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ORIGINAL ARTICLE

Usefulness of MRI detection of cervical spine and brain injuries in the evaluation of abusive head trauma

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Abstract
Background In the evaluation of children younger than 3 years with intracranial hemorrhage it can be difficult to determine whether the cause of hemorrhage was traumatic, and if so, whether abusive head trauma (AHT) is a possibility. Cervical spine MRI is not a routine part of the nationally recommended imaging workup for children with suspected abusive head trauma. There is increasing evidence that spinal injuries are found at autopsy or MRI in abused children. However the prevalence of cervical spine injuries in children evaluated for abusive head trauma is unknown. We sought to determine both the incidence and the spectrum of cervical spine and brain injuries in children being evaluated for possible abusive head trauma. We also examined the relationship between cervical and brain MRI findings and selected study outcome categories.
Materials and methods This study is a 3-year retrospective review of children evaluated for abusive head trauma. Inclusion criteria were: children with head trauma seen at our institution between 2008 and 2010, age younger than 36 months, availability of diagnostic-quality brain and cervical spine MRI, and child abuse team involvement because abusive head trauma was a possibility. A child abuse pediatrician and pediatric radiologists, all with board certification, were involved in data collection, image interpretation and data analysis. Statistical analysis was performed using Stata v12.1.
Results The study included 74 children (43 boys, 31 girls) with a mean age of 164 days (range, 20–679 days). Study outcomes were categorized as: n=26 children with accidental head trauma, n=38 with abusive head trauma (n=18 presumptive AHT, n=20 suspicious for AHT), and n=10 with undefined head trauma. We found cervical spine injuries in 27/74 (36%) children. Most cervical spine injuries were ligamentous injuries. One child had intrathecal spinal blood and two had spinal cord edema; all three of these children had ligamentous injury. MRI signs of cervical injury did not show a statistically significant relationship with a study outcome of abusive head trauma or help discriminate between accidental and abusive head trauma. Of the 30 children with supratentorial brain injury, 16 (53%) had a bilateral hypoxic–ischemic pattern. There was a statistically significant relationship between bilateral hypoxic–ischemic brain injury pattern and abusive head trauma (P<0.05). In addition, the majority (81%) of children with bilateral hypoxic–ischemic brain injuries had cervical injuries.
Conclusion Although detection of cervical spine injuries by MRI does not discriminate between accidental and abusive head trauma, it can help to distinguish a traumatic from non-traumatic intracranial subdural hemorrhage. Cervical MRI should be considered in children with acute intracranial bleeds and otherwise non-contributory history, physical examination and ophthalmological findings. There is a statistically significant relationship between diffuse hypoxic–ischemic brain injury patterns and abusive head trauma. The high incidence of cervical injuries in children with hypoxic–ischemic injuries suggests a causal relationship. Overall, increased utilization of brain and spine MRI in children being evaluated for abusive head trauma can be helpful.

Keywords Cervical spine · Brain · Child abuse · Magnetic resonance imaging · Pediatric

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Introduction

In children younger than 3 years who present with intracranial hemorrhage it is important to determine whether the cause of bleeding is traumatic or non-traumatic. If a bleed is believed to be of a traumatic etiology, care must be taken to differentiate accidental from abusive head trauma (AHT). Although trauma causes the majority of intracranial bleeds in the pediatric population, there are several non-traumatic etiologies, including vascular anomalies, coagulopathies, tumors and genetic and metabolic diseases [1, 2]. Concern for abusive head trauma is based on certain aspects of the clinical evaluation. For example, it has been shown that in an otherwise healthy child the lack of a history of trauma, or a history of trivial trauma in the setting of persistent neurological deficits, a change in initial history of present illness, or home resuscitation efforts as a sole source of trauma are all predictive of abuse [3]. When an abusive cause of intracranial injury is suspected at our institution, the child is referred to the hospital's child abuse pediatricians for further consultation. In addition, a social services and law enforcement investigation is typically launched at the time of referral to the child abuse pediatricians. The goal of a multidisciplinary investigation (medical, social services, law enforcement) is to determine whether the child's intracranial hemorrhage is of traumatic or non-traumatic etiology. After a traumatic etiology is established or considered highly likely, further workup is focused on determining whether the trauma was of an accidental or abusive etiology.

Injury to muscles, ligaments, bony spine, vascular structures and spinal cord has been occasionally reported [4] in children with abusive head trauma. Recently it has been reported that some children who have experienced abusive head trauma have radiologically apparent spinal subdural hemorrhages [5], cervical and thoracic injuries [6] and autopsy evidence of spinal cord injuries, such as nerve root avulsions and muscle and ligament injuries [7].

At our institution children with intracranial hemorrhages and concern for abusive head trauma frequently undergo cervical spine MRI in conjunction with brain MRI. In this work we report the incidence and spectrum of cervical spine and brain injuries in a cohort of children who underwent evaluation for abusive head trauma between 2008 and 2010 at our institution. We also examined the relationship between cervical and brain MRI findings and study outcome categories based on modified Duhaime criteria [8].

Materials and methods

This study was approved by the review board at our institution. Children entered into our hospital's child abuse database from 2008 to 2010 were considered for this retrospective study. During this time period the recommended brain imaging protocol at our institution for all children with suspected abusive head trauma who were referred to the child abuse physicians included non-contrast head CT, brain MRI and cervical spine MRI. Inclusion criteria for this study were age younger than 3 years, head trauma, referral to our hospital's child abuse pediatricians and diagnostic-quality MRI of the brain and cervical spine during the time the child was admitted. Excluded from this study were children who underwent brain and spine MRIs because of known, pre-existing, non-traumatic medical conditions and children not seen by the child abuse pediatricians.

