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ORIGINAL ARTICLE

Characteristics associated with spine injury on magnetic resonance imaging in children evaluated for abusive head trauma

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Abstract

Background Spine injuries are increasingly common in the evaluation for abusive head trauma (AHT), but additional information is needed to explore the utility of spine MRI in AHT evaluations and to ensure an accurate understanding of injury mechanism.

Objective To assess the incidence of spine injury on MRI in children evaluated for AHT, and to correlate spine MRI findings with clinical characteristics.

Materials and methods We identified children younger than 5 years who were evaluated for AHT with spine MRI. Abuse likelihood was determined a priori by expert consensus. We blindly reviewed spine MRIs and compared spinal injury, abuse likelihood, patient demographics, severity of brain injury, presence of retinal hemorrhages, and pattern of head injury between children with and without spine injury.

Results Forty-five of 76 (59.2%) children had spine injury. Spine injury was associated with more severe injury (longer intensive care stays [P<0.001], lower initial mental status [P=0.01] and longer ventilation times [P=0.001]). Overall abuse likelihood and spine injury were not associated. Spinal subdural hemorrhage was the only finding associated with a combination of retinal hemorrhages (P=0.01), noncontact head injuries (P=0.008) and a diagnosis of AHT (P<0.05). Spinal subdural hemorrhage was associated with other spine injury (P=0.004) but not with intracranial hemorrhage (P=0.28).

Conclusion Spinal injury is seen in most children evaluated for AHT and might be clinically and forensically valuable. Spinal subdural hemorrhage might support a mechanism of severe acceleration/deceleration head injury and a diagnosis of AHT.

Keywords Abusive head trauma · Child abuse · Children · Infants · Magnetic resonance imaging · Spine · Subdural hemorrhage · Trauma

Introduction

Compared to accidental head injury, brain injuries in abusive head trauma (AHT) are more severe, more often diffuse, and commonly involve hypoxic–ischemic injury [1, 2]. Retinal hemorrhages and noncontact injury patterns resulting in multifocal subdural hemorrhages located over the cerebral convexities or within the interhemispheric fissure are also highly associated with AHT [2, 3]. Occult spine injuries are increasingly common in AHT, likely related to increased awareness and screening for injury using improved imaging and autopsy techniques [4]. Although few spine injuries require surgical intervention [5], identification of occult injuries can strengthen maltreatment investigations by highlighting the severity of injury and risk of harm, and by clarifying the mechanism of abusive injuries. Given the potential for detection of clinically significant injury and improved child safety, the American College of Radiology (ACR) recommends MRI of the cervical spine in the evaluation for AHT, and that whole-spine MRI be considered [6].

Despite ACR guidelines, the use of spine MRI for AHT evaluations varies among institutions [7], suggesting that additional research on the utility of spine MRI in children evaluated for AHT is needed to promote its inclusion in

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institutional protocols. Additionally, the mechanism of some spine injuries is unclear [4]. An accurate understanding of injury mechanism is important in the medical assessment of child maltreatment to ensure evidence-based abuse diagnoses.

The purpose of this study was to assess the incidence of spine injury on MRI in children evaluated for AHT, and to correlate these MRI findings with the clinical characteristics of this population. We hypothesized that the clinical characteristics of rotational acceleration/deceleration typical in AHT (noncontact intracranial injury pattern, retinal hemorrhages, and severe diffuse brain injury) would correlate with spine injury.

Materials and methods

All procedures performed in this study were in accordance with the ethics standards of the institutional and national research committees and with the 1964 Helsinki Declaration and its later amendments or comparable ethics standards. Our institutional review board granted a waiver of informed consent, and the study complied with the Health Insurance Portability and Accountability Act of 1996. In this retrospective case series review we identified all children younger than 5 years who received an MRI of the brain for an abuse evaluation between January 2010 and December 2013. During this timeframe, the hospital's child protection team (CPT) used standard guidelines for abuse evaluation, including head CT in any child for whom there were concerns for AHT, and in infants younger than 6 months for whom there were concerns of physical abuse. If concerns for AHT remained based on the head CT or clinical findings, the CPT recommended a non-contrast MRI of the brain and spine. If a brain MRI was the first-line study rather than the head CT, we included the case for analysis if the MRI was part of an AHT evaluation. The spine MRI non-accidental trauma protocol included T1 sagittal, T2 sagittal and axial, 3-D T1 sagittal with axial and coronal reformations, axial gradient echo/susceptibility-weighted imaging, and sagittal short tau inversion recovery (STIR) sequences. The upper thoracic spine was included in cervical spine MR imaging through the 5th thoracic vertebral body. All children who received a brain MRI for an abuse evaluation were included in the study, regardless of whether an MRI spine was obtained or revealed any evidence of intracranial injury. We excluded children with a medical condition that might impact the appearance of spine injuries (skeletal dysplasia, connective tissue disorder, prior spinal surgery, a history of spine injury, or bleeding disorders).

Two members of the hospital's CPT abstracted clinical data from the medical record. They reviewed 10% of charts together to establish a uniform and accurate data collection process, and the lead researcher (A.L.R.; 12 years of experience) reviewed another 10% of data collection that occurred separately to ensure ongoing integrity and consistency. Two board-certified radiologists (a pediatric neuroradiologist, T.G.K., with 27 years' experience in pediatric radiology, 11 years in pediatric neuroradiology, and subspecialty certification in pediatric radiology and neuroradiology; and a pediatric radiologist, C.V.Q., with 10 years' experience in pediatric radiology and subspecialty certification in pediatric radiology and nuclear medicine) reviewed the anonymized spine MRIs and recorded findings by consensus.

Variables included patient demographics (age, gender, race, ethnicity, insurance status); likelihood of abuse (accidental, indeterminate, abuse); whether the child received an MRI of the spine and whether the imaging was of the whole spine or cervical spine only; injury severity (length of intensive care stay, ventilation time, initial mental status described by providers, initial Glasgow Coma Scale [GCS], neurosurgical intervention, and mortality); criminal convictions; confessions; mechanism of head injury (combined, contact, undetermined, noncontact); the presence of retinal hemorrhages; and presenting symptoms of spine injury.

Initial mental status was recorded from the first available physical exam pertaining to the abuse concern. A presenting symptom of spine injury was any symptom documented prior to the spine MRI that the treating provider or CPT consultant thought raised concern for a spine injury. The mechanism of head injury was determined using a previously described classification system based on the pattern and characteristics of the head injury [8]. This method classified injuries as:

(1) Contact: injuries from cranial impact without significant cranial acceleration or deceleration (skull fractures, craniofacial soft-tissue injuries, epidural hemorrhages);
(2) Noncontact: injuries from cranial acceleration or deceleration without evidence of cranial impact (concussion, abnormal subdural collection extending from the interhemispheric region, diffuse axonal injury);
(3) Combined: both contact and noncontact injuries; or
(4) Undetermined: injuries from contact or noncontact mechanisms (subarachnoid hemorrhages, brain contusions or lacerations, a subdural hemorrhage not extending from the interhemispheric region).

We classified children with hypoxic–ischemic injury but no intracranial hemorrhage as "undetermined" and those without intracranial injury confirmed on MRI as "no head injury." Abuse likelihood was determined a priori at the time of the initial CPT consultation. As standard practice, the CPT consultant assigns a physical abuse likelihood score to all cases using a previously described 1–7 scale (Table 1) [9]. A diagnosis of AHT is made by consensus after peer review by the CPT when a child presents with diffuse primary brain injury and extraaxial hemorrhage that cannot be reasonably explained by an accidental

Table 1 Summary of 7-point scale of abuse likelihood

1	Definitely not inflicted injury	Accidental
2	No concern for inflicted injury	While no evaluation can completely exclude abuse, the evaluation has not raised a reasonable suspicion of abuse. The injuries or findings could be reasonably explained by accidental or benign events.
3	Mildly concerning for inflicted injury	Indeterminate
4	Intermediately concerning for inflicted injury	The injuries or findings raise suspicion for abuse, but an accidental or benign event or preexisting medical condition cannot be excluded.
5	Very concerning for inflicted injury	
6	Substantial evidence of inflicted injury	Abuse
7	Definite inflicted injury	To a reasonable degree of medical certainty, the injuries/findings cannot plausibly be explained by accidental injury, preexisting medical illness, reasonable discipline, or benign events.

mechanism or a medical condition. The diagnosis is made after careful consideration of all historical and clinical data in collaboration with a multidisciplinary investigation. Although information about confessions and criminal convictions was collected, this information is unreliable for an accurate medical diagnosis and was not required to classify children as abused. Children <5 years of age were included to align with the narrow definition of AHT developed by the Centers for Disease Control and Prevention [10]. For this study, the cases were grouped into accidental (1–2), indeterminate (3–5), and abuse (6–7). Cases classified as abuse were further divided into "AHT" or "abuse, not AHT." Children with abusive extracranial injuries with no intracranial injuries, or intracranial injuries that were indeterminate for abuse were classified as "abuse, not AHT." To assess the effects of selection bias, we compared variables between children evaluated for AHT who did and did not receive a spine MRI.

