Whole-Spine MRI in Children With Suspected Abusive Head Trauma

Boaz Karmazyn, MD[1], Thomas A. Reher, MD[2], Nucharin Supakul, MD[1], Drew A. Streicher, MD[1], Neud Kiros, BS[3], Nicklaus Diggins, BS[3], S. Gregory Jennings, MD[4], George J. Eckert, MAS[5], Roberta A. Hibbard, MD[6], Rupa Radhakrishnan, MD[1]

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BACKGROUND. Abusive head trauma (AHT) in children has recently been associated with findings on cervical spine MRI.

OBJECTIVE. The purpose of this study was to evaluate whether whole-spine MRI in children with suspected AHT shows additional abnormalities not identified on cervical spine MRI.

METHODS. This retrospective study included 256 children younger than 3 years old (170 boys, 86 girls; mean age, 5.9 months) who underwent skeletal survey and head MRI for suspected child abuse from January 2019 to December 2020. Per institutional protocol, children with suspected AHT also underwent whole-spine MRI. AHT diagnoses were established by a combination of clinical information from medical record review and injuries described in reports from skeletal survey, head MRI, and head CT (if performed). Two pediatric neuroradiologists independently reviewed whole-spine MRI examinations for presence and level of intraspinal hemorrhage (classified as subarachnoid, subdural, or epidural), ligamentous injury, spinal cord edema, and vertebral fractures; subdural hematoma, epidural hematoma, ligamentous injury, and fracture unidentified by skeletal survey were considered major findings. Interobserver agreement was assessed; a third radiologist resolved discrepancies. Findings were summarized with attention to injuries isolated to the thoracolumbar spine.

RESULTS. A total of 148 of 256 (57.8%) children underwent whole-spine MRI. AHT was diagnosed in 79 of 148 (53.4%) children who underwent whole-spine MRI versus in 2 of 108 (1.9%) who did not undergo whole-spine MRI ($p < .001$). Interobserver agreement, expressed as kappa coefficient, was 0.90 for intraspinal hemorrhage, 0.69 for ligamentous injury, 0.66 for spinal cord edema, and 0.95 for fracture. A total of 57 of 148 (38.5%) whole-spine MRI examinations showed injuries, and 34 of 148 (23.0%) showed injuries localized to the thoracolumbar spine. A total of 47 of 148 (31.8%) whole-spine MRI examinations showed major findings, of which 24 (51.1%) were localized to the thoracolumbar spine. Isolated thoracolumbar injuries included 23 of 34 spinal subdural hematomas, 2 of 3 spinal epidural hematomas, and 9 of 11 vertebral fractures, including five fractures not identified by skeletal survey. Diagnosis of AHT was more common in children with positive, versus negative, whole-spine MRI examinations (76.8% vs 39.1%; $p < .001$).

CONCLUSION. In children with suspected AHT, whole-spine MRI commonly shows isolated thoracolumbar injuries.

CLINICAL IMPACT. The results support performing whole-spine MRI rather than cervical spine MRI in children with suspected AHT.

Abusive head trauma (AHT) is a leading cause of neurologic, cognitive, and developmental impairment in children and is the most common cause of traumatic death in children younger than 4 years old [1–4]. Thorough medical and imaging evaluation is crucial in children with suspected AHT [5]. As pathognomonic injuries for AHT are lacking, the diagnosis is based on a combination of a detailed history, physical examination, and imaging findings that are inconsistent with accidental injuries or any underlying medical condition [3, 6, 7].

[1]Department of Radiology and Imaging Sciences, Indiana University School of Medicine, Riley Hospital for Children, 705 Riley Hospital Dr, Rm 1053, Indianapolis, IN 46202. Address correspondence to B. Karmazyn (Bkarmazy@iupui.edu).

[2]Department of Radiology, University of Wisconsin Hospital and Clinics, Madison, WI.

[3]Indiana University School of Medicine, Indianapolis, IN.

[4]Department of Radiology and Imaging Sciences, Indiana University School of Medicine, Indianapolis, IN.

[5]Department of Biostatistics and Health Data Science, Indiana University School of Medicine, Indianapolis, IN.

[6]Department of Pediatrics, Indiana University School of Medicine, Riley Hospital for Children, Division of Child Protection Programs, Indianapolis, IN.

In recent years, spinal subdural hematoma and ligamentous injuries seen on cervical spine MRI have been recognized as findings that are more commonly associated with AHT than with accidental head trauma and that increase the specificity of the diagnosis of AHT [3, 7]. Evidence now supports the use of cervical spine MRI in children with suspected AHT, and the reported incidence of positive findings on cervical spine MRI has ranged from 15% to 69% [8–13]. However, little such evidence exists for the utility of whole-spine MRI. Prior studies of the utility of spine MRI in children with suspected AHT typically included isolated cervical spine imaging or only a small number of children who underwent whole-spine MRI [8, 9, 14, 15].

Given the limited evidence on the use of whole-spine MRI in children with suspected AHT, guidelines and practices vary. A policy statement from the American Academy of Pediatrics suggests that MRI of the spine should be considered to assess for AHT, emphasizing evidence on cervical spine injuries without discussing the use of whole-spine MRI [3]. In the American College of Radiology Appropriateness Criteria, performance of cervical spine MRI in children with suspected AHT is rated as "usually appropriate," whereas the use of whole-spine MRI is rated lower as "may be appropriate" [16]. To our knowledge, only the Royal College of Radiologists and a consensus statement by multiple societies have advocated for performing whole-spine MRI for evaluation of AHT [7, 17]. Thus, we conducted this study to evaluate whether whole-spine MRI in children with suspected AHT shows additional abnormalities not identified on cervical spine MRI.

HIGHLIGHTS

Key Finding

- *Among 148 children with suspected AHT who underwent whole-spine MRI, 23.0% of examinations showed injuries localized to the thoracolumbar spine; injuries were localized to the thoracolumbar spine in 51.1% of examinations with major findings (subdural hematoma, epidural hematoma, ligamentous injury, or fracture not identified by skeletal survey).*

Importance

- *When performing spine MRI in children with suspected AHT, whole-spine MRI rather than cervical spine MRI may be warranted to avoid missing isolated thoracolumbar injuries.*

Methods

Patients

This was a HIPAA-compliant retrospective single-center study performed at Riley Hospital for Children at Indiana University Health and approved by the institutional review board with waiver of written informed consent. Riley Hospital for Children is a tertiary medical center that evaluates a high volume of children with suspected child abuse. We searched the institutional radiology information system for all children younger than 3 years old who underwent skeletal survey for suspected child abuse and head MRI within 7 days after skeletal survey from January 2019 to December 2020. During this period, whole-spine MRI was routinely performed in children with clinical evaluation and/or first-line imaging (head CT or skeletal survey) suspicious for AHT. Patients were included whether or not they also underwent head CT and whether or not they underwent additional whole-body MRI. Patients were excluded if they underwent MRI limited to only the cervical spine, if they had an underlying disorder anticipated to exhibit imaging findings that potentially overlap with imaging findings of trauma (e.g., skeletal dysplasia, metabolic disease, rickets, or systemic disease predisposing to bleeding or bony abnormalities), or if they had prior spinal surgery or trauma. Other underlying diseases not anticipated to exhibit imaging findings that potentially overlap with findings of trauma did not serve as exclusion criteria. The REDCap tool, a secure electronic database, was used to collect and store all study-related information [18].

Review of Medical Records and Imaging Reports

Demographic information and underlying diseases were obtained by medical record review. In addition, final diagnoses of child abuse (classified as child abuse, indeterminate, or not child abuse) were recorded from medical records. These diagnoses had been established by board-certified child abuse pediatricians on the basis of a detailed medical history; complete physical examination including a dilated eye examination by a pediatric ophthalmologist; laboratory values; and imaging studies for accidental trauma, nonaccidental trauma, and medical conditions.