MRI technique

The MRI images were acquired at 1.5 T (GE Healthcare, Milwaukee, WI). Brain images were obtained in the following sequences: sagittal and axial spin-echo T1-W images (rotation time 450 ms, echo time 10 ms), axial spin-echo and coronal fast-spin-echo T2-W images (TR/TE 3,000/100 ms), axial proton density (TR/TE 3,000/30 ms), axial diffusion-weighted images (B0, B1000), axial or coronal gradient-echo T2-W images (TR/TE 650/20 ms). Images of the cervical spine were obtained as follows: sagittal and axial T1-W images (TR/TE 400/10 ms), sagittal fast-spin-echo inversion recovery images (TR/TE 5,000/25 ms), axial fat-saturated T2-W images (TR/TE 4,500/80 ms) and sagittal diffusion-weighted images (B0, B1000).

Cervical injuries as seen at MRI

Five observers compiled and interpreted data for this study. The MR imaging studies were independently reviewed by three board-certified and subspecialty-trained pediatric neuroradiologists (A, B, C), one with more than 20 years (C) and two with more than 7 years (A, B) of subspecialty experience. Reviewers A and B reviewed the cervical MRIs. Reviewers A and C reviewed brain MRIs. Reviewer B was blinded to intracranial MRI findings and reviewer C was blinded to cervical spine MRI findings. In cases of discrepant evaluations between the neuroradiology observers A/B and A/C, agreement was reached jointly at the workstation.

On neuroimaging, observers A and B assessed the presence or absence of the following cervical spine abnormalities: bone marrow edema, spinal cord edema, restricted cervical diffusion-weighted signal, intrathecal blood, disc pathology, soft-tissue and ligamentous injury. We classified cervical injury extent based on focality and location relative to C3: small extent if the injury was limited to the posterior ligament complex at a single cervical level above C3; moderate extent if the injury spanned more than one vertebral body level above C3, and large extent if the injury spanned multiple vertebral levels above and below C3 (Fig. 1). Observers A and C

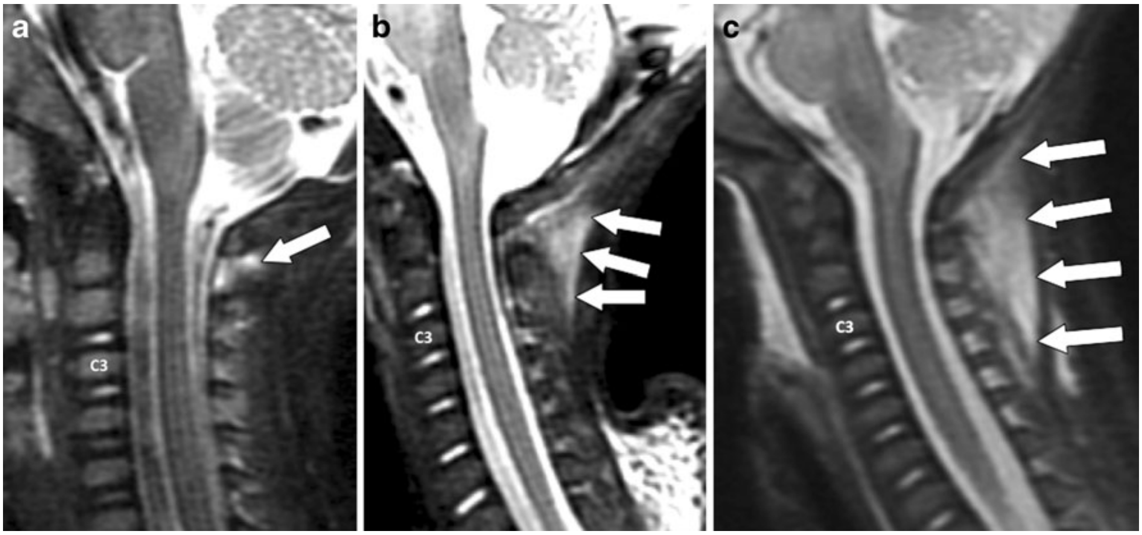

Fig. 1 Injury extent as seen on sagittal fast-spin-echo inversion recovery images in a 22-month-old boy (**a**), a 51-day-old boy (**b**) and a 36-day-old girl (**c**). **a** Small extent of injury with T2 bright signal limited to the posterior ligament complex at a single level above C3 (*arrow*). **b** Moderate extent of injury involving more than one vertebral body level above C3 (*arrows*). **c** Large extent of injury spanning multiple vertebral levels above and below C3 (*arrows*)

assessed brain images for the presence of extra-axial hemorrhage in the posterior fossa, for brainstem injury and cerebellar injury and for presence of non-hemorrhagic supratentorial injury. Supratentorial brain imaging patterns were further classified as bilateral hypoxic–ischemic pattern (including watershed), focal/contusion pattern, and unilateral ischemic pattern, based on previously described data [9].

Study outcomes based on Duhaime criteria

Patient outcomes for statistical purposes of this study were defined based on modified Duhaime criteria [8]. The original Duhaime algorithm results in one of two clinical outcomes based on combining a child's injury type (skull fractures, intracranial hemorrhage, blunt craniofacial trauma) with a certain history or associated findings (unexplained long-bone fractures or old fractures; soft-tissue injury; no history of trauma; history of trivial or remote trauma, and changing history or developmentally incompatible history). The original Duhaime outcome is either "suspicious "or "presumptive" for inflicted head injury. We modified this classification scheme by adding two additional outcomes: "accidental" and "undefined." We used the study outcome "accidental" for children in whom we had complete information about injury type, history and associated findings, and who did not fulfill "presumptive" or "suspicious" Duhaime criteria. We used the study outcome "undefined" for children in whom we were missing information on injury type, history or physical examination findings. A senior pediatric radiologist (observer D) with more than 20 years of experience who was blinded to the MRI results reviewed all brain CT data (reports and images) needed for the radiologic component of the modified Duhaime scheme. In addition, observer D reviewed skeletal surveys and abdominal CTs for axial and long-bone fractures, because these findings are also part of the Duhaime scheme. Observers A, B, C and D were blinded to the modified Duhaime classification and other clinical outcomes. A child abuse pediatrician with 8 years of experience (observer E) added the radiologic data to the pre-existing clinical, history and physical findings and used the information to assign children to one of four study outcome categories: presumptive, suspicious, accidental or undefined (modified Duhaime criteria).