Outcome variables included intramedullary injury (spinal cord hemorrhage or edema); extramedullary hemorrhage (subarachnoid, subdural and extradural); spinal fracture or bone marrow edema (bony injury); ligamentous edema or disruption (ligament injury); posterior paraspinous muscle edema; prevertebral soft-tissue swelling; and vertebral and carotid artery injury. Ligamentous injury was defined as ligamentous disruption or the presence of hyperintensity on STIR sequences surrounding the ligaments or membranes (Figs. 1 and 2). Spinal hemorrhages were classified as subdural if there was epidural fatty tissue without dural displacement and epidural if the hemorrhage caused dural displacement toward the spinal cord (Fig. 3). We compared clinical characteristics with the presence of spine injury seen on MRI. To explore the mechanism of spinal subdural hemorrhage (SDH), we performed a post hoc analysis to compare the association between spinal SDH and the presence of other spine injuries and the presence of intracranial hemorrhage. We used the chi-square or Fisher exact test to compare categorical variables. We used the Kruskal-Wallis or Mann-Whitney test to compare continuous variables. *P*-values <0.05 were considered significant. We used statistical software SAS 9.4 (SAS Institute, Cary, NC) for all the analyses.

Results

Study population

The study population is described in Fig. 4. Of the 137 children who received brain MRI as part of a physical abuse evaluation, 76 (55%) received spine MRI (age range 2.0 to 9.3 months; 44

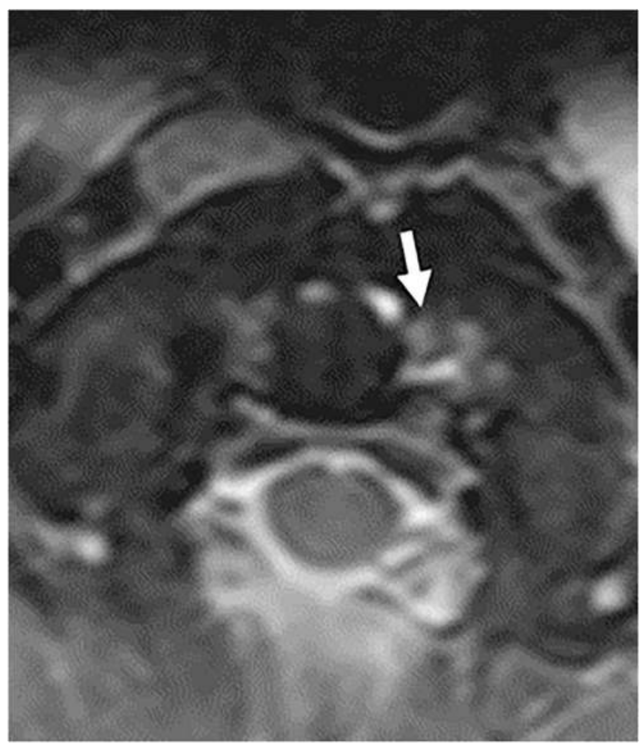


Fig. 1 MRI in a 5-month-old boy who presented with altered mental status requiring ventilatory support. A patterned left leg bruise was noted on exam. Father confessed to slapping the leg in anger. Brain MRI was normal. Axial short tau inversion recovery image of the spine shows left alar ligament edema with surrounding fluid (*arrow*)

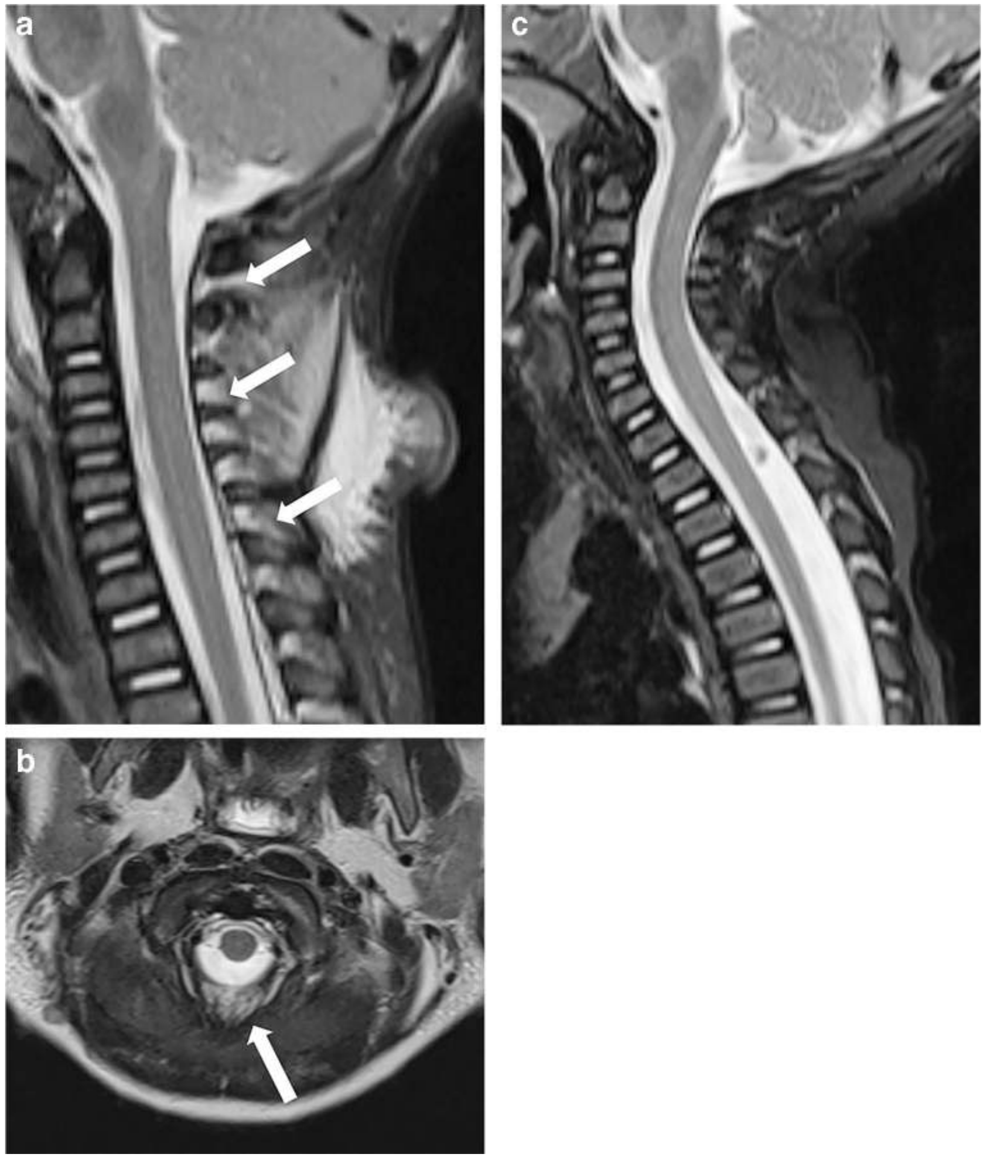


Fig. 2 MRI in a 5-month-old girl who presented with respiratory failure after a reported fall from a bed requiring prolonged intubation and intensive care. Abusive bruising, diffuse subdural intracranial hemorrhage, and severe retinal hemorrhages were also present. **a**, **b** Sagittal (**a**) and axial (**b**) short tau inversion recovery images show interspinous and nuchal ligament edema (*arrows*) in the 5-month-old. **c** Compare with normal sagittal spine MRI in a different child, age 4 months

boys). In the subset of 61 children with AHT, 47 (77%) received an MRI spine. Most spine imaging was of the cervical and upper thoracic spine only (93%). Children were more likely to receive a spine MRI if they were classified as abused (P<0.001); had lower initial mental status (P=0.02), longer intensive care unit stay (P=0.01) or retinal hemorrhages (P<0.001); and presented with an initial history of traumatic injury (P=0.02). There were no differences in patient demographics, criminal conviction rates, confessions, head injury mechanisms or the presence of spine injury symptoms between those with and without a spine MRI.