The presence of intracranial hemorrhage (classified as subarachnoid, subdural, or epidural), acute ischemia (defined by loss of gray-white matter differentiation and restricted diffusion), brain laceration, brain contusion, and cortical venous thrombosis was based on review of the clinical reports from head MRI examinations. The number and location of fractures were recorded on the basis of review of the clinical reports from skeletal surveys and any available head CT examinations.

Whole-Spine MRI Examinations

In patients who underwent whole-spine MRI, the whole-spine MRI examination was performed either concurrently with the brain MRI examination or within 2 days of the brain MRI examination. MRI examinations were performed on a 1.5-T (Magnetom Avanto, Siemens Healthineers) or 3-T (Magnetom Skyra, Siemens Healthineers) system. The whole-spine MRI protocol generally included sagittal T2-weighted 3D turbo spin-echo (TSE) (SPACE, Siemens Healthineers), sagittal T1-weighted TSE, sagittal STIR, axial T2-weighted TSE, and axial T1-weighted 3D gradient-recalled echo (GRE) (VIBE, Siemens Healthineers) sequences (Table S1, which can be viewed in the *AJR* electronic supplement to this article, available at doi.org/10.2214/AJR.21.26674). The sagittal T2-weighted 3D TSE sequence was reformatted in the axial and coronal planes. In addition, sagittal DWI and axial T2*-weighted GRE sequences were performed at the request of the protocoling radiologist.

For the purposes of this study, the whole-spine MRI examinations were reviewed independently by two pediatric neuroradiologists (N.S. and D.A.S., with 7 and 3 years of posttraining experience, respectively), who were blinded to clinical information and other imaging examinations. The readers recorded the presence of the following four spinal injuries: intraspinal hemorrhage (classified as subarachnoid, subdural, or epidural), ligamentous injury, spinal cord edema, and vertebral fractures. For each detected injury, the radiologists also recorded all vertebral levels involved by the injury. Discrepancies between the two radiologists regarding the overall presence or absence of spinal injuries were resolved by a third pediatric neuroradiologist (R.R., with 7 years of posttraining experience); the third radiologist did not assess the vertebral level of injuries.

The total number of each type of injury at each vertebral level was determined across the patient sample. This determination considered only those injuries deemed to be present by both radiologists who reviewed all examinations or, in the case of discrepancy, those deemed to be present after review by the third radiologist. Such injuries were counted as 0.5 in the total number of the given injury type at the given level when only one of the first two radiologists deemed the level to be involved by the injury. Further, injuries were classified as involving the cervical spine if at least one of the two radiologists considered the injury to involve at least one cervical level, and injuries were classified as involving the thoracolumbar spine if at least one of the two radiologists considered the injury to involve at least one thoracolumbar level.

Criteria for Spinal Injuries on Whole-Spine MRI

Spinal subarachnoid hemorrhage was defined as scattered hemorrhage along the nerve roots or hemorrhage within the spinal canal showing a horizontal CSF-blood interface, without mass effect on the spinal cord or nerve roots. Spinal subdural hemorrhage was defined as hemorrhage along the periphery of the spinal canal with preservation of the epidural fat and without elevation of the dura. Spinal epidural hemorrhage was defined as hemorrhage along the anterior or posterior spinal canal with obliteration of the epidural fat and uplifting of the dura. Ligamentous injury was defined as edema within and surrounding the ligaments or obvious ligamentous disruption or stripping. Spinal cord edema was defined as hyperintense signal within the spinal cord on a T2-weighted sequence. Fracture was defined as the presence of bone marrow edema, decreased vertebral body height, or the presence of a fracture line.

Among the spinal injuries, subdural hematoma, epidural hematoma, ligamentous injury, and fracture not identified by skeletal survey were considered to represent major findings. Though MRI can provide additional details regarding known fractures (e.g., confirmation of acuity or of any retropulsion of fracture), vertebral fractures that had already been identified by skeletal survey were not considered to represent major findings.

Classifications of Child Abuse and of Abusive Head Trauma

For the purposes of analysis, children were classified in a binary fashion as diagnosed with child abuse or not diagnosed with abuse; the latter category included those in whom the diagnosis of child abuse was indeterminate based on the assessment by the child abuse pediatrician. In addition, for the purposes of this study, patients were retrospectively classified in terms of the presence or absence of AHT. AHT was defined as any intracranial injury (intracranial hemorrhage, acute ischemia, brain laceration, brain contusion, or cortical venous thrombosis) on the previously described review of the reports from head MRI examinations, without any other underlying medical condition or accident that could explain these abnormalities in children diagnosed with child abuse by the child abuse pediatrician.

Statistical Analysis

Spinal injuries on whole-spine MRI were summarized, including a descriptive summary of those injuries localized to the thoracolumbar spine. Agreement between radiologists for the presence of findings on whole-spine MRI at the examination level was evaluated using kappa coefficients and percentages of absolute agreement. Agreement was classified on the basis of kappa coefficients as follows [19]: 0.01–0.20, none to slight; 0.21–0.40, fair; 0.41–0.60, moderate; 0.61–0.80, substantial; 0.81–1.00, almost perfect agreement. Wilcoxon rank sum tests were used to compare ages, and chi-square tests were used to compare demographic information, clinical information, and injuries between children who underwent whole-spine MRI versus children who did not undergo whole-spine MRI; children in whom whole-spine MRI showed injuries versus those in whom whole-spine MRI did not show injuries; and children who had AHT versus those who did not have AHT, among children who underwent whole-spine MRI. A two-sided 5% significance level was used for all tests. Statistical analyses were performed using SAS (version 9.4, SAS Institute).

Results

Demographic and Clinical Characteristics

From January 2019 to December 2020, 265 children younger than 3 years old underwent skeletal survey and subsequent head MRI for evaluation of suspected child abuse. Four children were excluded because they underwent additional MRI limited to the cervical spine, and five children were excluded because of an underlying disorder anticipated to be associated with imaging findings that potentially overlap with those of trauma (one patient each for hemophilia, Caffey disease, achondroplasia, Antley-Bixler syndrome, and myelomeningocele). The final study group included 256 children (170 boys, 86 girls) with a mean age of 5.9 months (range, 0.1–30.1 months). A total of 191 (74.6%) children underwent head CT.

A total of 148 (57.8%) children underwent whole-spine MRI in addition to head MRI, and 108 (42.2%) children were evaluated by head MRI without additional whole-spine MRI. The whole-spine MRI examination was performed concurrently with the brain MRI examination in 142 of 148 (95.9%) children and within 2 days of the brain MRI examination in 6 of 148 (4.1%) children. The whole-spine MRI examination included the sagittal DWI sequence in 62 (41.9%) children and the axial T2*-weighted GRE sequence in 28 (18.9%) children.

Fifty-nine children had a history of prematurity, of whom 12 were born extremely premature (gestational age, 23–28 weeks). Seven children had an underlying disease (one patient each for sickle cell disease, DiGeorge syndrome, trisomy 8, 1q21.1 microdeletion syndrome, congenital cytomegalovirus, neonatal abstinence syndrome, and congenital aqueduct stenosis with hydrocephalus) that was not anticipated to exhibit imaging findings that potentially overlap with findings of trauma.

Table 1 compares demographic and clinical characteristics between children evaluated only by head MRI and children evaluated by additional whole-spine MRI. Age and underlying disease were not significantly different between the two groups (both $p > .05$); however, children evaluated with additional whole-spine MRI, compared with children evaluated only by head MRI, were more commonly female (39.9% vs 25.0%; $p = .01$) and more commonly born premature (29.1% vs 14.8%; $p = .008$).

