AJNR

An In-Depth Analysis of Brain and Spine Neuroimaging in Children with Abusive Head Trauma: Beyond the Classic Imaging Findings

G. Orman, S.F. Kralik, N.K. Desai, T.G. Singer, S. Kwabena, S. Risen and T.A.G.M. Huisman

AJNR Am J Neuroradiol 2022, 43 (5) 764-768
doi: https://doi.org/10.3174/ajnr.A7492
http://www.ajnr.org/content/43/5/764

An In-Depth Analysis of Brain and Spine Neuroimaging in Children with Abusive Head Trauma: Beyond the Classic Imaging Findings

G. Orman, S.F. Kralik, N.K. Desai, T.G. Singer, S. Kwabena, S. Risen, and T.A.G.M. Huisman

ABSTRACT

BACKGROUND AND PURPOSE: Abusive head trauma is the leading cause of morbidity and mortality in young children. Radiology provides valuable information for this challenging diagnosis, but no single neuroimaging finding is independently diagnostic of abusive head trauma. Our purposes were to describe the prevalence of brain and spine neuroimaging findings and to analyze the association of neuroimaging findings with clinical factors to determine which neuroimaging findings may be used as prognostic indicators.

MATERIALS AND METHODS: Children with a confirmed abusive head trauma diagnosis between January 2018 to February 2021 were included in this single-center retrospective study. Patient demographics, survival, Glasgow Coma Scale score on admission, length of hospital stay, and intensive care unit stay were examined. Brain neuroimaging findings were categorized as classic and nonclassic findings. Spine MRIs were also assessed for spinal ligamentous injury, compression fracture, and hemorrhage. The χ^2 test or the Wilcoxon rank-sum test was used for the analysis.

RESULTS: One hundred two children (male/female ratio: 75:27; average age, 9.49; range, 0.27–53.8 months) were included. Subdural hematoma was the most common (83.3%) classic neuroimaging finding. Bridging vein thrombosis was the most common (30.4%) nonclassic neuroimaging finding. Spinal ligamentous injury was seen in 23/49 patients. Hypoxic-ischemic injury was significantly higher in deceased children ($P = .0001$). The Glasgow Coma Scale score was lower if hypoxic-ischemic injury ($P < .0001$) or spinal ligamentous injury were present ($P = .017$). The length of hospital stay was longer if intraventricular hemorrhage ($P = .04$), diffuse axonal injury ($P = .017$), hypoxic-ischemic injury ($P = .001$), or arterial stroke ($P = .0003$) was present. The intensive care unit stay was longer if intraventricular hemorrhage ($P = .02$), diffuse axonal injury ($P = .01$), hypoxic-ischemic injury ($P < .0001$), or spinal ligamentous injury ($P = .03$) was present.

CONCLUSIONS: Our results may suggest that a combination of intraventricular hemorrhage, diffuse axonal injury, hypoxic-ischemic injury, arterial stroke, and/or spinal ligamentous injury on neuroimaging at presentation may be used as potential poor prognostic indicators in children with abusive head trauma.

ABBREVIATIONS: AHT = abusive head trauma; AS = arterial stroke; BVT = bridging vein thrombosis; DAI = diffuse axonal injury; EDH = epidural hematoma; GCS = Glasgow Coma Scale; HII = hypoxic-ischemic injury; ICU = intensive care unit; IVH = intraventricular hemorrhage; LOS = length of hospital stay; PL = parenchymal laceration; SDH = subdural hematoma; SPH = subpial hemorrhage; VS = venous stroke

Quality neuroimaging and careful imaging interpretation are essential for the diagnosis and treatment of abusive head trauma (AHT), a leading cause of preventable morbidity and mortality.[1] A diagnosis of AHT is often challenging. The main diagnostic challenges are that abused children are usually too young to provide an adequate history, perpetrators are unlikely to provide a truthful account of the trauma, and/or clinicians may be biased that AHT is more or less likely in specific settings, for example, depending on the socioeconomic situation of the parents.[2,3] Both false-positive or false-negative AHT diagnoses may have critical implications for social and familial dynamics as well as the child's health. A false-positive diagnosis may result in infants being removed from their homes and parents losing child custody permanently or going to jail by mistake.[3] In addition, children who are abused are more likely to sustain repeat abuse;

Received January 28, 2022; accepted after revision February 23.