Incidence of spine injury on magnetic resonance imaging

Of the 76 children who received a spine MRI, 45 (59%) were abnormal. Spine injury included intramedullary hemorrhage (n=1; 1%; Fig. 5), spinal SDH (n=12; 16%), spinal epidural hemorrhage (n=6; 8%), ligament injury (n=32; 42%), bony injury (n=4; 5%), posterior paraspinous muscle edema (n=29; 38%), prevertebral soft-tissue swelling (n=24; 32%), and vertebral artery dissection (n=1; 1%). No children had extramedullary subarachnoid hemorrhage or carotid injury. Ligament injury included nuchal (n=18; 24%), apical (n=4; 5%), alar (n=10; 13%), transverse (n=2; 3%), posterior longitudinal (n=1; 1%) and interspinous (n=17; 22%). Table 2 describes the locations of spine hemorrhage and bony injury. Of the 24 with prevertebral soft-tissue swelling, 15 (63%) were intubated. The intubation occurred prior to the spine MRI in all 15 cases. All children with bony injury had vertebral body compression fractures with bone marrow edema. Children with whole spine imaging were more likely to have spinal SDH (P=0.03) and spinal epidural hemorrhage (P=0.003) compared to those

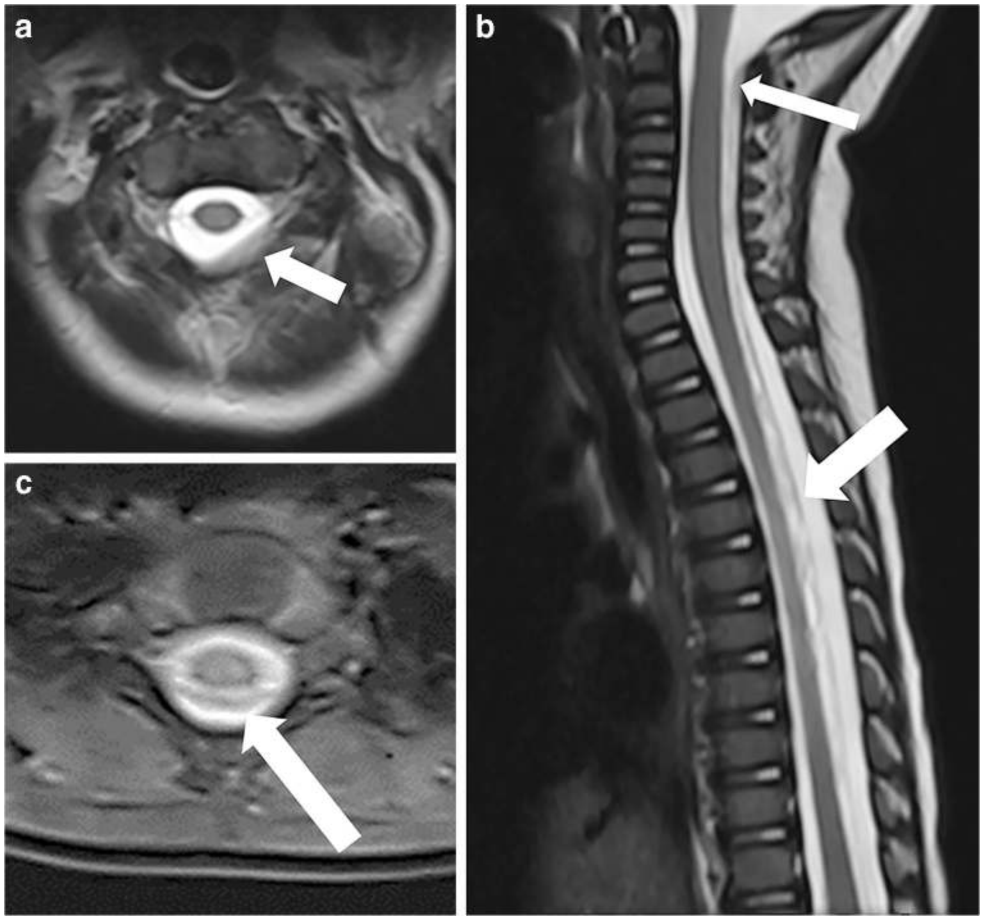


Fig. 3 Abusive head trauma in a 5-month-old boy with multiple bruises, diffuse severe brain injury and subdural intracranial hemorrhage, liver laceration and multiple fractures. **a** Axial T2-W spine MR image shows a small epidural collection posteriorly (*arrow*) on the left at the base of the odontoid process with displacement of the dura; low gradient recalled echo (GRE) signal was seen as well (not shown). **b** Sagittal T2-W spine MR image shows the epidural collection (*thin arrow*) as well as a subdural T2 hypointensity extending from C6 to T4 (*thick arrow*). **c** Axial GRE MR spine image shows corresponding low signal layering in the subdural space without epidural displacement (*arrow*)

with cervical spine imaging only. Three children had isolated ligament injury. Five had isolated posterior paraspinous muscle edema.

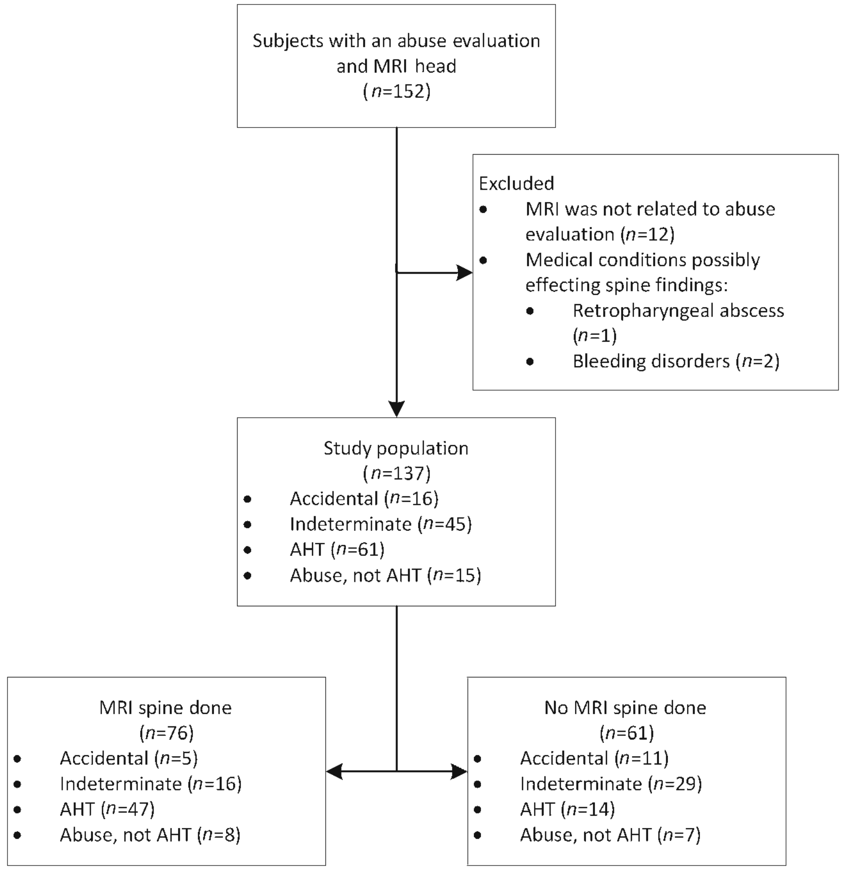
Of the 47 children diagnosed with AHT who had a spine MRI, 29 (62%) were abnormal. In 29 children who had a spine MRI as part of an evaluation for AHT, the CPT could not ultimately confirm AHT. Sixteen (55%) of these children had a spinal injury (Table 3). Injuries in these children would have been missed if MRI spine had been assessed only in children diagnosed with AHT. MRI spine findings often provided additional evidence of trauma when intracranial findings were otherwise nonspecific for trauma, evidence of injuries that were inconsistent with the history provided, or clinical information that influenced medical care (Figs. 6, 7 and 8).

