turbo spin echo.
scan. Furthermore, the sensitivity increased to 100% for detection of contusions, 86% for extraxial hemorrhage, and 93% for SAH. Across all pathology and both protocols, the sensitivity was increased when readers were not blinded to the HCT. The authors also reported that of 41 fractures identified on HCT, RSMRI identified only 11.

**Test Characteristics of RSMRI With T2-Weighted Imaging and Additional Sequences**

Of the 10 studies that included sequences in addition to T2-weighted imaging within their RSMRI protocols, 7 reported test characteristics relative to HCT or standard brain MRI, including the aforementioned study by Ryan et al., which utilized T2*GRE sequences on a cohort of patients. With an RSMRI protocol including T1-weighted imaging, FLAIR, T2*GRE, and DWI, Lindberg et al. reported relative test characteristics compared with HCT obtained within 24 hours for 225 patients with head trauma. The overall sensitivity and specificity for detection of any radiographic evidence of trauma were 92.8% and 96.2%, respectively. The authors noted 8 cases of missed pathology identified by CT; 6 were nondepressed skull fractures and 2 were SAHs. Conversely, 5 cases of missed pathology identified by RSMRI included 3 SDHs, 2 contusions, and 1 SAH. The authors stated that within their protocol, T2*GRE and T2 HASTE sequences were most likely to identify traumatic pathology, while DWI and T1-weighted sequences were least likely to identify traumatic pathology.

Dremmen et al. reported a retrospective series of 28 patients with head trauma who underwent an RSMRI protocol including T1-weighted imaging, FLAIR, DTI, SWI, and a novel “black bone” sequence to bolster sensitivity for skull fractures. Relative to an HCT scan obtained within 7 days, the sensitivity and specificity of RSMRI were both 100% for detection of skull fractures and/or intracranial hemorrhage. Examining skull fractures alone, RSMRI had a sensitivity and a specificity of 66.7% relative to HCT. Conversely, HCT had a sensitivity of 72.7% relative to RSMRI for detection of intracranial hemorrhage. With the black bone sequence, there were 2 false negatives and 2 false positives for skull fracture. The false negatives resulted from skull fractures being identified as cranial sutures, and false positives resulted from cranial sutures being identified as skull fractures. All the misinterpretations were in patients younger than 2 years of age.

Kralik et al. utilized an RSMRI protocol including DWI and T2*-weighted EPI sequences prior to a standard brain MRI in 24 patients with head trauma who initially underwent HCT. Relative to standard brain MRI, both RSMRI and HCT had a sensitivity and specificity of 50% and 100% for detection of radiographic evidence of trauma. Combining RSMRI and HCT, the sensitivity and specificity were 60% and 100% relative to standard brain MRI. Findings missed by RSMRI but detected by standard brain MRI (which included an SWI sequence) included 4 SAHs, 2 fluid-fluid levels within SDHs, and 3 tentorial SDHs. With RSMRI and HCT combined, the sensitivity for any traumatic finding was still lower compared with standard brain MRI, which the authors attributed to the high sensitivity of SWI within the standard brain MRI protocol for microhemorrhages and SAH.

Mehta et al. utilized an RSMRI protocol including DWI, FLAIR, T2*EPI, and T2*GRE sequences in 103 patients with head trauma in whom HCT had been obtained within 2 days. Between RSMRI and HCT, the authors reported a positive percentage agreement of 91% and negative percentage agreement of 94% for any radiographic evidence of trauma. For specific subtypes of injury, the positive and negative percentage agreement were 91% and 94% for extraaxial hemorrhage (defined as SDH, EDH, and SAH), 93% and 86% for intraxial hemorrhage (defined as IPH and contusions), 50% and 92% for DAI, and 78% and 94% for skull fractures. The authors attributed the lower positive percentage agreement for DAI to the increased sensitivity of RSMRI. They also noted 12 cases where RSMRI failed to detect a skull fracture.

Young et al. utilized an RSMRI protocol consisting of triplanar T2-weighted imaging and an EPI susceptibility sequence on 33 patients in whom HCT had been obtained within the concurrent 24 hours for head trauma. Overall, the percentage agreement was 82% for detection of any traumatic injury. By injury subtype, skull fractures were the only pathology with a significant difference in detection and had an overall percentage agreement of only 58%, with 14 of 21 skull fractures missed by RSMRI. The overall agreement for extraaxial hemorrhage (EDH and SDH) was 70%. Seven of 21 extraaxial hemorrhages identified by RSMRI were missed by CT, and conversely, 3 of 17 extraaxial hemorrhages seen on CT were missed by RSMRI. Missed hemorrhages by either modality were less than 4 mm. For SAH, there was an overall agreement of 76%, with 12 of 13 cases identified by RSMRI and 6 of 13 cases identified by CT.