TABLE 1: Comparison of Demographic and Clinical Findings Between Children Evaluated Only by Head MRI and Children Evaluated by Additional Whole-Spine MRI

Characteristic	Only Head MRI (n = 108)	Additional Whole-Spine MRI (n = 148)	Total (n = 256)	p
Age (mo), mean (range)	5.5 (0.1–23.1)	6.1 (0.3–30.1)	5.9 (0.1–30.1)	.24
Sex				.01
Female	27 (25.0)	59 (39.9)	86 (33.6)	
Male	81 (75.0)	89 (60.1)	170 (66.4)	
Prematurity	16 (14.8)	43 (29.1)	59 (23.0)	.008
Underlying disease	4 (3.7)	3 (2.0)	7 (2.7)	.42
Diagnosis of child abuse	21 (19.4)	106 (71.6)	127 (49.6)	< .001
Diagnosis of abusive head trauma	2 (1.9)	79 (53.4)	81 (31.6)	< .001
Physical injury on examination	35 (32.4)	79 (53.4)	114 (44.5)	.001
Bruising	26 (24.1)	53 (35.8)	79 (30.9)	.045
Burn injury	2 (1.9)	2 (1.4)	4 (1.6)	.75
Retinal hemorrhage	5 (4.6)	35 (23.6)	40 (15.6)	< .001
Subconjunctival hemorrhage	1 (0.9)	8 (5.4)	9 (3.5)	.06
Torn frenulum	2 (1.9)	2 (1.4)	4 (1.6)	.75

Note—Unless otherwise indicated, data are expressed as number of patients with percentage in parentheses.

Clinical record review revealed evidence of injury on physical examination in 114 of 256 (44.5%) children. The most common injuries on physical examination were bruising (n = 79), retinal hemorrhage (n = 40), subconjunctival hemorrhage (n = 9), torn frenulum (n = 4), and burn injuries (n = 4). Children evaluated with additional whole-spine MRI, compared with children evaluated only by head MRI, had significantly higher frequencies of injury on physical examination (53.4% vs 32.4%; p = .001), including a higher frequency of retinal hemorrhage (23.6% vs 4.6%; p < .001).

Child abuse was diagnosed in 127 of 256 (49.6%) children, and AHT was diagnosed in 81 of 256 (31.6%) children. Children evaluated with additional whole-spine MRI, compared with children evaluated only by head MRI, had significantly higher frequencies of child abuse diagnosis (106/148 [71.6%] vs 21/108 [19.4%]; p < .001) and AHT diagnosis (79/148 [53.4%] vs 2/108 [1.9%]; p < .001).

Table 2 summarizes injuries identified by head MRI, head CT if available, and skeletal survey. MRI of the head was abnormal in 125 of 256 (48.8%) children; of these 125 children, 81 (64.8%) had AHT. The most common findings in these 125 children were subdural hematoma in 108 (86.4%), subarachnoid hemorrhage in 56 (44.8%), acute ischemia in 38 (30.4%), and brain contusion in 6 (4.8%). Children evaluated with additional whole-spine MRI, compared with children evaluated by only head MRI, had significantly higher frequencies of subdural hematoma (59.5% vs 18.5%; p < .001), acute ischemia (24.3% vs 1.9%; p < .001), and brain contusion (4.1% vs 0.0%; p < .001). The skeletal survey was positive in 108 of 256 (42.2%) children. Fractures on skeletal survey and/or head CT most commonly involved the skull (n = 50), ribs (n = 37), lower extremities (n = 33), upper extremities (n = 18), and clavicle (n = 13). Children evaluated with additional whole-spine MRI, compared with children evaluated by only head MRI, had a significantly higher frequency of skull fractures (25.7% vs 11.1%; p = .004).

Whole-Spine MRI

Interobserver variability—Agreement between the two radiologists was almost perfect for presence of any injury on whole-spine MRI (κ = 0.86; 95% CI, 0.77–0.94), with 93% (138/148) absolute agreement; almost perfect for presence of intraspinal hemorrhage (κ = 0.90; 95% CI, 0.82–0.98), with 96% (142/148) absolute agreement; substantial for presence of subdural hemorrhage (κ = 0.79; 95% CI, 0.67–0.91), with 93% (138/148) absolute agreement; substantial for spinal ligamentous injuries (κ = 0.69; 95% CI, 0.50–0.88), with 94% (139/148) absolute agreement; substantial for spinal edema (κ = 0.66; 95% CI, 0.04–1.00), with 99% (147/148) absolute agreement; and almost perfect for vertebral fractures (κ = 0.95; 95% CI, 0.86–1.00), with 99% (147/148) absolute agreement.

Findings—On the basis of the consensus interpretations, injuries on whole-spine MRI were found in 57 of 148 (38.5%) children who underwent additional whole-spine MRI; major findings were identified in 47 of 148 (31.8%) children who underwent whole-spine MRI. The total number of specific types of spinal injuries at each vertebral level is depicted in Figure 1. In 34 of 148 (23.0%) children, whole-spine MRI showed injuries localized to the thoracolumbar spine. In 24 of 47 (51.1%) children with major findings, the major findings were localized to the thoracolumbar spine (Table 3).

Spinal subdural hematoma was found in 34 of 148 (23.0%) children. Of these 34 cases, 23 (67.6%) only involved the thoracolumbar spine (Figs. 2 and 3). A total of 21 of 34 (61.8%) children with spinal subdural hematoma also had intracranial subdural hematoma. Three children with isolated spinal subdural hematoma also had a vertebral spine fracture. Spinal epidural hematoma was found in 3 of 148 (2.0%) children (Fig. 4). In two of these children, the spinal epidural hematoma only involved the thoracolumbar spine. The spinal epidural hematoma was associated with

TABLE 2: Comparison of Injuries Found on Skeletal Survey, Head CT, and Head MRI Between Children Evaluated Only by Head MRI and Children Evaluated by Additional Whole-Spine MRI

Injury or Fracture	Only Head MRI (n = 108)	Additional Whole-Spine MRI (n = 148)	Total (n = 256)	p
Subarachnoid hemorrhage	12 (11.1)	44 (29.7)	56 (21.9)	< .001
Subdural hematoma	20 (18.5)	88 (59.5)	108 (42.2)	< .001
Epidural hematoma	2 (1.9)	8 (5.4)	10 (3.9)	.15
Acute ischemia	2 (1.9)	36 (24.3)	38 (14.8)	< .001
Brain laceration	1 (0.9)	4 (2.7)	5 (2.0)	.31
Brain contusion	0 (0.0)	6 (4.1)	6 (2.3)	< .001
Cortical venous thrombus	0 (0.0)	5 (3.4)	5 (2.0)	.05
Fracture on skeletal survey	37 (34.3)	71 (48.0)	108 (42.2)	.03
Skull	12 (11.1)	38 (25.7)	50 (19.5), 60[a]	.004
Ribs	14 (13.0)	23 (15.5)	37 (14.5), 149[a,b]	.56
Upper extremity	7 (6.5)	11 (7.4)	18 (7.0), 19[a,c]	.77
Lower extremity	15 (13.9)	18 (12.2)	33 (12.9), 55[a,d]	.68
Spine	1 (0.9)	6 (4.1)	7 (2.7), 16[a]	.13
Hands	0 (0.0)	1 (0.7)	1 (0.4), 1[a]	.39
Feet	0 (0.0)	1 (0.7)	1 (0.4), 3[a]	.39
Clavicle	3 (2.8)	10 (6.8)	13 (5.1), 13[a]	.15

Note—Data are expressed as number of patients with percentage in parentheses.
[a]Number of fractures, considering possible multiple fractures in a single patient.
[b]Includes 55 posterior rib fractures and 10 costochondral rib fractures.
[c]Includes four classic metaphyseal lesions (CMLs).
[d]Includes 28 CMLs.