Clinical characteristics associated with spine injury among children with spine MRI

Spine injury was suspected prior to MRI in 2 (4%) of those with spine injury, but the assessment was limited by altered mental status at initial presentation in 25 (56%). Table 4 describes the demographics and clinical characteristics of children with and without spine injury. There was a confession of shaking in 7 (9%) and of impact in 18 (24%). Ultimately 31 (41%) perpetrators were convicted criminally. Spinal injury was not significantly associated with an initial history of trauma (P=0.09), confession of shaking (P=0.69) or impact (P=0.20), or criminal convictions (P=0.13). When considered individually, many types of spinal injuries were associated with increased measures of injury severity; however, spinal SDH was the only injury also associated with the combination of non-contact head injury mechanism, retinal hemorrhages and an AHT diagnosis (Table 5).

Fifty-nine children (78%) who received an MRI spine had an intracranial hemorrhage on MRI brain. Of these, 11 (19%) had co-occurring spinal SDH. Intracranial hemorrhage was not associated with spinal SDH (P=0.28). None of the three children with accidental intracranial subdural hemorrhage had spinal SDH. The presence of other spinal injuries was significantly associated with spinal SDH compared to those without other spinal injuries (30% vs. 5%; P=0.004). All but one child with spinal SDH had co-occurring subdural hemorrhage, with subdural hemorrhage in the posterior fossa. Hypoxic–ischemic injury was the only intracranial finding in the one child with spinal SDH without co-occurring intracranial hemorrhage (Case 1 in Table 3, Fig. 8). She did not receive a lumbar puncture for a sepsis evaluation until after completion of the spine MRI.

Fig. 4 Flowchart describes the study population, exclusions and abuse likelihood classifications. *AHT* abusive head trauma



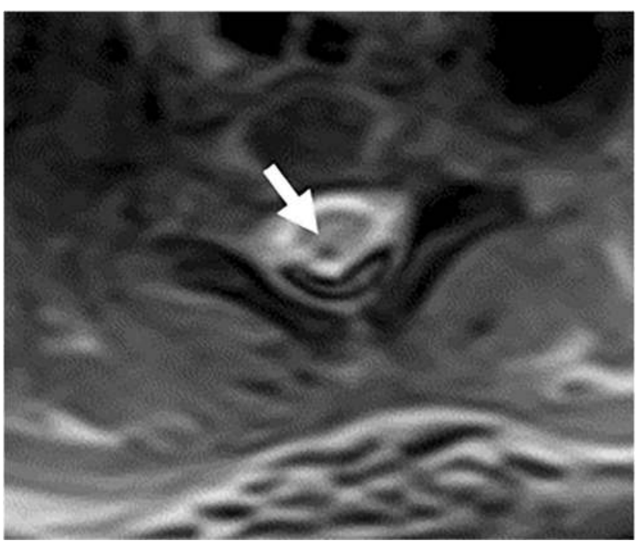


Fig. 5 Abusive head trauma in a 1-month-old boy who presented with altered mental status and cardiorespiratory failure. Axial gradient recalled echo (GRE) spine MRI demonstrates susceptibility artifact in the peripheral posterior right spinal cord at C7 (*arrow*). Prevertebral soft-tissue swelling, nuchal ligament edema, posterior paraspinous muscle edema and spinal subdural hemorrhage were also present (not shown). Multiple extremity bruises, metaphyseal fractures, diffuse intracranial subdural hemorrhage, and severe retinal hemorrhages were also present. Prolonged unilateral extremity weakness was noted after he regained consciousness. Father confessed to shaking him and throwing him onto a bed and was convicted of physical abuse

Five of six children with epidural spinal hemorrhage were victims of AHT (Fig. 3); none of the five had a lumbar puncture prior to spine MRI. The one child with an epidural spinal hemorrhage not classified as having AHT was a 2-month-old who presented with sepsis and an incidental skull fracture with a history of a short fall, and this infant did have a lumbar puncture prior to spine MRI. Epidural hemorrhages were not associated with bony injury.

Table 2 Level of spine injury

	Cervical *n*=8	Cervical and thoracic *n*=9	Thoracic *n*=4	Thoracic and lumbar *n*=1	Whole spine *n*=1
Bony injury	2 (3%)	0	2 (3%)	0	0
Spinal cord hemorrhage	1 (1%)	0	0	0	0
Spinal subdural hemorrhage	4 (5%)	6 (8%)	1 (1%)	1 (1%)	0
Spinal epidural hemorrhage	1 (1%)	3 (4%)	1 (1%)	0	1 (1%)

Imaging was of the cervical spine only in 93%. Cervical spine MRI extended through T5. Percentage is of total number who received a spine MRI (*n*=76)

Table 3 Spine abnormalities in children without confirmed abusive head trauma (AHT)

Case	Presenting history	MRI brain findings	Hospital course	MRI spine findings
1	2-month-old girl with respiratory failure, seizures and shock. No history of trauma, no prior illness. Unexplained delay in seeking care after baby became unresponsive	• Diffuse cerebral edema concerning for diffuse hypoxic–ischemic injury • No intracranial hemorrhage	• No skin, skeletal or intraabdominal injury • Infectious and metabolic workup negative (lumbar puncture done after spine MRI)	• Prevertebral swelling from skull base to C4 • Posterior paraspinous muscle edema from skull base to T9 • Nuchal ligament edema • Interspinous ligament edema C7–T9 • Spinal SDH T1–T9
2	4-month-old boy with decreased leg movement after aunt hit leg against table. Femur fracture noted on radiograph. CT with possible parenchymal hemorrhage	• Normal	• Alert/responsive at presentation • No ocular, skin or intra-abdominal injury • No additional skeletal injuries	• Alar ligament edema • Nuchal ligament edema
3	5-month-old boy found by babysitter in a crib with blood-tinged emesis, respiratory distress. No history of trauma, no prior illness	• Diffuse cerebral edema consistent with diffuse hypoxic–ischemic injury • No intracranial hemorrhage	• Pulmonary hemorrhage • No ocular, skin, skeletal or intraabdominal injury	• Posterior paraspinous muscle edema skull base to C3 • Prevertebral soft-tissue edema C1–C3 • Interspinous ligament edema C1–C7 • Nuchal ligament edema
4	18-month-old boy found by mother unresponsive and not breathing in crib. No history of trauma	• Deep white matter injury possibly from toxic insult vs. hypoxic–ischemic injury • No intracranial hemorrhage	• Drug screen positive for methadone • No ocular, skin, skeletal or intra-abdominal injury • Possible diagnosis of toxic leukoencephalopathy secondary to methadone exposure	• Interspinous ligament edema C1–C3 • Prevertebral soft-tissue swelling skull base through C3 • Posterior paraspinous muscle edema skull base to C4
5	35-month-old girl presenting with altered mental status, lethargy and vomiting. Fell from standing height in bathtub, hitting her head, while in care of stepmother	• Early subacute infarct to the inferior vermis and medial cerebellar hemispheres • No intracranial hemorrhage	• Multiple unexplained skin injuries suspicious for abuse	• Bilateral vertebral artery dissection
6	17-month-old boy presented with abdominal pain, altered mental status, respiratory distress. No history of trauma	• Normal	• Bruising to abdomen and eye • Perforated duodenum • Normal skeletal survey	• Posterior paraspinous muscle edema from skull base to T7 • Prevertebral soft-tissue swelling from skull base to C3 • Alar ligament edema • Nuchal ligament edema • Interspinous edema from skull base to T4
7	5-month-old boy presented with GCS 9 and a patterned bruise to leg	• Normal	• Admitted to intensive care for 2 days due to altered mental status and poor feeding • Father confessed to slapping the leg in anger, no confession of AHT • No ocular, skeletal or intraabdominal injury	• Alar ligament edema
8	41-month-old girl found unresponsive by mother's boyfriend	• Parenchymal contusion	• Suspicious bruising to the face, trunk, extremities • Unexplained complex skull fracture • Rib fractures • No ocular or intraabdominal injury	• Prevertebral soft-tissue swelling C1–C2 • Nuchal ligament edema • Interspinous ligament edema C1–T2 • Posterior paraspinous muscle edema C1–C7

Table 3 (continued)