Sheridan et al. published a prospective study with concurrent RSMRI (including T2*GRE) and HCT imaging, reporting an RSMRI sensitivity of 89% for any TBI and 95% for clinically important TBI. The single “missed” clinically important CT finding was a focal 2-mm subdural hematoma read by neuroradiology but felt by the clinical team to be equivocal, which received no intervention and had no sequelae. The addition of T2*GRE did aid in the identification of minor intracranial hemorrhages without significantly increasing the study time (the median study duration was still < 5 minutes). As with previous studies, RSMRI was insensitive to isolated and clinically insignificant convexity skull fractures that required no further clinical intervention for that hospitalization. Of note, the Sheridan series included all severities of TBI, including two injuries that resulted in death.

**Clinical Implementation and Utilization of RSMRI**

Four of the 12 studies described clinical implementation and utilization of an RSMRI protocol without concurrent imaging by another modality. Berger et al. implemented an RSMRI protocol to screen for abusive head trauma with both conventional and single-shot T2-weighted imaging, as well as DWI, T2*GRE, and T1-weighted inversion recovery sequences. The authors reported 158 patients scanned with only 2% of studies considered nondiagnostic secondary to patient motion. They reported
99% agreement between conventional T2-weighted imaging and single-shot T2-weighted imaging, suggesting no significant loss of sensitivity with single-shot T2-weighted imaging. Only 8 patients required follow-up imaging due to a motion artifact or possibly abnormal findings on RSMRI, with follow-up imaging read as normal. Therefore, the authors reported that 94% of patients with normal imaging avoided HCT.

Ramgopal et al. reported RSMRI and CT utilization in periods before and after the introduction of multiple RSMRI protocols, with one specific to head trauma and including T2*GRE, FLAIR, T2-weighted radial sampling technique (periodically rotated overlapping parallel lines with enhanced reconstruction [PROPELLER]), and DWI. RSMRI as an index study increased from 10.8% to 38.5%, while HCT use declined from 70% to 48.5%, and standard brain MRI declined from 19.2% to 13%. The time to neuroradiographic study was greater for RSMRI in the implementation period at a median of 182 minutes compared with 86 minutes for HCT. Additionally, emergency department (ED) length of stay was longer for patients who underwent RSMRI at a median of 396 minutes compared with 257 minutes for HCT. In the implementation period, 118 patients went on to have a standard brain MRI within 14 days of their index scan. For these patients, the false-negative rate for RSMRI was 0% and was between 18% and 25% for HCT. The authors noted that a higher proportion of patients received any neuroimaging within the implementation period.

Cohen et al. reported an age-matched cohort study of patients with head trauma who underwent RSMRI with EPIC susceptibility sequences compared with patients who underwent HCT. The time from ED arrival to image completion was longer for the RSMRI group at a median of 172 minutes compared with a median of 93 minutes for HCT. However, this relative delay decreased over the duration of the study. Total ED length of stay was also longer for RSMRI patients at a median of 266 minutes compared with 225 minutes for HCT. More radiographic abnormalities were found in the HCT group, and the HCT group was on average triaged to higher levels of care. No clinically significant injuries were known to be missed in either group as determined by the need for follow-up imaging or return to care.

Missios et al. reported a case series inclusive of patients with head trauma that used a triplanar T2-weighted imaging RSMRI protocol across a nearly 5-year period. The total number of RSMRI scans increased each year of the study. Their RSMRI protocol was used both as an index study and for follow-up of known traumatic injuries. They reported that no patient was known to have returned with a missed lesion.

**Discussion**

RSMRI for pediatric head trauma is a useful alternative to HCT and standard brain MRI, although important limitations to its use remain, as highlighted by the studies included in this systematic review. RSMRI protocols were variable across the included studies in both how they were used and the MRI sequences included. All studies included T2-weighted imaging, which has been reported as effective in the evaluation of hydrocephalus. Tripolaran T2-weighted imaging alone may be insufficient for evaluation of head trauma due to its low sensitivity for small hemmorhages and skull fractures. Additional sequences that are more sensitive for hemorrhage appear to strengthen the sensitivity of these protocols for detection of traumatic findings and can do so with minimal additional scan time.

The exact blood-sensitive sequence used differed among the studies, raising the question of which sequence is optimal. Although both SWI and T2*GRE techniques rely on the local magnetic field inhomogeneity caused by paramagnetic blood products to detect intracranial hemorrhage, SWI has improved susceptibility sensitivity relative to conventional T2*GRE because of higher imaging resolution and postprocessing. In prior studies of DAI, SWI was more sensitive than T2*GRE and CT in detecting hemorrhages of hemorrhagic lesions. In terms of the volume and number of detected hemorrhagic lesions, SWI is 3 to 6 times more sensitive than T2*GRE in children and adolescents with posttraumatic DAI. The most important limitation of the SWI application in RSMRI is the longer acquisition time than T2*GRE. This longer acquisition time makes the imaging quality of SWI more likely to be degraded by motion artifacts.