TABLE 3: Frequency and Location of Spinal Injuries Detected on Whole-Spine MRI

Spinal Injury	Total	Cervical Spine	Thoracolumbar Spine	Only Thoracolumbar Spine
Subarachnoid hemorrhage	9	0	9	9
Subdural hematoma	34	11	31	23
Epidural hematoma	3	1	3	2
Ligamentous injury	15	15	1	0
Spinal cord edema	2	2	2	0
Vertebral fracture	11	2	10	9

Note—Data are expressed as number of patients. Injuries may involve both the cervical spine and thoracolumbar spine in an individual patient.

intracranial subdural hematoma in two children and with intracranial epidural hematoma and spinal vertebral fracture in one child. Spinal subarachnoid hemorrhage was found in 9 of 148 (6.1%) children; all involved only the thoracolumbar spine (Fig. 2). Six of these children also had spinal subdural hemorrhage. None of these children also had intracranial subarachnoid hemorrhage.

Spinal ligamentous injury was found in 15 of 148 (10.1%) children. The most commonly injured ligament was the nuchal ligament (n = 9) (Figs. 2 and 4). Extension of interspinous ligamentous injury from the cervical spine to the thoracic spine (T9-10) was observed in one patient by one of the two radiologists who performed the retrospective image review. Otherwise, the spinal ligamentous injuries involved only the cervical spine in all cases for both readers. Spinal cord edema was found in 2 of 148 (1.4%) children; both involved the spinal cord at both the cervical and thoracic levels (Fig. 2).

Spinal vertebral fracture was found in 11 of 148 (7.4%) children. Nine (81.8%) fractures were located only in the thoracolumbar spine. Seven fractures, including five localized to the thoracolumbar spine, were not prospectively identified on the skeletal survey (Figs. 2 and 4). Only one vertebral fracture identified on skeletal survey was not identified on whole-spine MRI. Specifically, a chronic L4 fracture found on skeletal survey was not identified on whole-spine MRI (Fig. 5).

Comparison of Children With Positive Versus Negative Findings on Whole-Spine MRI

Children with positive findings on whole-spine MRI, compared with those with negative findings on whole-spine MRI, were significantly more likely to have a diagnosis of child abuse (91.1% vs 59.8%; p < .001), a diagnosis of AHT (76.8% vs 39.1%; p < .001), evidence of injury on physical examination (73.2% vs 41.3%; $p < .001$), and retinal hemorrhage (46.4% vs 9.8%; $p < .001$). Further comparisons between these two groups are provided in Table 4.

Comparison of Children Evaluated by Whole-Spine MRI Who Were Diagnosed Versus Not Diagnosed With Abusive Head Trauma

A total of 79 of 148 (53.4%) children who underwent whole-spine MRI were diagnosed with AHT. Among children evaluated by whole-spine MRI, those diagnosed with AHT, in comparison with those not diagnosed with AHT, were significantly more likely to have retinal hemorrhage (41.8% vs 2.9%; $p < .001$), intracranial subdural hematoma (91.1% vs 23.2%; $p < .001$), acute ischemia (38.0% vs 8.7%; $p < .001$), brain contusion (7.6% vs 0.0%; $p = .02$), and any spinal injury (54.4% vs 18.8%; $p < .001$). Further comparisons between these two groups are provided in Table 5.

Discussion

In this study, we retrospectively reviewed whole-spine MRI examinations performed in children with suspected AHT, with attention to findings present only in the thoracolumbar spine. In 23.0% of children who underwent whole-spine MRI, all injuries were observed only in the thoracolumbar spine. In addition, major findings (subdural hematoma, epidural hematoma, ligamentous injury, and spine fracture not identified by skeletal survey) were detected in 31.8% of whole-spine MRI examinations. In

TABLE 4: Comparison Between Children With Negative and Positive Findings on Whole-Spine MRI

Characteristic	Negative (n = 92)	Positive (n = 56)	p
Age (mo), mean (range)	6.1 (1.0–24.9)	6.1 (0.1–30.1)	.68
Sex			
Female	38 (41.3)	21 (37.5)	.65
Male	54 (58.7)	35 (62.5)	
Prematurity	30 (32.6)	13 (23.2)	.22
Underlying disease	3 (3.3)	0 (0.0)	.17
Diagnosis of child abuse	55 (59.8)	51 (91.1)	< .001
Diagnosis of abusive head trauma	36 (39.1)	43 (76.8)	< .001
Physical injury on examination	38 (41.3)	41 (73.2)	< .001
Bruising	26 (28.3)	27 (48.2)	.01
Burn injury	1 (1.1)	1 (1.8)	.72
Retinal hemorrhage	9 (9.8)	26 (46.4)	< .001
Subconjunctival hemorrhage	4 (4.3)	4 (7.1)	.47
Torn frenulum	2 (2.2)	0 (0.0)	.27
Fracture on skeletal survey	44 (47.8)	27 (48.2)	.96
Skull	25 (27.2)	13 (23.2)	.59
Ribs	15 (16.3)	8 (14.3)	.74
Upper extremity	6 (6.5)	5 (8.9)	.59
Lower extremity	11 (12.0)	7 (12.5)	.92
Spine	1 (1.1)	5 (8.9)	.02
Hands	0 (0.0)	1 (1.8)	.20
Feet	0 (0.0)	1 (1.8)	.20
Clavicle	6 (6.5)	4 (7.1)	.88
Injuries on brain CT and MRI			
Subarachnoid hemorrhage	25 (27.2)	19 (33.9)	.38
Subdural hematoma	46 (50.0)	42 (75.0)	.003
Epidural hematoma	6 (6.5)	2 (3.6)	.44
Acute ischemia	14 (15.2)	22 (39.3)	.001
Brain laceration	0 (0.0)	4 (7.1)	.009
Brain contusion	2 (2.2)	4 (7.1)	.14
Cortical venous thrombus	2 (2.2)	3 (5.4)	.30

Note—Unless otherwise indicated, data are expressed as number of patients with percentage in parentheses.

TABLE 5: Comparison Between Children With and Without Abusive Head Trauma (AHT) Among Children Evaluated by Whole-Spine MRI

Characteristic	No AHT ($n = 69$)	AHT ($n = 79$)	p
Age (mo), mean (range)	7.0 (0.3–24.9)	5.2 (1.0–30.1)	.009
Sex			
Female	28 (40.6)	31 (39.2)	.87
Male	41 (59.4)	48 (60.8)	
Prematurity	18 (26.1)	25 (31.6)	.46
Underlying disease	3 (4.3)	0 (0.0)	.06
Diagnosis of child abuse	27 (39.1)	79 (100)	< .001
Physical injury on examination	23 (33.3)	56 (70.9)	< .001
Bruising	17 (24.6)	36 (45.6)	.008
Burn injury	1 (1.4)	1 (1.3)	.92
Retinal hemorrhage	2 (2.9)	33 (41.8)	< .001
Subconjunctival hemorrhage	3 (4.3)	5 (6.3)	.60
Torn frenulum	1 (1.4)	1 (1.3)	.92
Fracture on skeletal survey	37 (53.6)	34 (43.0)	.20
Skull	22 (31.9)	16 (20.3)	.11
Ribs	10 (14.5)	13 (16.5)	.74
Upper extremity	2 (2.9)	9 (11.4)	.049
Lower extremity	9 (13.0)	9 (11.4)	.76
Spine	4 (5.8)	2 (2.5)	.32
Hands	1 (1.4)	0 (0.0)	.28
Feet	1 (1.4)	0 (0.0)	.28
Clavicle	1 (1.4)	8 (10.1)	.08
Injuries on brain CT and MRI			
Subarachnoid hemorrhage	16 (23.2)	28 (35.4)	.10
Subdural hematoma	16 (23.2)	72 (91.1)	< .001
Epidural hematoma	4 (5.8)	4 (5.1)	.84
Acute ischemia	6 (8.7)	30 (38.0)	< .001
Brain laceration	0 (0.0)	4 (5.1)	.06
Brain contusion	0 (0.0)	6 (7.6)	.02
Cortical venous thrombus	1 (1.4)	4 (5.1)	.23
Any spine injury on whole-spine MRI	13 (18.8)	43 (54.4)	< .001
Hemorrhage	3 (4.3)	40 (50.6)	< .001
Ligamentous injury	3 (4.3)	12 (15.2)	.03
Spinal cord edema	0 (0.0)	2 (2.5)	.18
Vertebral fracture	5 (7.2)	6 (7.6)	.94