Case	Presenting history	MRI brain findings	Hospital course	MRI spine findings
9	2-month-old girl; father's friend fell onto the baby's head while wrestling with father	• Parafalcine subdural hemorrhage	• Alert at presentation • Facial bruising • Occipital skull fracture • Few retinal hemorrhages in posterior pole of left eye	• Posterior paraspinous muscle edema, suboccipital
10	4-month-old boy fell out of a shopping cart with face hitting concrete	• Small bi-frontal subdural hemorrhages	• Alert at presentation • Facial abrasions • No ocular, skeletal or intraabdominal injury	• Prevertebral soft-tissue swelling skull base to C3
11	8-month-old boy became limp and unresponsive at a babysitter's home	• Normal	• Metatarsal fracture • No skin, ocular or intraabdominal injury	• Posterior paraspinous muscle edema C2–C7
12	1-month-old girl with irritability and poor feeding for several days	• Cerebral edema	• Confused/lethargic at presentation • Respiratory failure with ventilator support ×11 days • Diagnosed with molybdenum cofactor deficiency	• Prevertebral soft-tissue swelling occiput to C3 • Posterior paraspinous muscle edema C2–C6
13	4-week-old boy presented with abnormal eye movements, irritability, increased head circumference, CT with concern for subdural hemorrhage	• Normal with increased subarachnoid space	• Healing metacarpal fracture • No skin, ocular or intraabdominal injury	• Posterior paraspinous muscle edema C4–C7
14	1-month-old girl, fell 2–5 ft out of mother's arms onto a tile floor	• Scattered subarachnoid hemorrhage • Thin left subdural fluid collection • Frontal parenchymal contusion	• Biparietal skull fractures with overlying scalp swelling • GCS 15	• Posterior paraspinous muscle edema C7–T4
15	13-month-old boy, seizure activity during a bath	• Normal	• Partial thickness burns to 10% body surface • No other skin injury, skeletal or intraabdominal injury	• Prevertebral soft-tissue swelling skull base to C3
16	8-month-old girl fell off a couch, subsequent lethargy	• Small occipital subdural hemorrhage	• Facial bruising, intra-oral injury • GCS 15 • Fracture to mandible and two ribs • Grade 2 liver laceration • Few retinal hemorrhages to posterior pole • Father pleaded guilty to physical abuse	• Mild apical ligament edema

GCS Glasgow Coma Scale, *MRI* magnetic resonance imaging, *SDH* subdural hemorrhage

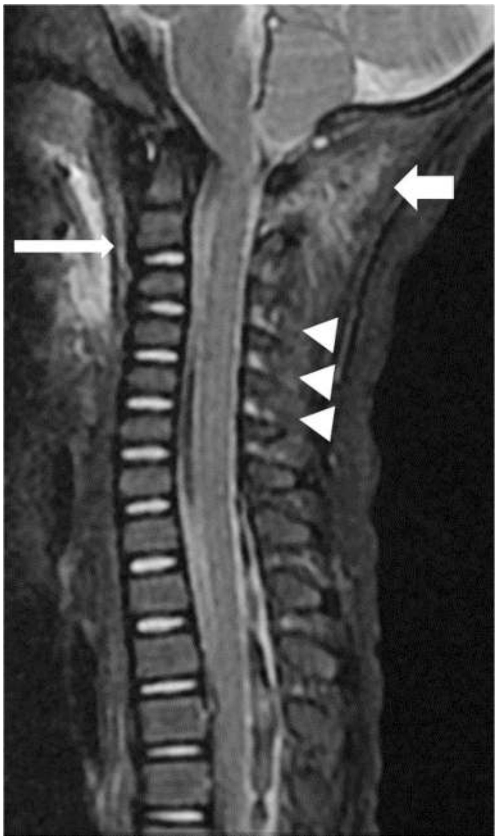


Fig. 6 Case 4 in Table 3, an 18-month-old boy found by mother unresponsive and not breathing in the crib. Sagittal short tau inversion recovery spine MR image shows prevertebral soft-tissue swelling (*long arrow*), posterior paraspinous muscle edema (*short arrow*) and subtle interspinous ligament injury (*arrowheads*)

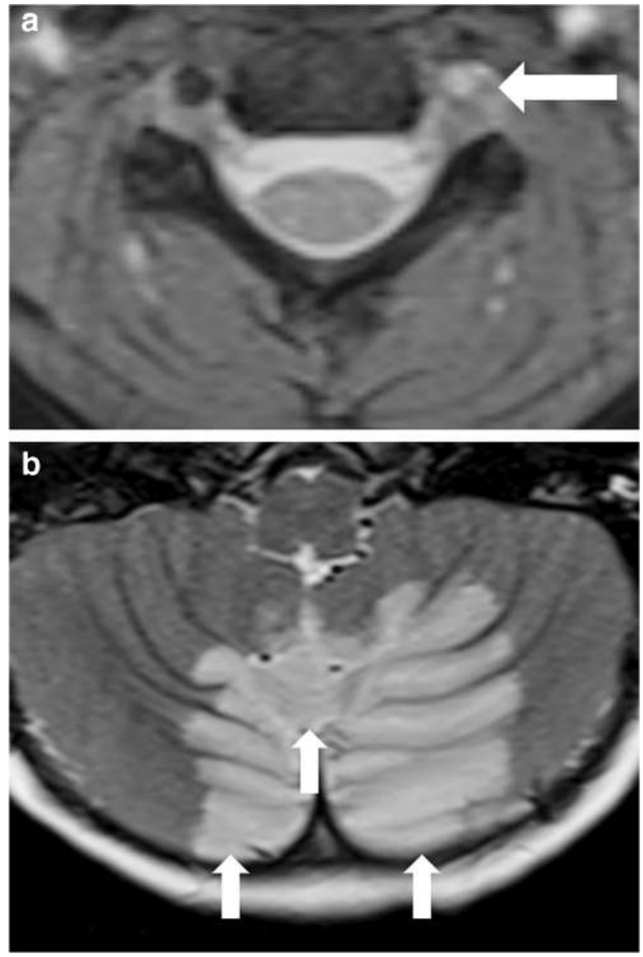


Fig. 7 Case 5 in Table 3, a 35-month-old girl presenting with altered mental status, lethargy and vomiting after a reported fall from standing height in a bathtub. **a** Axial gradient recalled-echo spine MR image shows abnormal left vertebral artery flow void compatible with dissection (*arrow*). **b** T2-W axial MR image of the brain shows evidence of completed infarcts in the distribution of bilateral medial branches of the posterior inferior cerebellar arteries (*arrows*)

Discussion

Incidence and clinical characteristics associated with spinal injury on MRI

We found a high incidence of spinal injury (59%) in children evaluated for AHT and in those ultimately diagnosed with AHT (62%). The reported incidence of spinal injury in AHT varies considerably (13% to 78%) [11, 12] because of variations in the extent of imaging performed and study designs. In publications with methods like ours, which assessed for a wide range of spinal injuries regardless of whether AHT was ultimately diagnosed, the incidence of spinal injury ranges from 30% to 69% [5, 13, 14]. Among these studies, Jacob et al. [14] described a similar rate of spinal subdural hemorrhage (18%) and spinal epidural hemorrhage (10%) compared to our population, but higher rates of ligament and bony injury (67% and 9%, respectively). In contrast, Kadom et al. [13] and Oh et al. [5] found no bony injury and spinal subdural hemorrhage in only 1% of cases. The addition of sagittal STIR sequences improves the detection of soft-tissue injury and is useful to confirm the presence of spinal hemorrhage [12, 14], and this might have contributed to the higher percentage of injury detected in our subjects. Whole-spine imaging can also result in increased injury detection compared to cervical spine imaging alone [12]. If we had excluded thoracic and lumbar spine MRI, we would have missed three children with spinal extramedullary hemorrhages and two with thoracic vertebral body fractures. Additionally, 3-D T1-W sequences used in our MRI protocol might have facilitated detection of spine fractures (Fig. 9).