While RSMRI with blood-sensitive sequences was more sensitive than CT for the detection of hemorrhage, it was invariably less sensitive for the detection of skull fractures. Missed skull fractures were typically small, linear, and nondisplaced, which are generally not associated with development of delayed fracture-related complications. While the addition of novel sequences, such as a black blood-sensitive sequence, may improve detection of fractures, HCT remains the most sensitive study. As such, providers should exercise caution in using RSMRI to rule out skull fractures unless in concert with another imaging modality. In cases of high suspicion of skull fracture, such as suspected abusive trauma or a high-energy mechanism of trauma, additional imaging with either HCT or a skeletal survey may be needed.

Ultimately, beyond the addition of a blood-sensitive sequence, the optimal RSMRI protocol for evaluation of pediatric head trauma remains unclear. To develop a standard protocol, institutions must define study sufficiency (i.e., what pathology, or what degree of pathology, is appropriate to miss) relative to HCT and standard brain MRI. A near-unanimous point made by the studies was that pathology missed by an RSMRI protocol was clinically insignificant and required no surgical intervention. It was implied in these studies that clinically insignificant findings were those that required no immediate intervention or subsequent alteration of care plans. Therefore, if the goal of an RSMRI protocol is to screen out clinically actionable pathology, then it appears that RSMRI with an additional blood-sensitive sequence is sufficient. However, there may be long-lasting prognostic and clinical implications of traumatic head injuries, even if initial findings were not clinically actionable. In some cases, RSMRI may be more useful in this context, particularly given its enhanced sensitivity to DAI, the presence of which can
predict clinical outcome. Consequently, identifying pathology that does not require clinical intervention may still have prognostic value. Furthermore, in the setting of suspected abusive trauma, a missed finding, even without clinical significance, may have legal ramifications or put a child at risk for repeated abusive injury.

Frequently noted limitations to RSMRI protocol implementation were scanner availability and relative time delays to complete imaging. Although many centers still favor HCT for the evaluation of neurologically unstable trauma patients, RSMRI has been used in this context as well. RSMRI use is even less common in the context of cardiovascular and/or respiratory instability. However, the decreased time required to complete RSMRI was noted across study implementation periods, likely reflecting increased comfort with ordering and interpretation, as well as improved institutional efficiency. Subsequently, RSMRI may be appropriate for patients with higher levels of acuity as an institution integrates RSMRI into their workflows.

There are limitations to this study. As a systematic review, this work inherently relies on the quality of data reported by others and is susceptible to selection bias. The studies were graded on an evidentiary table using the QUADAS-2 assessment tool (Table 2 and Fig. 2). Many of the studies performed RSMRI after traumatic pathology was diagnosed by HCT, which may introduce selection bias and alter the test characteristics of RSMRI, limiting what could be concluded if RSMRI were an index study. Universally, the studies excluded clinically unstable patients or patients requiring neurosurgical intervention, which, while likely clinically appropriate given institutional ca-

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**TABLE 2. QUADAS-2 assessment**

<table>
<thead>
<tr>
<th>Authors &amp; Year</th>
<th>Risk of Bias</th>
<th>Applicability Concerns</th>
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<tbody>
<tr>
<td>Sheridan et al., 2020</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Berger et al., 2020</td>
<td>High</td>
<td>Unclear</td>
</tr>
<tr>
<td>Ramgopal et al., 2020</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Kabakus et al., 2019</td>
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<td>Low</td>
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<td>Lindberg et al., 2019</td>
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<td>Missios et al., 2008</td>
<td>High</td>
<td>Unclear</td>
</tr>
</tbody>
</table>

High = high risk; low = low risk; unclear = unclear risk.

FIG. 2. QUADAS-2 assessment of risk of bias and applicability.
pabilities, may also introduce selection bias. Intervals between different scanning modalities also varied when concurrent scans were compared, raising the possibility that evolution or resolution of traumatic pathology could alter a scan’s test characteristics. Additionally, reporting of relative test characteristics varied in terms of sensitivity/specificity versus percentage agreement/disagreement to HCT. While HCT is the historic gold standard for pediatric TBI, this assumes that any specific disagreement between HCT as the reference scan and RSMRI implies incorrect classification by RSMRI, which may not be the case for certain pathology (e.g., small hemorrhages, DAI).

Conclusions

RSMRI is a promising option for evaluation of pediatric TBI because of its avoidance of ionizing radiation exposure and greatly reduced requirement for sedation when compared with HCT and standard MRI protocols, although important limitations remain. There is no current standard set of RSMRI sequences across institutions, even though sequence selection appears to influence the sensitivity of clinical findings in various contexts. RSMRI is less sensitive for certain traumatic pathology, specifically skull fractures and very small hemorrhages. While traumatic pathology missed by RSMRI is often clinically inconsequential, missed findings may have forensic ramifications in certain clinical contexts. Selection of appropriate imaging modalities for pediatric patients with TBI should include consideration of clinical context and other findings, as well as institutional capabilities.

References

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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: Quinsey, Kessler. Acquisition of data: Kessler. Analysis and interpretation of data: Kessler, Goh, Pajer, Asher, Northam. Drafting the article: Kessler. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Quinsey. Administrative/technical/material support: Quinsey. Study supervision: Quinsey.

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