Note—Unless otherwise indicated, data are expressed as number of patients with percentage in parentheses.

51.1% of children with major findings, the major findings were limited to the thoracolumbar spine. Though practice guidelines have recognized the role of cervical spine MRI in children with suspected AHT, our findings indicate a role for whole-spine MRI, rather than cervical spine MRI, in this setting.

Limited available evidence supports the use of whole-spine MRI in children suspected of AHT, which has contributed to variation in published guidelines and institutional practices. Indeed, only a small number of studies have reported findings on whole-spine MRI in children with suspected AHT [8, 9, 14, 15, 20]. To our knowledge, the current study is the largest such study (148 children who underwent whole-spine MRI) as well as the first study to compare children who underwent additional whole-spine MRI with those who were evaluated only by head MRI. This is in contrast to prior studies that included mixed samples in which most children underwent cervical spine MRI [8, 10, 15]. The two largest series (12 and 31 children) that evaluated findings in the thoracolumbar spine on MRI were both performed at the same medical center and compared children with a diagnosis of AHT to children with accidental trauma [8, 15]. In addition, our series is the first, to our knowledge, in which whole-spine MRI examinations underwent detailed independent review by two pediatric neuroradiologists who were blinded to clinical information and other imaging studies; agreement was excellent for most assessed findings.

At the study institution, the indication for whole-spine MRI in children with suspected child abuse is clinical suspicion for AHT. To represent the population for whom whole-spine MRI may be considered, we did not limit the study sample to only children with a diagnosis of AHT. AHT was diagnosed in most children who underwent whole-spine MRI, compared with less than 2% of children who were evaluated only by head MRI. This comparison indicates the performance of whole-spine MRI in children with even a low suspicion of AHT during the study period.

Our findings substantiate existing literature on spinal injuries in children with AHT [9, 10, 12, 21, 22]. A total of 38.5% of whole-spine MRI examinations were positive for spinal injury. Consistent with a prior study [9], the most common spinal injuries were subdural hematoma, ligamentous injury, and vertebral body fracture. The frequency of ligamentous injury of 10.1% is within a broad range of frequencies of 3.8–71% reported in earlier studies [9, 11, 13, 15]. All cases of ligamentous injury involved the cervical spine, and only one case exhibited extension to the thoracic spine (identified by one reader). Ligamentous injuries in the craniocervical junction and cervical spine are hypothesized to be more common in AHT because of substantial repetitive neck stretch and shear stresses from vigorous shaking, as compared with injury resulting from a single impact in children with accidental neck trauma [22].

Spinal subdural hematoma is considered to be specific for AHT, as it is uncommon after accidental injury [8, 15]. In a prior study of children with AHT [8], subdural hematoma involving the thoracolumbar spine was observed in 63% (24/38) of children who underwent thoracolumbar imaging (7 imaged by both MRI of the thoracolumbar spine and CT of the abdomen and pelvis, 5 by only MRI of the thoracolumbar spine, 26 by only CT of the abdomen and pelvis). In another study [15], 32 of 67 (48%) children with AHT who underwent spine MRI exhibited spinal subdural hematoma. However, only 31 of the spine MRI examinations included the whole spine; of these, spinal subdural hematoma was present in 21 (67%). Further, 32 of 54 (59.3%) children with AHT and intracranial subdural hematoma also had spinal subdural hematoma, as compared with 1 of 20 (5%) children with subdural hematoma due to accidental injury, supporting the specificity of spinal subdural hematoma for AHT. The authors hypothesized that, compared with accidental trauma, repeated trauma from AHT pulls the arachnoid membrane away from the underlying dura, allowing posterior fossa subdural blood to migrate caudally into the spinal subdural space [15]. The prior studies lack rigorous analysis of the frequency of spinal subdural hematoma that is localized to the thoracolumbar spine. In the current study, spinal subdural hematoma was found in 23.0% of children who underwent whole-spine MRI; in 67.6% of those children, the subdural hematoma was only seen in the thoracolumbar spine. These findings support the clinical relevance of whole-spine MRI in this population.

In an earlier series of 67 children with AHT, only one child had epidural hematoma associated with spinal fracture [8]. In our series, only 2.0% of children had spinal epidural hematoma, and only one child with spinal epidural hematoma also had spinal vertebral fracture. Further, all nine cases of spinal subarachnoid hemorrhage involved only the thoracolumbar spine. To our knowledge, no study has evaluated the specificity of subarachnoid hemorrhage for AHT. Future studies can further evaluate the clinical significance of spinal subarachnoid hemorrhage in children with suspected AHT.

Imaging of the thoracolumbar spine also increased detection of spinal vertebral fractures. Vertebral fractures in child abuse most commonly involve the thoracolumbar lumbar spine and rarely involve the cervical spine [14]. It is therefore not surprising that 81.8% of spinal fractures in the present series only involved the thoracolumbar spine. In seven patients, thoracolumbar spine fractures had not been detected on the skeletal survey radiographs. We identified only one case of a false-negative interpretation for vertebral fracture on whole-spine MRI, occurring in a child with a chronic L4 fracture. A paucity of prior evidence describes the detection of vertebral fractures by MRI that are occult on radiographs. In a series of 14 children with 22 fractures who underwent selective spine imaging by CT and MRI, four spinal fractures were detected only by these modalities. Details on the level of the fractures were lacking [14]. In another series, two of 11 children who underwent whole-spine MRI had thoracic vertebral fractures that were not seen on radiographs [20].

Our study has limitations. First, this was a retrospective study conducted at a single institution. In addition, although whole-spine MRI was performed in children with suspicion for AHT, the practice of requesting whole-spine MRI likely varied among referring clinicians, which may have introduced selection bias. In some children, the whole-spine MRI examination did not include GRE and DWI sequences; thus, subtle abnormalities in the spinal cord and subtle intraspinal hemorrhages may have been missed in these cases. Because this was a retrospective study, we do not know whether findings from whole-spine MRI would have altered clinical management. Finally, though children with positive findings on whole-spine MRI were significantly more likely to be diagnosed with AHT and to have evidence of injury on physical examination, we do not know from this study whether physical evidence of injury should be used to select children with suspected AHT to undergo whole-spine MRI.

In conclusion, to our knowledge, this study represents the largest reported series of children with suspected AHT who were evaluated by whole-spine MRI. In 23.0% of children who underwent whole-spine MRI, all injuries were observed in the thoracolumbar spine. Further, in 51.1% of children with major findings (subdural hematoma, epidural hematoma, ligamentous injury, and spine fracture not identified by skeletal survey) on whole-spine MRI, the major findings were localized to the thoracolumbar spine. These results support performing MRI of the whole spine rather than of only the cervical spine in children with suspected AHT.