Research by Baerg et al. [15], the only prospective study assessing spine injury in AHT, found the lowest rate of injury (15%). The authors used strict inclusion criteria requiring loss of consciousness, and imaging findings of intracranial hemorrhage, diffuse axonal injury, hypoxic injury or cerebral edema. Abuse cases without a confession or witnessed abuse were

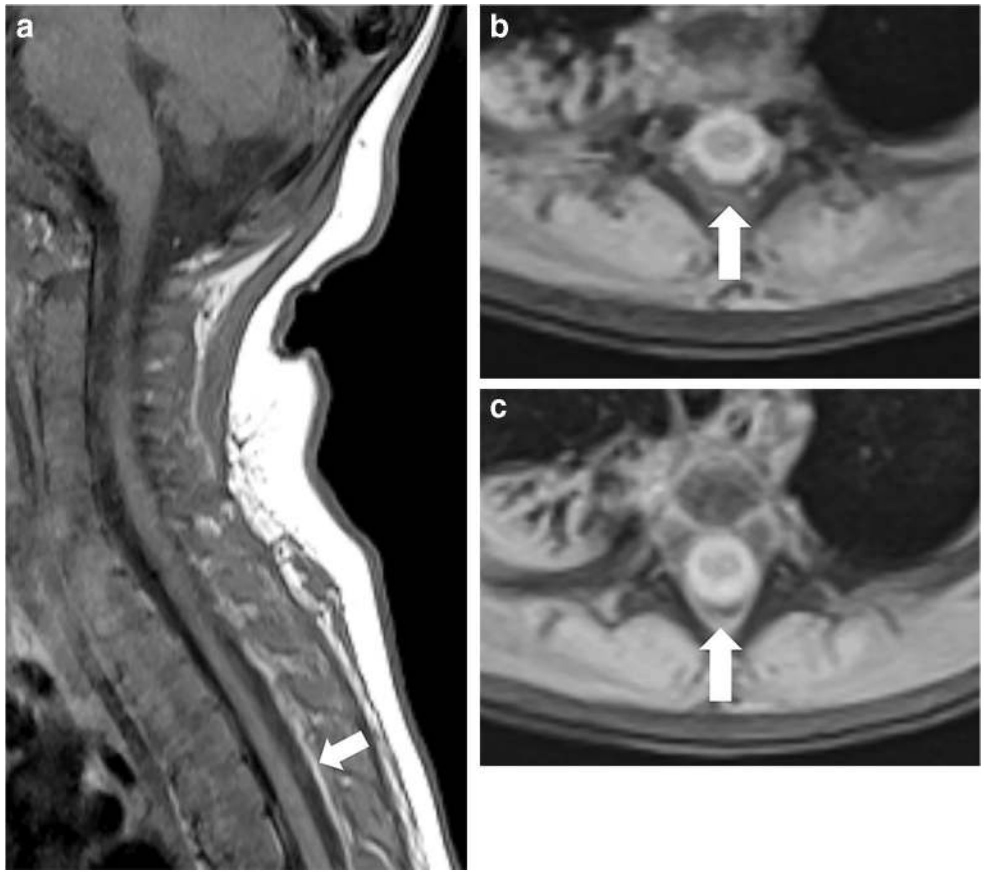


Fig. 8 Case 1 in Table 3, a 2-month-old girl with diffuse cerebral hypoxic–ischemic injury and no history of trauma and no intracranial hemorrhage. **a** Sagittal T1-W spine MR image shows linear posterior hyperintensity (*arrow*). **b** Axial gradient recalled-echo spine MR image shows a corresponding hypointensity layering in the subdural space (*arrow*) representing hemorrhage without a posterior epidural concave displacement of the dura. **c** Axial gradient recalled-echo spine MR image shows distal extension of subdural hemorrhage without dural displacement (*arrow*). Prevertebral swelling, posterior paraspinous muscle edema, nuchal ligament edema, and interspinous edema were also present on short tau inversion recovery sequences (not shown)

excluded. MRI STIR sequences were included, but authors did not describe how ligament injury was defined or whether paraspinous muscle edema or prevertebral soft-tissue injury was recorded as injury. If we had used similar inclusion criteria, our incidence of spine findings would have remained high at 67%. If we had also used a more restrictive definition of injury by excluding paraspinous muscle edema, prevertebral soft-tissue injury, and ligamentous edema without disruption, the incidence of spine injury in our study would have remained comparatively higher (33%) than in Baerg et al.'s (15%).

Utility of spine magnetic resonance imaging in abuse evaluations

Useful interpretation of spine pathology in child abuse evaluations depends on clinicians' ability to interpret findings as traumatic injury and to differentiate abusive from accidental mechanisms. MRI findings might overestimate the extent of disruptive ligamentous injury, limiting the utility of spine MRI when the goal is to detect potentially unstable injuries requiring surgical intervention [16, 17]. However, in child abuse evaluations the goal is to detect both apparent and occult injuries to outline the severity of injury to the child and support opinions regarding injury mechanism. Soft-tissue pathology on spine MRI does correlate with clinical impairment in adults with whiplash injuries as compared to controls [18]. In children, Choudhary et al. [12] compared spine MRI findings among AHT, accidental trauma and non-traumatic cohorts. After excluding medical causes, the only spinal finding in the non-traumatic cohort was a nuchal ligament injury in a child with sepsis who sustained a 20-min tonic-clonic seizure. The authors concluded that bony or ligamentous spinal abnormalities in the accidental and abusive cohorts were from injury and not normal variants [12].

Although spine MRI rarely resulted in additional medical treatment, it did often provide clinically and forensically valuable information including additional evidence of trauma when intracranial findings were otherwise nonspecific for trauma, and identification of injuries that were inconsistent with the history provided. Consistent with other studies [15, 19], spine injuries in our subjects were often occult. None of the fractures noted on MRI were identified on preceding plain radiographs. Symptoms are difficult to assess in very young children and the symptoms can be masked by severe brain injury. Evidence of unexplained trauma might prompt additional investigation for maltreatment and in this way affects medical decision-making. Interestingly, in several children with altered mental status, respiratory distress and hypoxic–ischemic injury, the spine findings were the only clear

Table 4 Demographics and characteristics of subjects with and without spine injury (*n*=76)

		Spine injury *n*=45	No spine injury *n*=31	*P*-value
Demographics				
Age in months		4.4 (2.0–7.2)	3.7 (2.1–9.3)	.56
Male gender		25 (56)	19 (61)	.62
Race[a]				
White		24 (53)	17 (55)	.71
Black/African American		15 (33)	7 (23)	
Other		5 (11)	2 (6)	
Insurance				
Private		7 (16)	6 (19)	.52
Public		38 (84)	24 (77)	
None/self-pay		0 (0)	1(3)	
Type of imaging done				
Whole spine		4 (9)	1 (3)	.64
Cervical spine		41 (91)	30 (97)	
Abuse likelihood				
Accidental		3 (7)	2 (6)	.92
Indeterminate		9 (20)	7 (23)	
Abuse	AHT	29 (64)	18 (58)	
	Not AHT	4 (9)	4 (13)	
Injury severity				
Length of ICU stay (spine pathology vs. none)		3(2–9)	0 (0–1)	**<.001**
Length of ventilation (spine pathology vs. none)		0 (0–7)	0 (0–0)	**.001**
Initial mental status	Alert/responsive	20 (44)	24 (77)	**.01**
	Confused/lethargic	14 (31)	5 (16)	
	Somewhat responsive	4 (9)	2 (6)	
	Flaccid/unresponsive	7 (16)	0 (0)	
Initial GCS[b]	<8	7 (16)	2 (6)	.32
	9–12	6 (13)	1 (3)	
	12–15	11 (24)	9 (29)	
Neurosurgical intervention required		9 (20)	8 (26)	.55
Mortality		3 (7)	0 (0)	.27
Mechanism of head injury				
Combined		18 (40)	13 (42)	.20
Contact		7 (16)	5 (16)	
Noncontact		14 (31)	5 (16)	
No head injury/undetermined		6 (13)	8 (26)	
Retinal hemorrhages		25 (56)	13 (42)	.30

AHT abusive head trauma, *GCS* Glasgow Coma Score, *ICU* intensive care unit

Data presented are median (interquartile range) for continuous variables and count (%) for categorical variables. Percentages from some subgroups do not add up to be 1 because of the rounding of numbers. Bolded *P*-values are statistically significant

[a] Race information is missing in 6 patients

[b] Initial GCS was not assessed in 40 patients

evidence of trauma (Table 3). These cases suggest a need for research assessing the prevalence of spinal injury in infants who present with severe unexplained respiratory compromise.