From the Edward B. Singleton Department of Radiology (G.O., S.F.K., N.K.D., T.A.G.M.H.), Global Child Health Residency (T.G.S.), Department of Pediatrics (S.K.), Division of Public Health Pediatrics, and Department of Pediatrics (S.R.), Division of Child Neurology and Developmental Neuroscience, Texas Children's Hospital, Baylor College of Medicine, Houston, Texas; and Division of General Surgery (T.G.S.), Department of Surgery, David Geffen School of Medicine, University of California, Los Angeles, Los Angeles, California.

Please address correspondence to Gunes Orman, MD, Texas Children's Hospital, Edward B. Singleton Department of Radiology, 6701 Fannin St, Suite 470.12, Houston, TX 77030; e-mail: gxorman@texaschildrens.org

Indicates article with online supplemental data.
http://dx.doi.org/10.3174/ajnr.A7492

therefore, a false-negative diagnosis or missed diagnosis puts the child at risk of possible future injury, including a fatal brain injury.[4,5]

Radiology often provides critical diagnostic information for patients with suspected AHT, especially when the clinical history and physical examination may not reveal an abusive injury etiology at the time of presentation.[6] The optimal recommended imaging studies are not standardized, and no single neuroimaging finding is independently specific or diagnostic of AHT.[2] Rather, the diagnosis of AHT depends on the multiplicity and severity of imaging findings as well as consideration of the veracity of the provided clinical history and reported mechanism of trauma.[7] Therefore, familiarity with the classic as well as the nonclassic neuroimaging findings of AHT will assist radiologists and clinicians in a specific, sensitive, and timely diagnosis. The most common classic finding in AHT includes subdural hematoma (SDH) of varying CT densities and varying MR imaging signal intensities suggesting repeated injuries. Recently, nonclassic neuroimaging findings such as the "lollipop sign" or "tadpole sign," parenchymal or cortical lacerations, and subpial hemorrhage (SPH) have been described in the scientific literature.[2,8-11] However, there is limited evidence describing and evaluating the multiplicity of neuroimaging findings in a well-defined large group of children with confirmed AHT.

AHT is associated with a variable outcome scale, including mild developmental delay to severe disability and even mortality. Neuroimaging may be helpful in identifying the prognosis of patients with AHT by defining the extent of brain injury. However, prognostic markers in neuroimaging in children with AHT were rarely reported previously.

The goals of this study were the following: 1) to describe the prevalence of classic and nonclassic brain and spine neuroimaging findings in a well-defined large group of children with a confirmed AHT diagnosis at a quarternary Children's Hospital; and 2) to analyze the association of neuroimaging findings with survival, Glasgow Coma Scale (GCS) score on admission, length of hospital stay (LOS), and length of intensive care unit (ICU) stay, to determine which of the neuroimaging findings or combination of findings may be used as prognostic indicators.

MATERIALS AND METHODS

Following institutional review board approval (H-45947), all children with a confirmed diagnosis of AHT through a multidisciplinary approach with radiology, neurology, and child abuse specialists and ultimate determination by the board-certified Child Abuse Pediatricians at Texas Children's Hospital, seen between January 2018 and February 2021, were included in this single-center retrospective study. Informed consent was waived due to the retrospective nature of the study.

Patient demographic, clinical, and neuroimaging (CT and/or MR imaging) data were gathered through electronic medical record review. Patient age, sex, race, survival after AHT, GCS on admission, LOS, and ICU stay were noted.

CT studies of the brain were performed using standard departmental protocols without IV contrast. The scanning volume covered the region from up to 10 mm below the skull base to 10 mm superior to the skull vertex with the FOV ranging from 20 to 50 cm with 1- to 3-mm section thickness. All examinations were subject to volume-rendered 3D reconstruction algorithms with 360° feet-to-brain spin and 360° left-to-right spin for standardization processes and then were stored on the PACS system.

MR imaging studies of the brain were performed using standard departmental protocols on a 1.5T or 3T MR imaging scanner. Basal available sequences included noncontrast axial and sagittal T1-weighted, axial and/or coronal T1 and/or T2-FLAIR, axial and coronal T2-weighted, axial T2*-weighted gradient-echo or susceptibility weighted imaging, axial diffusion-weighted imaging, or diffusion tensor imaging. Section thickness varied between 3 and 4 mm, depending on the sequence used and age of the child.

MR imaging of the spine was performed using standard departmental protocols on a 1.5T or 3T MR imaging scanner. Routine conventional sequences of the spine were performed, including axial and sagittal T1- and T2-weighted turbo spin-echo imaging and sagittal short inversion recovery sequences.

Two experienced board-certified pediatric neuroradiologists (N.K.D. with 10 years' and S.F.K. with 9 years' experience) who knew that all children had a confirmed diagnosis of AHT but were blinded to data regarding GCS, LOS, ICU stay, and survival after AHT reviewed all patient neuroimaging studies independently. Any discrepancies in interpretation were resolved in a second consensus reading session. Consensus reading results were used for the final analysis.