In an effort to avoid circularity of reasoning, we used the aforementioned modified Duhaime classification as our study outcome measure because this classification does NOT depend on presence of neck injuries or parenchymal brain injuries. In reality, when providing clinical care and medico–legal assessments for the children included in this study, the brain and cervical MRI findings were taken into consideration by our hospital's consulting child abuse pediatricians. Therefore, the final clinical assessments of the child abuse pediatricians regarding etiology (accidental or abusive head trauma) were not used to classify our study cohort.

Statistics

All statistical analyses were conducted with Stata 12.1 (StataCorp, College Station, TX). The Fisher exact test was used to examine whether the presence of a particular demographic characteristic or image-related finding (each of which was coded into two categories: younger/older, male/female, present/absent, etc.) was associated with the child's study outcome category. Study outcomes were designated in two ways. The first designation included study outcomes "accidental," "presumptive," "suspicious" or "undefined." The second designation consolidated "presumptive" and "suspicious" into "abusive," maintained the "accidental" designation and dropped 10 children from the analysis who were "undefined." P values <0.05 were considered indicative of a statistically significant association.

Results

A total of 161 children younger than 3 years were seen by the child abuse pediatricians for suspected abusive head injury in the study period. Of these, 85 (53%) underwent only brain MRI and 74 (46%) underwent both a brain and cervical spine MRI. Of the 74 patients who fulfilled the inclusion criteria there were 43 boys (58%) and 31 girls (42%). Their mean age was 164 days (range, 20–679 days).

Twenty-six of 74 (35%) children had a study outcome of "accidental" trauma. Twenty of 74 (27%) cases were "suspicious" for abusive head trauma and 18/74 (24%) were "presumptive" abusive head trauma. The remaining 10/74 (14%) children had an "undefined" study outcome (Fig. 2). After excluding the 10 children with an "undefined" outcome and combining "suspicious" or "presumptive" study outcomes into a single "abusive" head trauma category, there were 26/64 (41%) children with "accidental" trauma and 38/64 (59%) with "abusive" trauma study outcomes (Fig. 2).

The cervical MRI studies did not show bone marrow edema, restricted diffusion of the cervical spine, or disc pathology. Cervical soft-tissue injury was present in 27/74 (36%) children. Most injuries were of moderate extent (12/27) (44%), followed by small extent (10/27) (37%) and large extent (5/27) (19%) (Fig. 3). Only one child had intrathecal hemorrhage (Fig. 4). Two children had spinal cord injury and both also had extensive brain injuries (Fig. 5), as well as ligamentous injury.

Posterior fossa injuries were as follows: There were 37/74 (50%) children with posterior fossa extra-axial hemorrhage, 11/74 (15%) with injury to the cerebellum, and 9/74 (12%) with injury to the brainstem (Fig. 6). Supratentorial brain injury was seen in 30/74 (41%) children on MRI and fell into three major categories: bilateral hypoxic–ischemic pattern in 17/30 (57%) patients (Fig. 7), focal/contusion pattern in 12/30 (40%) children (Fig. 8) and unilateral ischemic pattern in 1/30 (3%) children (Fig. 9).

When children were classified into the modified Duhaime-based study outcome categories (presumptive, suspicious, accidental, undefined) we found a statistically significant association with posterior fossa hemorrhage (P<0.0001) and presumed mechanism of injury (P=0.03) (Table 1). To further assess the relationship of brain injury with our study outcome variables we repeated the analysis using only two outcome categories (accidental versus abusive) and the two brain injury variables bilateral hypoxic–ischemic and unilateral/focal pattern (focal/contusion and unilateral ischemic combined). The results showed that posterior fossa hemorrhage (P=0.01) and bilateral hypoxic–ischemic injury pattern (P=0.02) occurred more frequently in children with abusive trauma (Table 2). We did not find a statistically significant relationship between cervical spine injuries and abusive head trauma study outcomes. There were 13 children with bilateral hypoxic–ischemic brain injury pattern among the 27 children who had MRI evidence of cervical injury (Fig. 10). Of the children with cervical injury evidence on MRI and a bilateral hypoxic–ischemic brain injury pattern, 10/13 (77%) were classified as abusive (presumptive or suspicious) (Fig. 10), 2/13 (15%) were accidental and 1/13 (8%) remained undefined.

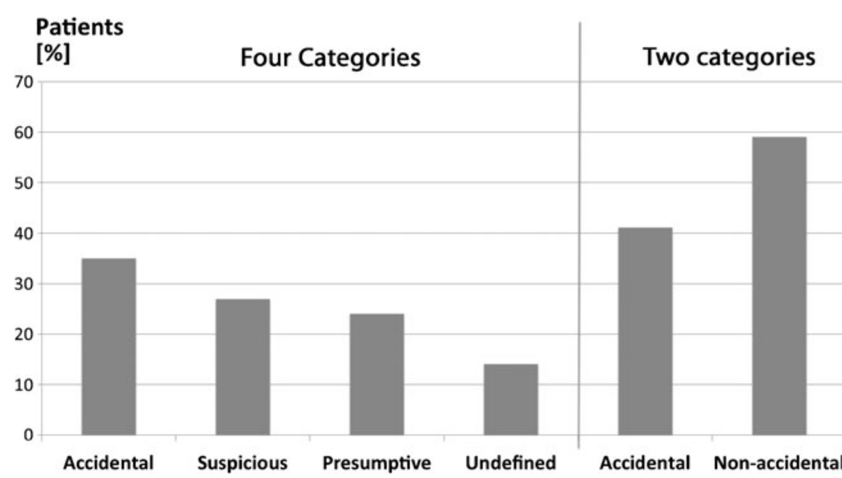

Fig. 2 Graph shows patient distribution into four non-accidental head trauma outcome categories based on modified Duhaime classification [8]: accidental trauma, suspicious for abusive trauma, presumptive abusive trauma, and undefined for patients with insufficient data. The categories of suspicious and presumptive were combined to compare accidental findings to non-accidental findings. In the latter comparison the undefined category was thrown out