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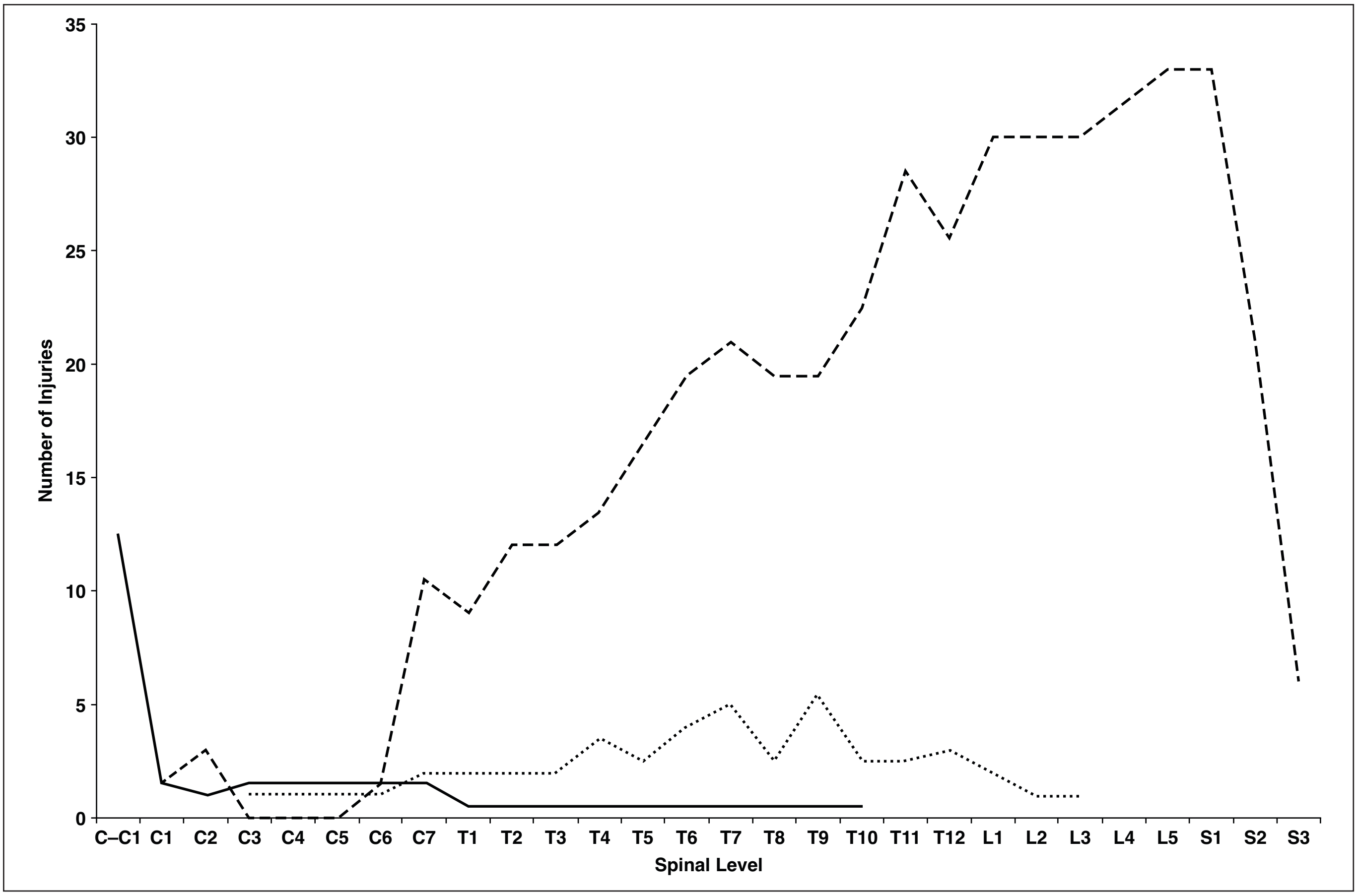
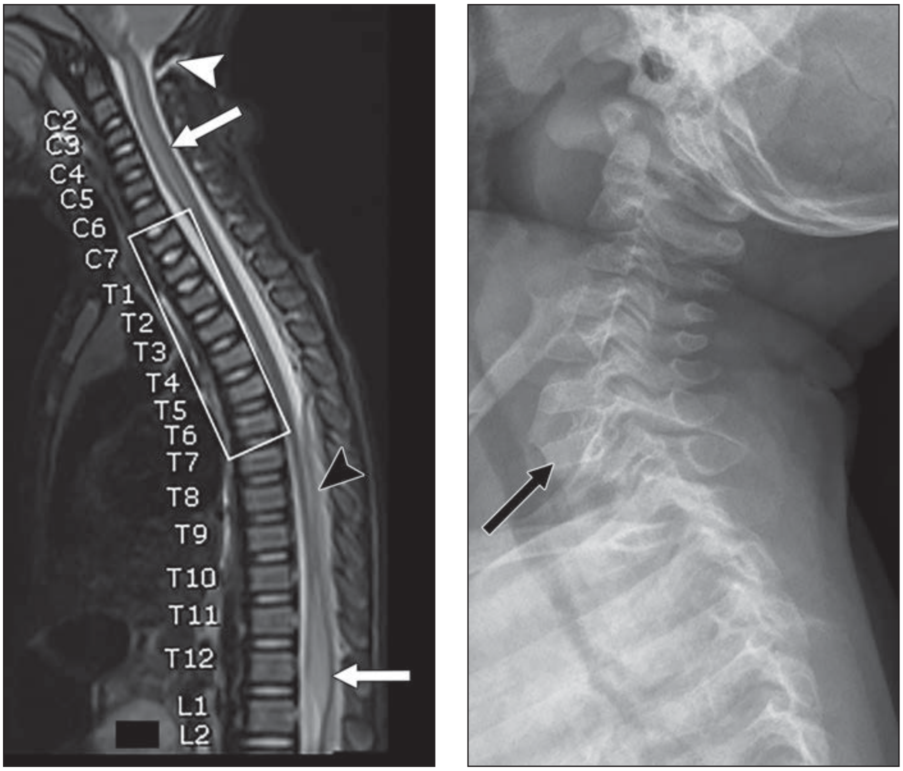


Fig. 1—Graph shows total number of injuries detected at each vertebral level on whole-spine MRI across study sample. Solid line indicates ligamentous injuries, dotted line indicates vertebral fractures, and dashed line indicates subdural hematoma. C–C1 = craniocervical junction.