Neuroimaging study findings of the brain were then categorized as classic and nonclassic findings based on previous literature.[2] Classic findings included skull fractures, epidural hematoma (EDH), SDH, SAH, intraventricular hemorrhage (IVH), contusions, diffuse axonal injury (DAI), and hypoxic-ischemic injury (HII). To define DAI, we included the presence of multiple microhemorrhages on MR imaging at the interface of gray matter and white matter, in addition to the commissures, corpus callosum, internal capsule, and brainstem. HII associated with AHT included changes in CT density and/or MR imaging signal intensity in the cortex, subcortical white matter, and/or deep gray matter. Nonclassic findings included bridging vein thrombosis (BVT), SPH, parenchymal laceration (PL), arterial stroke (AS), and venous stroke (VS). Spinal MRIs were also assessed for ligamentous injury (cruciform, apical, tectorial, anterior atlanto-occipital, posterior atlanto-occipital, posterior atlanto-axial, posterior longitudinal, anterior longitudinal, interspinous, and nuchal), compression fracture, and spinal hematoma (SDH and EDH). Each of the neuroimaging-based parameters was recorded as a yes/no response. The time period between admission and initial neuroimaging was also noted.

All statistical analyses were performed using SAS/STAT Software, Version 9.3 (SAS Institute). All variables were assessed for normality. Comparisons between the 2 groups were then evaluated by the χ^2 test or Wilcoxon rank-sum test. A P value $< .05$ was considered statistically significant.

RESULTS

One hundred two children were diagnosed with AHT during the study period and included in this study. There were 73.5% males ($n = 75$) and 26.5% females ($n = 27$) with an average age of 9.49

(range, 0.27–53.8) months. All patients had initial head CT imaging the same day or next day at admission. Race distribution of the patients was Asian ($n = 4$), Black ($n = 30$), Hispanic ($n = 37$), White ($n = 29$), and unknown ($n = 2$).

Thirty-six children had only brain CT, and 66 children had both brain CT and MR imaging for neuroimaging evaluation. Classic neuroimaging findings were the following: 1) skull fractures, 32.4% of the children ($n = 33$). These fractures were either single ($n = 25$) or multiple ($n = 8$) and linear ($n = 26$) or comminuted ($n = 7$). 2) EDH was found in 6.8% of the children ($n = 7$), ranging from 2- to 42-mm thickness. 3) SDH was seen in 83.3% of the children ($n = 85$), ranging from 2- to 35-mm thickness. Thirteen patients had SDH in a single location, and 72 patients had SDH in multiple locations. These locations were frontal 89.4% ($n = 76$), parietal 87% ($n = 74$), temporal 68.2% ($n = 58$), occipital 77.6% ($n = 66$), tentorial 75.3% ($n = 64$), and posterior fossa 43.5% ($n = 37$). 4) SAH was seen in 30.4% of the children ($n = 31$). Nine patients had SAH in a single location, and 22 had SAH in multiple locations. These locations were frontal 93.5% ($n = 29$), parietal 71% ($n = 22$), temporal 48.4% ($n = 15$), occipital 25.8% ($n = 8$), posterior fossa 6.5% ($n = 2$), and basal cisterns 14.3% ($n = 5$). 5) IVH was seen in 15.7% of children ($n = 16$). 6) Contusions were found in 20.6% of children ($n = 21$). 7) DAI was seen in 6.9% of the patients ($n = 7$), and 8) HII was found in 47.1% of the children ($n = 48$) in the cortex 100% ($n = 48$), subcortical white matter 62.5% ($n = 30$), and/or deep gray matter 60.4% ($n = 29$) (Online Supplemental Data).

Nonclassic neuroimaging findings were the following: 1) BVT was found in 30.4% of the children ($n = 31$); 2) SPH, in 5% of the children ($n = 5$) in the frontal ($n = 2$) and parietal ($n = 3$) regions; 3) PL, in 10% of the children ($n = 10$); 4) AS, in 5% of the children ($n = 5$); and 5) VS, in 1% of the patients ($n = 1$) in the frontoparietal region (Online Supplemental Data).