In contrast to other spinal injuries, posterior paraspinous muscle edema was interpreted with caution by the CPT because it was often thought to be the result of fluid shifts during resuscitation rather than primary injury. MRI spine has only poor to moderate specificity for paraspinous muscle injury when intraoperative findings are used as a gold standard [17]. However, in adults with whiplash injuries from motor vehicle collisions, cervical muscle strain (defined as altered structure, size and signal intensity) and muscle tears/hematomas on cervical spine MRI are significantly more common compared to non-injured controls, as are spinal fractures and bony contusions (defined as altered bone marrow signal intensity without fracture line) [20]. Similar comparative studies in children and in more severely injured patients are needed to guide the interpretation of spinal findings in children with isolated paraspinous muscle edema.

Although no children in the accidental trauma group had bony, hemorrhagic or ligamentous injuries, overall spinal injury and AHT were not associated. Spinal SDH was the only injury associated with a diagnosis of AHT. The low number of accidentally injured children who received a spine MRI (*n*=5)

Table 5 Clinical characteristics associated with spine injury type (n=76)

	Intramedullary hemorrhage[a] n=1(1)	Extramedullary hemorrhage		Spinal fracture and marrow edema n=4 (5)	Ligament injury n=32 (42)	Posterior paraspinous muscle edema n=29 (38)	Prevertebral soft-tissue edema n=24 (32)	Vertebral artery dissection[a] n=1 (1)
		Subdural n=12 (16)	Extra-dural n=6 (8)					
Age (months)	–	4 (1–7)	4 (2–8)	3 (1–6)	5 (2–7)	**3 (1–7)[c]**	4 (2–7)	–
Abuse likelihood								
Accidental	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	3 (10)	0 (0)	0 (0)
Indeterminate	0 (0)	1 (8)	1 (17)	0 (0)	5 (16)	4 (14)	6 (25)	1 (100)
Abuse								
AHT	1 (100)	**11 (92)[c]**	5 (83)	4 (100)	23 (72)	20 (69)	16 (67)	0 (0)
Not AHT	0 (0)	0 (0)	0 (0)	0	4 (13)	2 (7)	2 (8)	0 (0)
Injury severity								
Length of ICU stay (days)	–	**7 (1.5–13.5)[c]**	3 (0–13)	**7 (2–14.5)[c]**	**5.5 (2–11.5)[e]**	**5 (1–12)[e]**	**7 (2–12)[e]**	–
Length of ventilation (days)	–	**5 (0–9)[d]**	0 (0–8)	4.5 (0–9.5)	**3 (0–8)[e]**	**3 (0–8)[e]**	**4.5 (0–8.5)[e]**	–
Initial mental status								
Alert/responsive	–	**3 (25)[c]**	4 (67)	2 (50)	**9 (28)[e]**	**11 (38)[c]**	**8 (33)[c]**	–
Confused/lethargic	–	5 (42)	2 (33)	2 (50)	12 (38)	9 (31)	8 (33)	–
Somewhat responsive	–	2 (17)	0 (0)	0 (0)	4 (13)	4 (14)	4 (17)	–
Flaccid/unresponsive	–	2 (17)	0 (0)	0 (0)	7 (22)	5 (17)	4 (17)	–
Initial GCS[b]								
<8	–	**4 (33)[c]**	1 (17)	1 (25)	**7 (22)[c]**	6 (21)	**5 (21)[c]**	–
9–12	–	1 (8)	0 (0)	1 (25)	5 (16)	5 (17)	4 (17)	–
12–15 (n=20)	–	1 (8)	2 (33)	1 (25)	5 (16)	6 (21)	3 (13)	–
Neurosurgical intervention required	–	**6 (50)[c]**	**4 (67)[c]**	0 (0)	7 (22)	6 (21)	3 (13)	–
Mortality	–	1(8)	0 (0)	0 (0)	3 (9)	3 (10)	2 (8)	–
Mechanism of head injury								
Combined	–	3 (25)	2 (33)	2 (50)	15 (47)	10 (34)	7 (29)	–
Contact	–	0 (0)	1 (17)	0 (0)	4 (13)	6 (21)	3 (13)	–
Undetermined	–	1 (8)	1 (17)	0 (0)	1 (3)	1 (3)	0 (0)	–
Noncontact	–	**8 (67)[d]**	2 (33)	2 (50)	10 (31)	10 (34)	**12 (50)[c]**	–
No head injury	–	0 (0)	0 (0)	0 (0)	2 (6)	2 (7)	2 (8)	–
Retinal hemorrhages	–	**10 (83)[c]**	4 (67)	2 (50)	19 (59)	15 (52)	12 (50)	–

AHT abusive head trauma, *GCS* Glasgow Coma Scale, *ICU* intensive care unit

Data presented are median (interquartile ratio) for continuous variables and count (%) for categorical variables. Percentages from some subgroups do not add up to be 1 because of the rounding of numbers. Results in bold are statistically significant (P<0.05)

[a] Subarachnoid hemorrhage was not described and intramedullary hemorrhage and vertebral artery dissection were not analyzed because of an n of 1

[b] Initial GCS was not assessed in 40 children

[c] P<0.05 compared to those without the specific type of spine injury

[d] P<0.01 compared to those without the specific type of spine injury

[e] P<0.001 compared to those without the specific type of spine injury

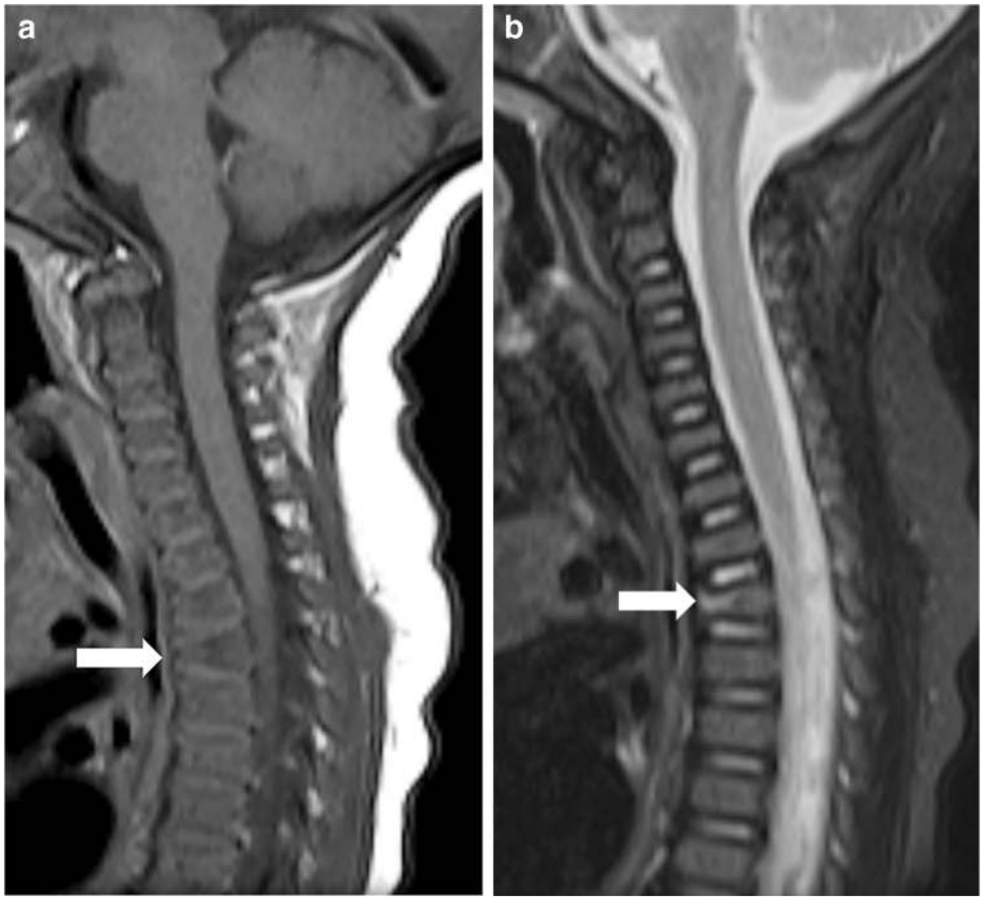


Fig. 9 Spine imaging in a 2-month-old girl with abusive head trauma. **a** Sagittal 3-D T1-W MR image shows wedge compression deformity of T2 (*arrow*). **b** Sagittal short tau inversion recovery image shows corresponding hyperintensity (*arrow*). The baby also had multiple bruises, rib fractures, a skull fracture, diffuse subdural intracranial hemorrhage and retinal hemorrhages. The father confessed to squeezing her chest and throwing her onto a couch, resulting in a criminal conviction for physical abuse. Bony injury was not noted on initial skeletal survey. Repeat skeletal survey 2 weeks later confirmed sclerosis and wedge deformity of T2, and also L3 and L4 vertebral body compression fractures