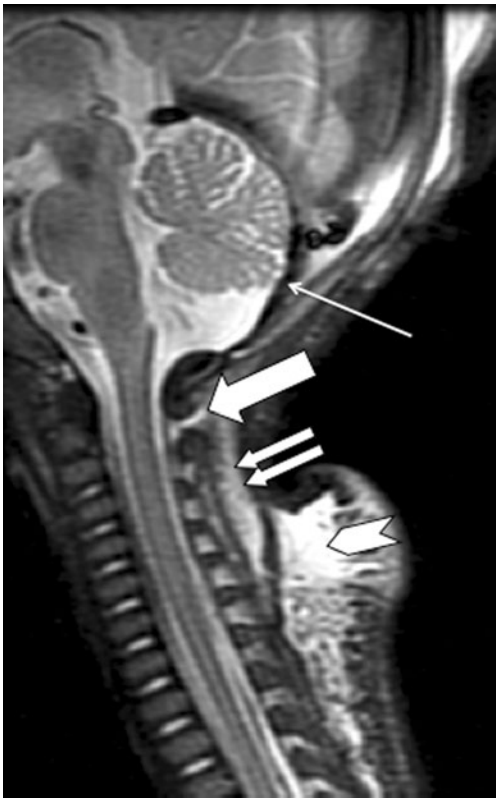

Fig. 3 Example of severe cervical soft-tissue injury. Sagittal fast-spin-echo inversion recovery MR image in a 3-month-old boy demonstrates the spectrum of soft-tissue pathology. There is T2 bright signal as evidence of injury near the C1/2 posterior ligamentous complex (*thick arrow*), T2 bright signal superior to the inter-spinous ligament (*double thin arrows*) above and below C3, and likely compressed subcutaneous fat with failure of fat suppression mimicking edema and possibly related to the cervical collar (*arrowhead*). Of note, the boy also has a small posterior fossa subdural hemorrhage (dark on T2, *thin arrow*)

Discussion

Our study is the largest cohort of children evaluated for abusive head trauma in which the prevalence of cervical spine soft-tissue injuries has been determined. We found MRI signs of cervical injury in 27/74 (36%) children in our study cohort. We did not find a statistically significant relationship between cervical spine injuries and abusive trauma, the latter defined as either “presumptive” or “suspicious” outcomes based on the algorithm by Duhaime [8]. Nonetheless the detection of MRI-apparent cervical injury might have implications for clinical care and medico–legal assessments.

Although cervical radiographs are obtained with the skeletal survey for bone injuries as part of the clinical workup, radiographs lack the ability to detect spinal cord and dorsal soft-tissue injuries. In our study there were two infants in whom we detected cervical spinal cord damage by MRI. If the spinal cord MRI had not been obtained, clinical symptoms may have been erroneously attributed to brain pathology. From another perspective, although many studies have proved the general ability of MRI to detect injuries to the cervical soft tissues (high sensitivity), it is also known that MRI has poor ability to differentiate ligamentous rupture from edema or hemorrhage (low specificity) [10–13]. Thus, detection of cervical soft-tissue injuries by MRI might complicate clinical decisions regarding treatment of these injuries with conservative versus surgical measures. In our cohort a neurosurgery consult was obtained for all children with abnormal cervical MRI findings, but none required surgical intervention.

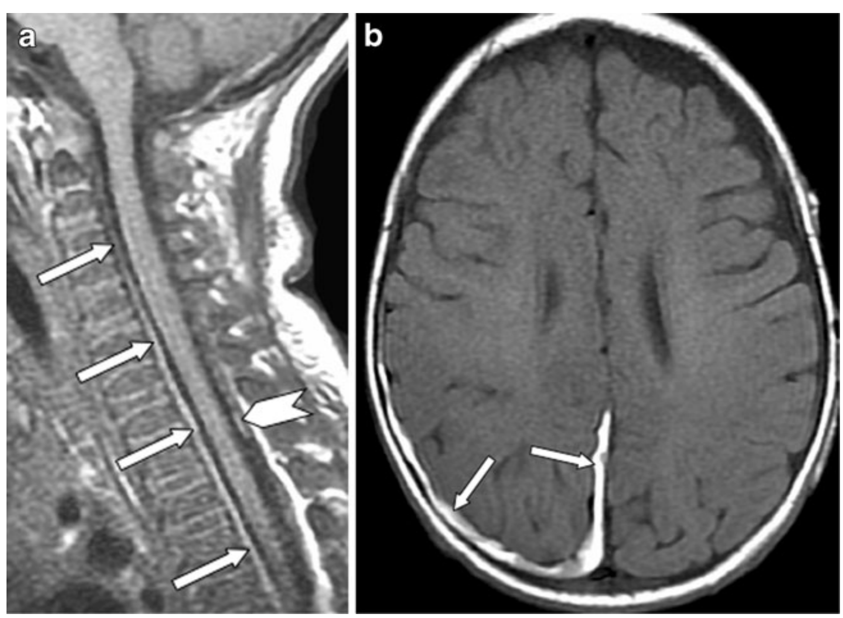

Fig. 4 Subdural and subarachnoid hemorrhages. Sagittal T1-W spine (**a**) and axial T1-W brain (**b**) MR images in a 4-month-old boy. **a** Note the linear distribution of T1 bright signal compatible with subdural blood anterior to the spinal cord (*arrows*) and the small amount of subarachnoid hemorrhage seen posteriorly (*arrowhead*). **b** These hemorrhages could represent descending blood products from the brain (*arrows*) or could have originated in the spine