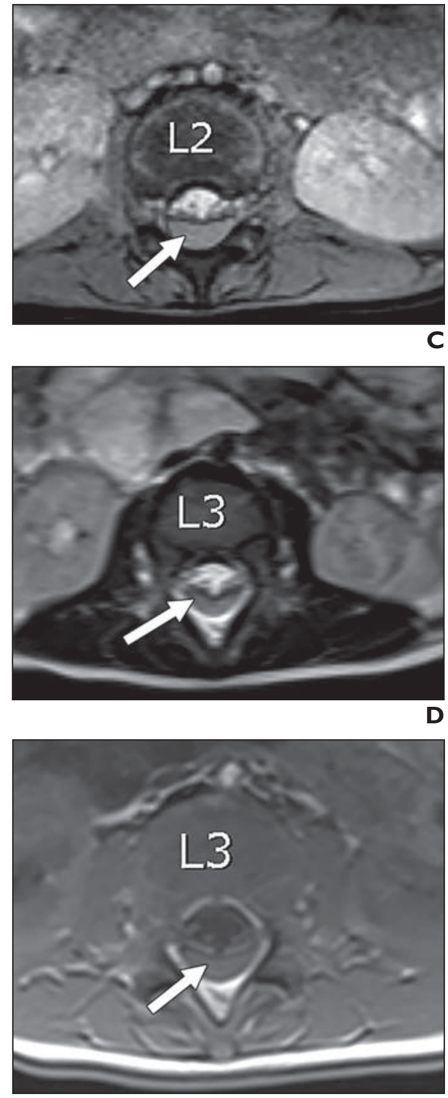


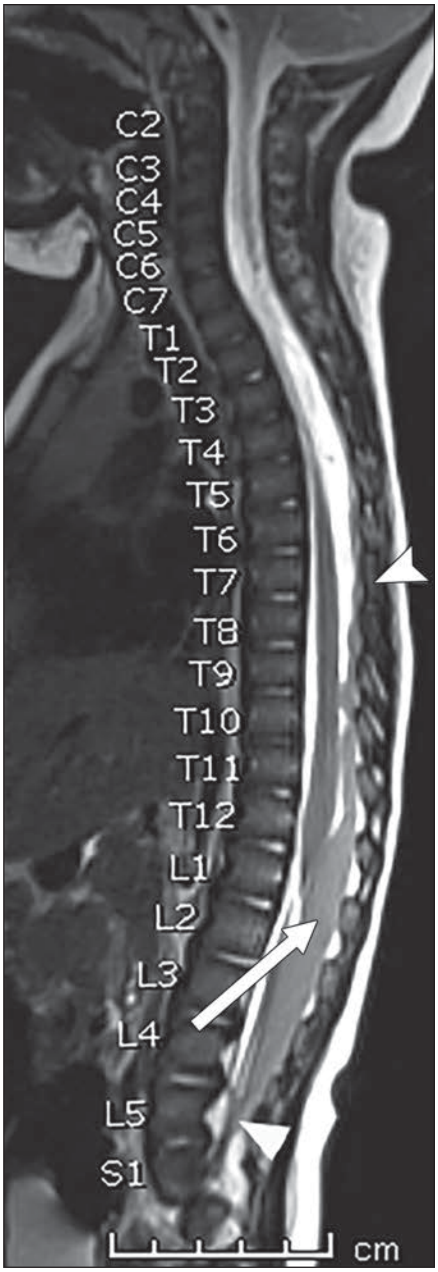
Fig. 2—Previously healthy 17-month-old boy who presented with bilateral ear bruising and left forearm swelling. He also had bilateral retinal hemorrhages, severe acute hypoxic brain injury with cerebellar tonsillar herniation, and intracranial subdural hematoma. Child was diagnosed with abusive head trauma.

A, Sagittal 3D T2-weighted turbo spin-echo image from whole-spine MRI shows edema in C1-2 interspinous ligament consistent with nuchal ligamentous injury (*white arrowhead*), spinal cord edema at level of cervical and thoracic spine (*arrows*), compression fractures from C7 to T6 (*rectangle*), and subdural hematoma extending along thoracic spine (*black arrowhead*). Subdural hematoma is isolated to thoracolumbar spine.

B, Lateral radiograph of thoracic spine was clinically interpreted as negative, though mild C7 compression fracture (*arrow*) can be retrospectively identified.

C, Axial gradient-recalled echo T2-weighted MR image at L2 shows straight blood-CSF interface, consistent with subarachnoid hemorrhage (*arrow*). Subarachnoid hemorrhage is isolated to thoracolumbar spine.

D and **E,** Axial turbo spin-echo T2-weighted (**D**) and axial spin-echo T1-weighted (**E**) MR images show posterior hematoma with preserved epidural space, consistent with subdural hematoma (*arrows*).



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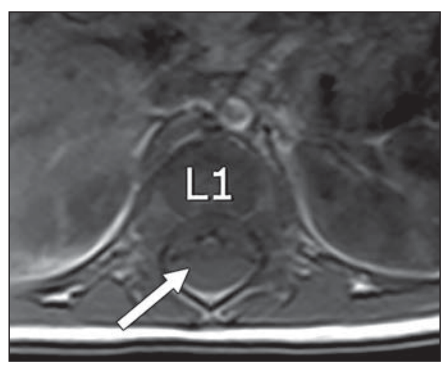
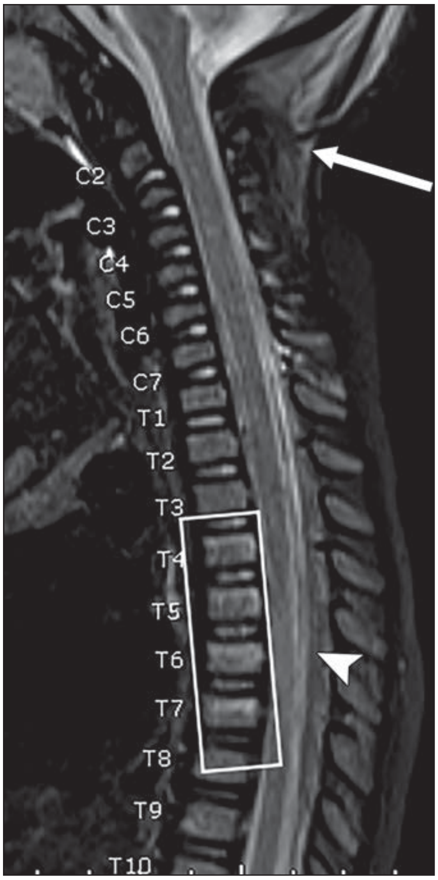


B

Fig. 3—7-month-old boy, born at gestational age 35.5 weeks, who presented after fall from his father's arms. He had bruises in both forearms; bilateral retinal hemorrhage; and intracranial subdural hematoma in interhemispheric falx, both occipital and cerebellar hemispheres, and tentorium. Child was diagnosed with abusive head trauma.

A, Sagittal 3D T2-weighted turbo spin-echo image from whole-spine MRI shows subdural hematoma (*arrow*) extending from midthoracic spine to sacrum (*arrowheads*). Subdural hematoma is isolated to thoracolumbar spine.

B, Axial spin-echo T1-weighted MR image at L1 shows posterior hematoma and preserved epidural space, consistent with subdural hematoma (*arrow*).



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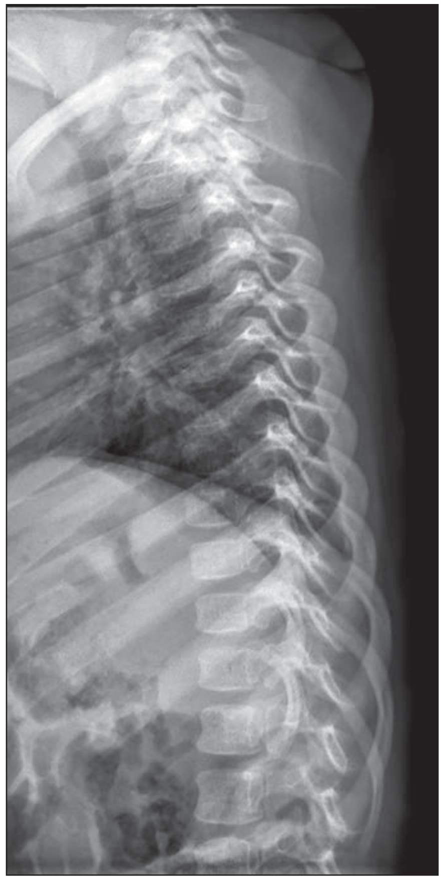