compared to the abuse (n=55) and indeterminate groups (n=16) might have caused a lack of power to detect differences; higher-powered comparative studies do suggest cohorts with a higher incidence of spinal injury in abused infants [12, 19, 21]. Choudhary et al. [12] found a higher rate of both cervical ligamentous injury (78% vs. 46%) and spinal SDH (48% vs. 2%) in children with AHT compared to accidental injury. When Henry et al. [19] compared spinal injury in children with AHT and with accidental injury associated with non-motor vehicle crash, the authors found a higher incidence of spine injury overall in children with AHT (31.3% vs. 7.1%), but the rate of ligamentous injury was similar (8.7% for AHT and 5.8% for accidental head injury) [19]. In contrast, other studies did not find a higher incidence of spinal injury in abused infants [11, 13]. The lower number of children with spinal extramedullary hemorrhage in these studies might contribute to the lack of significant findings between their abusive and accidental cohorts. Additionally, Baerg et al. [11] included children with severe accidental rotational acceleration/deceleration head injuries who can have spinal injury similar to that found in AHT. Although spinal injury and AHT were not associated in Baerg et al.'s study, spinal injuries were associated with other clinical findings of severe rotational acceleration/deceleration head injury typical of both AHT and severe accidental head injury involving similar mechanisms [11].

Potential mechanisms of spinal injury

We found higher severity of brain injury in children with spinal injury and an association between spinal SDH and other injuries typical of AHT. Although the association between injury severity and spinal injury should be interpreted with caution because of the low number of less severely injured children who received a spine MRI, it is consistent with previous literature [11, 19]. Like AHT, spinal injury is associated with global parenchymal injury [16], hypoxic–ischemic injury [12–15] and a rotational acceleration/deceleration mechanism of head injury in both accidental and abusive trauma [15]. Using autopsy techniques that preserve the entire spine for microscopic analysis, Matshes et al. [22] found that 100% of subjects with injuries involving hyperflexion/extension forces to the head had injury to the spinal nerve roots. In living children, spinal nerve root injuries are infrequently reported but might be below the current level of detection on MRI [12, 23]. Although we did not analyze the association between hypoxic–ischemic injury and spinal injury, other research suggests that hypoxic–ischemic injury is more common in children with ligamentous spinal injury [12, 13, 15], and spinal SDH is rarely identified in accidentally head-injured children [12, 21]. Our study supports and adds to this literature by highlighting an association between spinal SDH and a combination of higher injury severity, noncontact head injury pattern, retinal hemorrhages, and an AHT diagnosis.

Despite the association between spinal SDH and AHT, the source of the bleeding in spinal SDH is debated. Spinal SDH is most commonly attributed either to direct injury to spinal vasculature or tracking of intracranial blood [4]. Sequential migration of intracranial blood into the spinal subdural space has been reported in adults [24]. Case studies of children with AHT report spontaneous resolution of subdural hemorrhages at the clivus, which seemed to have migrated into the spinal subdural space [25, 26]. Spinal subdural hemorrhage is also reported as a complication of ventriculoperitoneal shunting, where low intracranial pressure from the shunt is suspected to cause dissection between the dura and arachnoid layer of the spine, allowing migration of the intracranial subdural hemorrhage [24]. However, in the only prospective study assessing the incidence of spinal SDH in people with intracranial subdural hemorrhage, only 2 (1.2%) of 168 adults with intracranial hemorrhage had spinal hemorrhage; both of those people had experienced concurrent injury to the head and the back [27]. Direct vascular injury to radicular veins traveling through the spinal nerve root is also a known cause of spinal SDH in victims of AHT, likely caused by traction on spinal nerve roots during hyperflexion/extension from shaking [28].

If migration of an intracranial hemorrhage were the sole mechanism for spinal SDH, we would expect to see an association between intracranial and spinal hemorrhage, regardless of the presence of other spinal injuries. Although all but one child with spinal SDH also had intracranial hemorrhage in our study, intracranial subdural hemorrhage was not predictive of spinal SDH. Spinal SDH was associated with other spine injuries. The lack of association between intracranial and spinal SDH suggests that caudal migration of an intracranial hemorrhage is not the sole mechanism for spinal SDH. Our findings suggest that either the spinal SDH is caused by direct spinal injury at least in some cases, or that a similar injury mechanism caused the other spinal injuries and the caudal extension of the intracranial hemorrhage into the spine. Choudhary et al. [12] also found a higher incidence of spinal SDH in children with AHT compared to their accidentally injured cohort and a correlation between ligamentous spinal injury and spinal SDH. The authors proposed that traction on myodural bridges and the intradural nerve roots and dentate ligaments during flexion/extension of the spinal cord in AHT could cause disruption of the dura-arachnoid interface, facilitating the migration of blood from the intracranial compartment into the spine [12]. The association among spinal SDH, other injuries typical of rotational acceleration/deceleration of the head, and a diagnosis of AHT in our subjects supports this theory. However, it is important to consider that spine MRI extended past T5 in a minority of our subjects, so the incidence of spinal SDH might be underrepresented. Additional studies using whole-spine MRI are needed.

Limitations

There are several limitations to this study. First, there is a risk of circular reasoning if the presence of spinal SDH heightened providers' concern for AHT. However, upon review of consultation reports for children with spinal injury, no children were classified as abused because of a spinal injury. To further assess for circular reasoning, AHT likelihood was compared to a second classification method developed by Duhaime et al. [29] and then modified by Kadom et. al [13] that does not use spinal injury as a diagnostic consideration. Because this classification system was meant for people with head injuries, people without concern for head injury were excluded. Using the weighted kappa statistic, abuse classifications determined by the modified Duhaime criteria and Lindberg scale were significantly correlated (κ=0.67, 95% confidence interval [CI] 0.57–0.77).

Second, the potential for sampling bias exists. Because the majority (93%) of spine MRIs included cervical spine only, our study might underestimate the incidence of spinal injury. The number of children with isolated lumbar and lower thoracic injuries is unknown. Abused children and children with higher severity of injury were more likely to receive a spine MRI, potentially causing under-detection of spinal injury in accidental, lower-severity injuries and resulting in a lack of power to detect differences between abused and non-abused children. If we assume that all children who were not imaged had a normal spine MRI, the incidence of spine injury would remain relatively high at 33%.

Finally, because we did not assess inter- and intraobserver variability in radiologists' readings of the spine MRIs, our ability to comment on the validity of the interpretations is limited. Our rates of spinal hemorrhage and ligamentous and bony spinal injury overall and within our AHT population were similar or lower than reported by other studies that used methods and MRI sequences comparable to those in our study [12, 14]. This suggests that our interpretation of the spine MRI was similar to or more conservative than those of researchers at other institutions.

Conclusion

There is a high incidence of spinal injury in children evaluated for AHT (59%) and those ultimately diagnosed with AHT (62%). Higher measures of injury severity were the only variables associated with spinal injury overall. However when considered separately, spinal SDH was associated with AHT and with other head injuries typical of a rotational acceleration/deceleration injury mechanism. Spinal SDH might support a mechanism of severe acceleration/deceleration head injury and a diagnosis of AHT when interpreted in conjunction with other intracranial and ocular findings. MRI of the whole spine should be included in future studies to further examine the predictive value of spinal SDH for an AHT diagnosis. While bone, ligamentous and other soft-tissue spine injuries likely result from a wider range of injury mechanisms, detection of occult injury could be clinically and forensically valuable.

Additional research assessing spine findings in accidentally and less severely injured children and investigating potential nontraumatic causes of posterior paraspinous muscle edema in children could further our ability to interpret spinal pathology on MRI. Finally, studies assessing the incidence of spinal injury in children presenting with unexplained hypoxic–ischemic injury and respiratory distress would be useful to examine the emerging link between hypoxic–ischemic injury and spinal injury in abuse evaluations.

Compliance with ethical standards

Conflicts of interest None

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