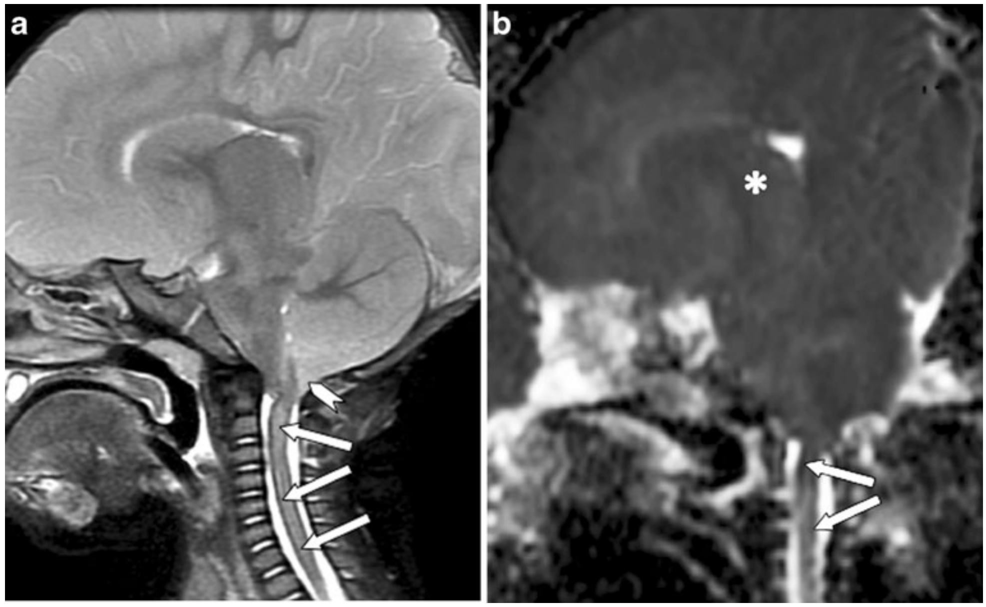

Fig. 5 Spinal cord injury (possible anoxia) in a 4-month-old girl. Sagittal fast-spin-echo inversion recovery spine (**a**) and sagittal ADC spine and brain (**b**) MR images show increased cord T2 signal (**a**, *arrows*) and corresponding restricted diffusion on ADC (**b**, *arrows*). There is extensive brain swelling and tonsillar herniation on sagittal fast-spin-echo inversion recovery image (**a**, *arrowhead*), as well as restricted diffusion of the brain (**b**, *star*). *ADC* apparent diffusion coefficient

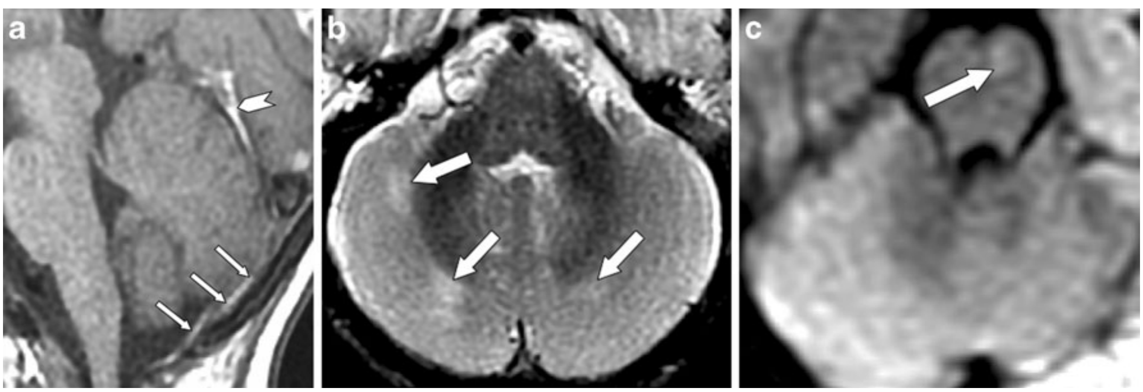

Fig. 6 Posterior fossa injuries in a 4-month-old boy. **a** Sagittal T1-W MR image demonstrates extra-axial T1 bright signal compatible with blood along the tentorium (*arrowhead*) and occiput (*arrows*). **b** Axial T2-W fat-saturated MR image shows T2 bright lesions of the cerebellum compatible with diffuse axonal injuries (*arrows*). **c** Axial diffusion-weighted image shows focal restricted diffusion (ADC map not shown) in the left anterior pons (*arrow*). *ADC* apparent diffusion coefficient

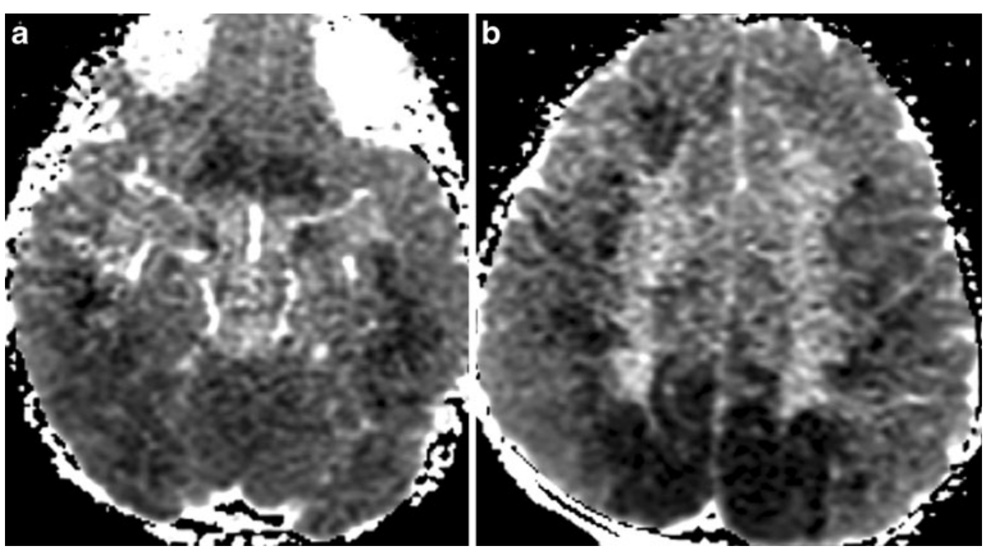

Fig. 7 Bilateral hypoxic–ischemic brain injury pattern in a 22-month-old girl. **a, b** Axial apparent diffusion coefficient maps show extensive dark signal, indicating extensive cerebral infarction