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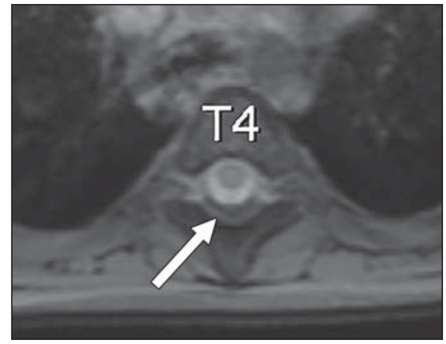

C

Fig. 4—16-month-old boy, born at gestational age 28 weeks, who presented with unexplained facial burns. He also had unexplained rib, humerus, and tibial fractures; three skull fractures; severe acute hypoxic brain injury with transtentorial herniation; and intracranial subdural hematoma in interhemispheric falx and tentorium. Child was diagnosed with abusive head trauma.
A, Sagittal STIR image from whole-spine MRI shows edema in nuchal ligament consistent with ligamentous injury (*arrow*) and epidural hematoma extending along thoracic spine (*arrowhead*), associated with compression fractures from T4 to T7 (*rectangle*). Epidural hematoma is isolated to thoracolumbar spine.
B, Lateral radiograph of thoracic spine was clinically interpreted as negative for spine fracture.
C, Axial gradient-recalled echo T2-weighted MR image at T4 shows posterior hematoma obliterating epidural fat, consistent with epidural hematoma (*arrow*).

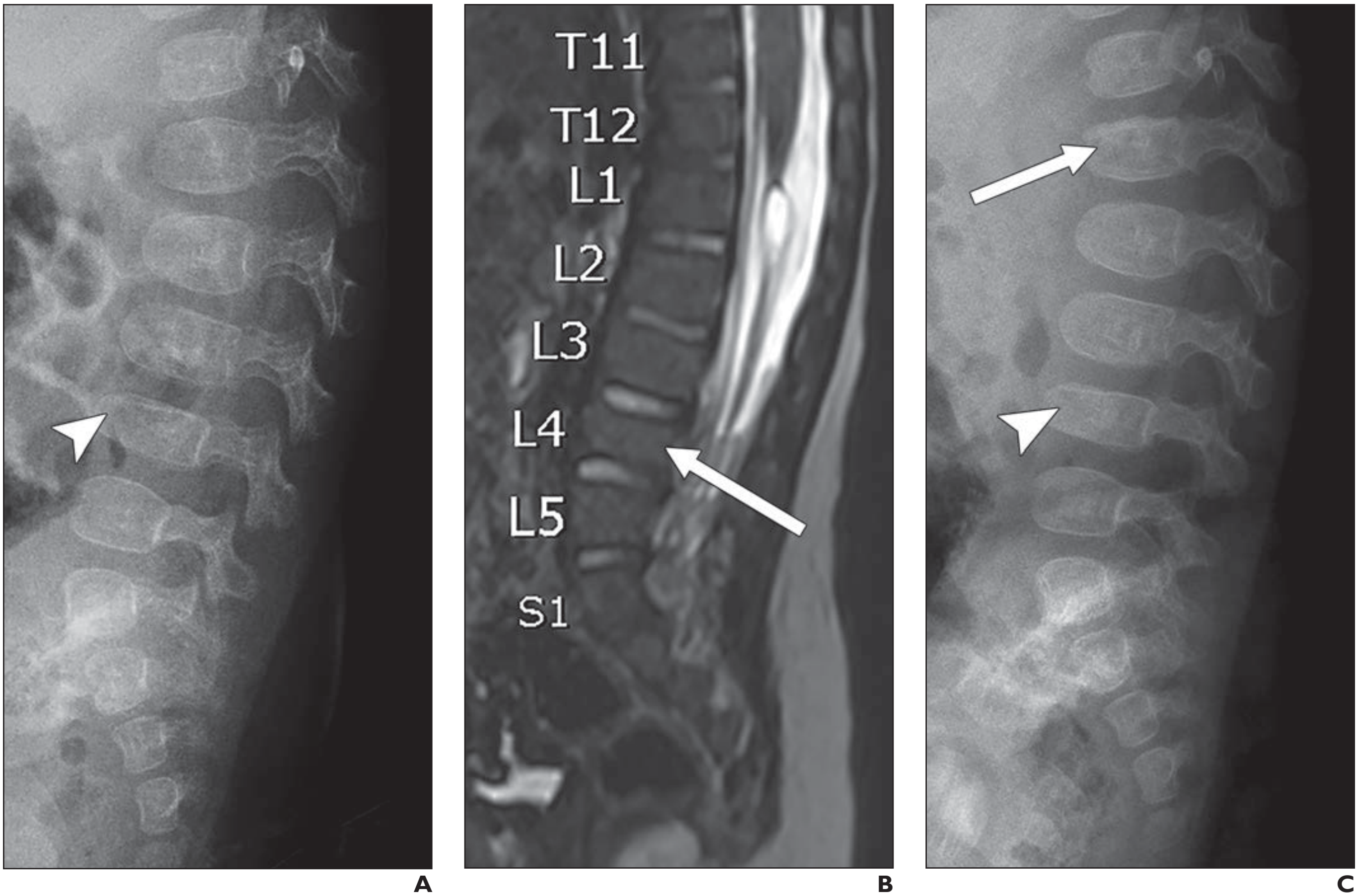

Fig. 5—False-negative whole-spine MRI performed to assess chronic L4 fracture detected by skeletal survey in 5-month-old boy with DiGeorge syndrome who later developed rib fractures (not shown) and L1 compression fracture.

A, Lateral lumbar spine radiograph shows flattening and deformity of L4 (*arrowhead*); examination was clinically interpreted as fracture. No other injuries were identified at time of skeletal survey.

B, Sagittal 3D T2-weighted turbo spin-echo MR image of lumbar spine shows normal bone marrow. Blinded readers both interpreted examination as negative for fracture. In retrospect, mild flattening of L4 vertebral body (*arrow*) is present.

C, Five-month follow-up lumbar spine radiograph shows additional L1 vertebral body compression fracture (*arrow*). Arrowhead denotes compression fracture of L4.

(Editorial Comment starts on next page)

Editorial Comment: Weighing Cost and Benefits

Several aspects of this article warrant further discussion before implementation of the authors' recommended whole-spine MRI protocol consisting of seven MRI series for each patient who undergoes MRI for suspected abusive head trauma (AHT).

The cost of medical care is much higher for children who experience physical abuse compared with children with accidental trauma [1]. This is largely due to higher resource use, including imaging [1]. The cost of increasing resource use should be outweighed by the benefits to patients and/or society.

The authors state that because of their study's retrospective nature, they do not know whether findings from whole-spine MRI would have altered clinical management. However, a cross-sectional comparison study in a large cohort ($n = 595$) reported that no surgical spine interventions were performed in patients who sustained injuries from physical abuse [1].

The whole-spine protocol suggested by the authors would add 16–19 minutes of acquisition time to the MRI examination, which may substantially affect the MRI schedule and increase the need for sedation.

Although the spine imaging practice that is recommended in this study might provide additional medicolegal evidence [2], there is no scientific evidence that this added information would change the outcome of medicolegal proceedings.

Overall, whole-spine imaging has utility in patients undergoing MRI for suspected AHT, but the benefits must be weighed against the costs. At my institution, the cervical spine sequence in the MRI protocol for AHT has been expanded to a single large-FOV sagittal T2-weighted fat-saturated whole-spine sequence to screen for spinal injuries [2]; a comprehensive whole-spine MRI protocol is reserved for use in patients with specific clinical concerns for spinal injury.

Nadja Kadom, MD
Children's Healthcare of Atlanta
Emory University School of Medicine
Atlanta, GA
nkadom@emory.edu

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