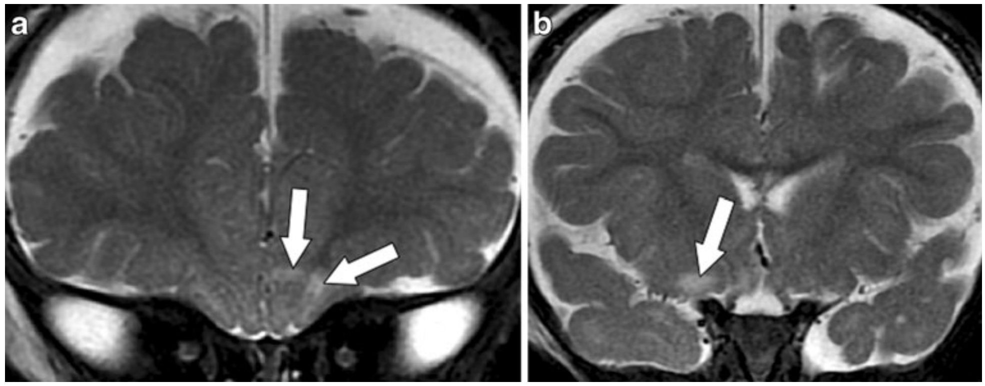

Fig. 8 Focal/contusion brain injury pattern in a 14-month-old boy. **a, b** Coronal T2-W fat-saturated MR images show multiple focal T2 bright areas in the brain parenchyma near the skull base (*arrows*)

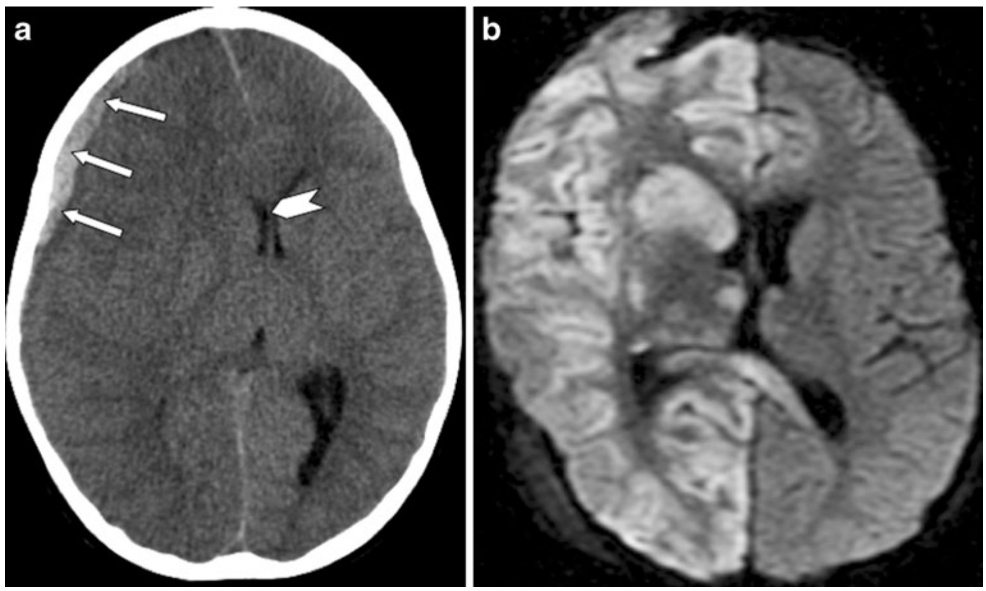

Fig. 9 Unilateral ischemic brain injury pattern in a 3-year-old boy. **a** Axial non-contrast brain CT shows a right subdural hemorrhage (*arrows*) and diffuse right hemispheric swelling with midline shift (*arrowhead*). **b** Axial diffusion-weighted MR image post right hemicraniectomy shows extensive right hemispheric bright diffusion signal with restriction (not shown), compatible with infarction

Table 1 Association between demographic and image-related variables and the four Duhaime-related trauma outcome categories (accidental, suspicious, presumptive, undefined) among all 74 children

Variable	*P*-value*
Age group	0.27
Gender	0.80
Soft-tissue injury	0.40
Injury extent	0.21
Posterior fossa hemorrhage	<0.0001*
Normal brainstem	0.08
Normal cerebellum	0.40
Brain injury	0.08
Type of brain injury	0.03*

*Assessed with the Fisher exact test, *P*-values <0.05 were considered statistically significant. Note that the mean age of the patient cohort (164 days) was used as a cutoff to define younger versus older children

Table 2 We found associations between (1) the presence of posterior fossa hemorrhage or (2) type of brain injury and the two modified Duhaime-related trauma outcome categories, accidental versus abusive, using the Fisher exact test

Posterior fossa hemorrhage**			
Posterior fossa hemorrhage	Accidental	Non-accidental	*P*-value*
No	16	11	0.01
Yes	10	27	
Brain injury type***			
Brain injury type	Accidental	Non-accidental	*P*-value*
Bilateral/diffuse	2	15	0.02
Unilateral/focal	7	6	

**P*-values <0.05 were considered statistically significant. ***n*=64 (all children) ****n*=29 (only among those with a brain injury)

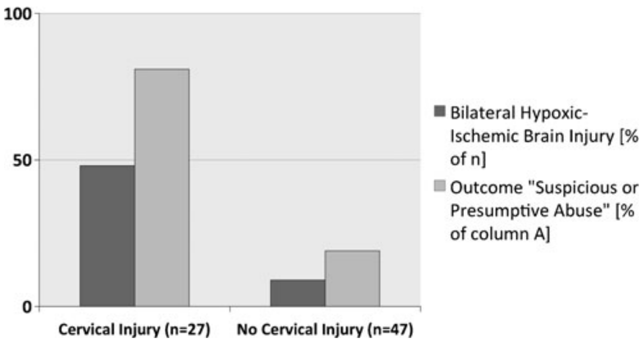

Fig. 10 Percentages of bilateral hypoxic–ischemic brain injury and outcome of "presumptive or suspicious abusive" head trauma in patients with and without MRI signs of cervical injury. The percentage of bilateral hypoxic–ischemic brain injury is much higher in patients with cervical injury on MRI (48%) than in patients without (9%). In patients with both MRI signs of cervical injury and bilateral hypoxic-ischemic injury there was a much higher suspicion or presumption of abusive trauma (81%) than in patients without MRI signs of cervical injury but with bilateral hypoxic–ischemic brain injury pattern (19%). These results did not reach statistical significance

Medico–legally, the detection of cervical injuries (soft-tissue and ligamentous injury) in a child with isolated acute subdural hemorrhage (subdural hemorrhage without retinal hemorrhages, fractures, bruising, abdominal injuries or a history of trauma) should prompt consideration of trauma. In addition to trauma (accidental, abusive, birth and iatrogenic), the differential diagnosis of isolated subdural hemorrhage encompasses a diverse range of non-traumatic conditions such as congenital malformations, genetic conditions, oncological disorders, autoimmune disorders, coagulopathies and infectious conditions [1]. In the appropriate clinical context, identification of significant cervical injury might help narrow the aforementioned differential considerations to a traumatic etiology, including possible abusive trauma. Missing abusive head trauma in infants imposes a significant risk of re-injury and death [14]. We thus propose that cervical spine MR imaging helps inform both clinical and medico–legal assessments. In order to reduce scanning and anesthesia for patients, screening for soft-tissue injuries could be performed with a sagittal fat-suppressed T2-W MR sequence.

Researchers who previously utilized the Duhaime criteria noted hypoxic injury to be associated with presumptive and suspicious abusive head trauma [15]. We found a significant (P=0.02) relationship between bilateral hypoxic–ischemic injury and the outcome of abusive (presumptive and suspicious) head trauma. The presence of parenchymal brain injury is not part of the Duhaime algorithm. In our cohort, after excluding children with an "undefined" study outcome, 29/64 (45%) children had parenchymal brain injuries. Of these, 16/29 (55%) had a bilateral hypoxic–ischemic pattern and 13/29 (45%) had a focal/contusion or unilateral ischemic pattern. Most children in the bilateral hypoxic–ischemic pattern group (14/16, 88%) were classified as abusive trauma (presumptive and suspicious), while in the non-hypoxic group the distribution of accidental versus abusive trauma was almost equal (7/13 were accidental and 6/13 were abusive).

Interestingly, of 16 children with a bilateral hypoxic–ischemic brain injury pattern, 12 (75%) also had cervical injury evidence on MRI. Of those with both MRI-apparent cervical injuries and a bilateral hypoxic–ischemic brain injury pattern, we found that 10/12 (83%) were classified as abusive (presumptive or suspicious, Fig. 10). The high prevalence of cervical injuries in children with abusive head trauma and diffuse hypoxic–ischemic cerebral injuries is consistent with a concept first proposed by Geddes et al. [16], whereby injury to the upper cervical spine can cause injuries to the lower medulla, resulting in apnea and subsequent anoxic brain injury.

The presence of various distinct brain injury patterns on MRI has been described in abusive head trauma patients [9, 17]. Diffusion-weighted imaging techniques in particular can be very useful in the detection and characterization of white matter injuries [18]. Overall, these findings suggest that using brain MRI for the detection of hypoxic–ischemic brain injury patterns could help differentiate accidental from abusive head trauma. Of interest, one child in our cohort had unilateral brain edema in the presence of an ipsilateral subdural hemorrhage. It has been proposed that this unilateral ischemia is the result of a second traumatic impact in association with dys-autoregulation [19] or is caused by unilateral vascular compression in the neck [20].

It is not surprising that in our study posterior fossa hemorrhage was associated with the outcome of abusive head trauma because presence of intracranial hemorrhage is a variable for classification of both presumptive and suspicious outcomes in the Duhaime algorithm, which we used for classification of our study outcome variables.

Our cohort differs from previous imaging and autopsy reports in that we observed fewer spinal hemorrhages. Specifically, we only saw one child with spinal subdural hemorrhage. Choudhary et al. [5] reported a 60% incidence of thoracolumbar subdural hemorrhage in patients with abusive head trauma. Koumellis et al. [21] reported 8/18 (44%) patients had mostly thoracic and lumbar subdural spine hemorrhages. Because we only imaged the cervical spine and others reported hemorrhages in thoracic and lumbar regions, we likely missed these hemorrhages. Kemp et al. [6] conducted a systematic literature review for inflicted spinal injury spanning a 33-year time period and found 16 reports of MRI findings, including 12 cases of spinal cord injury, 2 of fracture dislocations, 4 of musculoskeletal injuries localized to ligaments or intervertebral discs, and 4 of soft-tissue swelling. In our cohort we saw only two children with spinal cord injury, and they both had extensive supratentorial injuries along with extensive soft-tissue and ligament injury. The cervical cord in these children might have been injured secondary to cardiorespiratory events. Alternately, cervical cord injuries could have resulted from primary injury to the cervical spinal cord, which then led to cardiorespiratory complications. We did not see any intervertebral disc injuries or vertebral fractures in our cohort. Brennan et al. [7] reported nerve root avulsions in 16/52 children who died as the result of abusive head trauma. It is possible that our MR protocol using axial T2 images with 4-mm slice thickness caused us to miss nerve root avulsions. Given the relatively high number of cases of nerve root avulsions in Brennan's study [7] it might be warranted to include high-resolution images or high-resolution T2-weighted 3-D spinal acquisitions of cervical nerve roots in the spinal imaging protocol.

Limitations of our study include the retrospective design, the relatively small sample size of patients with abusive head trauma outcomes, and lack of a similar-age control group of non-trauma patients with cervical MRIs. There was also some selection bias based on inclusion of only those patients in whom the child abuse team's recommendation to obtain brain and cervical MRI was executed. We observed that primary teams failed to obtain recommended cervical MR imaging in children who were clinically very well, when the cervical MRI was unlikely to change clinical management or diagnosis, and in children who were clinically unstable and could not undergo MRI safely.

Conclusion

We consider it best practice to make a diagnosis of abusive versus accidental head trauma based on a careful medical evaluation by child abuse pediatricians and other subspecialists, complemented and informed by law enforcement and social services investigations. In our study population a high incidence (36%) of MRI signs of cervical injury was identified. We also found that diffuse hypoxic–ischemic cerebral injury occurred more frequently in children with abusive trauma and that the prevalence of cervical injury in children with abusive head trauma and diffuse hypoxic–ischemic cerebral injuries was very high (75%). Hypoxic–ischemic brain injury and cervical ligamentous injuries are both best detected with MR imaging. Based on our study results and review of the literature, we believe that MRI of the brain and cervical spine in children undergoing evaluation for abusive head trauma can yield important clinical and forensic information. We propose greater utilization of MRI imaging of the cervical spine during the evaluation for abusive head trauma.

Conflict of interest None

References

1. Hymel KP, Jenny C, Block RW (2002) Intracranial hemorrhage and rebleeding in suspected victims of abusive head trauma: addressing the forensic controversies. Child Maltreat 7:329–348
2. Kemp AM (2002) Investigating subdural haemorrhage in infants. Arch Dis Child 86:98–102, Review
3. Hettler J, Greenes DS (2003) Can the initial history predict whether a child with a head injury has been abused? Pediatrics 111:602–607
4. Boos SC, Feldman K (2011) Neck and spinal cord injuries in child abuse. In: Child abuse and neglect: diagnosis, treatment and evidence, 1st edn. Saunders, St. Louis, pp 396–398.
5. Choudhary AK, Bradford RK, Dias MS et al (2012) Spinal subdural hemorrhage in abusive head trauma: a retrospective study. Radiology 262:216–223
6. Kemp AM, Joshi AH, Mann M et al (2010) What are the clinical and radiological characteristics of spinal injuries from physical abuse: a systematic review. Arch Dis Child 95:355–360
7. Brennan LK, Rubin D, Christian CW et al (2009) Neck injuries in young pediatric homicide victims. J Neurosurg Pediatr 3:232–239
8. Duhaime AC, Alario AJ, Lewander WJ et al (1992) Head injury in very young children: mechanisms, injury types, and ophthalmologic findings in 100 hospitalized patients younger than 2 years of age. Pediatrics 90:179–185
9. Foerster BR, Petrou M, Lin D et al (2009) Neuroimaging evaluation of non-accidental head trauma with correlation to clinical outcomes: a review of 57 cases. J Pediatr 154:573–577
10. Anderson SE, Boesch C, Zimmermann H et al (2012) Are there cervical spine findings at MR imaging that are specific to acute symptomatic whiplash injury? A prospective controlled study with four experienced blinded readers. Radiology 262: 567–575
11. Brockmeyer DL, Ragel BT, Kestle JR (2012) The pediatric cervical spine instability study. A pilot study assessing the prognostic value of four imaging modalities in clearing the cervical spine for children with severe traumatic injuries. Childs Nerv Syst 28:699–705
12. Schoenwaelder M, Maclaurin W, Varma D (2009) Assessing potential spinal injury in the intubated multitrauma patient: does MRI add value? Emerg Radiol 16:129–132
13. Goradia D, Linnau KF, Cohen WA et al (2007) Correlation of MR imaging findings with intraoperative findings after cervical spine trauma. AJNR Am J Neuroradiol 28:209–215
14. Jenny C, Hymel KP, Ritzen A et al (1999) Analysis of missed cases of abusive head trauma. JAMA 282:621–629
15. Ichord RN, Naim M, Pollock AN et al (2007) Hypoxic–ischemic injury complicates inflicted and accidental traumatic brain injury in young children: the role of diffusion-weighted imaging. J Neurotrauma 24: 106–118
16. Geddes JF, Vowles GH, Hackshaw AK et al (2001) Neuropathology of inflicted head injury in children. II. Microscopic brain injury in infants. Brain 124:1299–1306
17. Zimmerman RA, Bilaniuk LT, Farina L (2007) Non-accidental brain trauma in infants: diffusion imaging, contributions to understanding the injury process. J Neuroradiol 34:109–114

18. Chan YL, Chu WC, Wong GW et al (2003) Diffusion-weighted MRI in shaken baby syndrome. Pediatr Radiol 33: 574–577
19. Cantu RC, Gean AD (2010) Second-impact syndrome and a small subdural hematoma: an uncommon catastrophic result of repetitive head injury with a characteristic imaging appearance. J Neurotrauma 27:1557–1564
20. McKinney AM, Thompson LR, Truwit CL et al (2008) Unilateral hypoxic–ischemic injury in young children from abusive head trauma, lacking craniocervical vascular dissection or cord injury. Pediatr Radiol 38:164–174
21. Koumellis P, McConachie NS, Jaspan T (2009) Spinal subdural haematomas in children with non-accidental head injury. Arch Dis Child 94:216–219