Neuroimaging findings when only brain CT was available ($n = 36$) were the following: 1) Classic neuroimaging findings were 33.3% skull fracture ($n = 12$), 11.1% EDH ($n = 4$), 72.2% SDH ($n = 26$), 27.8% SAH ($n = 10$), 5.6% IVH ($n = 2$), 13.9% contusions ($n = 5$), 0% DAI ($n = 0$), and 47.2% HII ($n = 17$); and 2) nonclassic neuroimaging findings were the following: 5.6% BVT ($n = 2$), 0% SPH ($n = 0$), 2.8% PL ($n = 1$), 2.8% AS ($n = 1$), and 0% VS ($n = 0$).

Forty-nine spine MRIs were available for the study. Spine MR imaging findings included the following: 1) ligamentous injury in 46.9% of the children ($n = 23$), of whom 3 had nuchal ligament injury and 21 had interspinous and nuchal ligament injury; 2) 2% of the children had compression fracture ($n = 1$) at the T1 vertebra; and finally 3) spinal hemorrhage was seen in 22.4% of the children ($n = 11$): SDH ($n = 7$), EDH ($n = 2$), and SDH+EDH ($n = 2$) (Online Supplemental Data).

We noted the survival rates during hospital admission due to AHT and found that 82.4% of the children ($n = 84$) survived and 17.6% of the children ($n = 18$) died within an average of 6.7 (range, 1–33) days. We compared the neuroimaging findings between surviving and deceased children (Online Supplemental Data). HII was significantly higher in deceased children (88.9%) compared with surviving children (38.1%) ($P = .0001$), and BVT was significantly lower in deceased children (5.9%) compared with surviving children (36.1%) ($P = .01$) (Online Supplemental Data). No significant difference was found for the rest of the neuroimaging findings between the 2 groups.

The GCS score at admission ranged between 3 and 15 for 99 patients; 3 patients had no GCS records available. We compared the median (interquartile range) GCS scores between negative and positive neuroimaging findings (Online Supplemental Data). We found that the median (interquartile range) GCS was significantly lower if the patient had HII (3.0 [3–15]) on brain neuroimaging compared with negative findings on neuroimaging (15.0 [3–15]) ($P < .0001$) and if the patient had ligamentous injury (4.5 [3–9]) on spine MR imaging compared with negative results (12.5 [3–15]) ($P = .017$) (Online Supplemental Data). No significant difference was found for the rest of the neuroimaging findings for median (interquartile range) GCS scores.

The average LOS was 15.62 (range, 1–97) days. We found a significantly longer LOS if IVH (23.6 days versus 14.1 days, $P = .04$), DAI (30.4 versus 14.5 days, $P = .017$), HII (21.3 versus 10.5 days, $P = .001$), and AS (42.2 versus 14.3 days, $P = .0003$) or a combination was present on initial neuroimaging (Online Supplemental Data).

A total 68.6% of the patients ($n = 70$) were admitted to the ICU for an average of 10.38 (range, 1–53) days. We found significantly longer ICU stays if IVH (12.2 versus 6.2 days, $P = .02$), DAI (15.6 versus 6.5 days, $P = .01$), HII (11.8 versus, 2.9 days, $P < .0001$), or ligamentous injury (14.6 versus 8.2 days, $P = .03$) or a combination was present on initial neuroimaging (Online Supplemental Data).

Representative patients are shown in the Online Supplemental Data.

DISCUSSION

In this detailed neuroimaging analysis in a well-defined large group of children with a confirmed AHT diagnosis, our findings of the prevalence of the classic neuroimaging findings including SDH, skull fracture, EDH, SAH, IVH, contusions, and DAI were consistent with prior reports. The incidence of HII was reported between 31% and 39% previously,[12-14] but HII was found in nearly half of our patient group, emphasizing the need to keep AHT in the differential diagnosis of infants and children presenting with HII and lack of a specific etiology. BVT was the most common nonclassic neuroimaging finding, observed in 30.4% of the children with AHT in our study. In previous literature, BVT was reported between 29% and 44%.[8,9,15] Although less frequent, the additional nonclassic imaging findings are critical to recognize clinically to suggest a diagnosis of AHT. SPH in neonates following vaginal delivery was reported previously.[16] PL has been described in subjects with AHT younger than 5 months of age.[17] Khan et al[18] reported 28% cerebrovascular accidents in patients, of whom 23% had AS, in their retrospective study of 282 children with AHT. The incidence of AS in their study was 6.4%, which was similar to our results. However, in the same study, Khan et al reported that 8% of their study population had VS. Spinal ligamentous injury was the most common (46.9%) spinal MR imaging finding in our study, and interspinous and nuchal ligaments were the most commonly affected ligaments. Ligamentous injury in child abuse was reported between 36% and 78% in the previous literature.[19-21] Spinal ligamentous injury is a clinically critical finding highly suggestive of AHT, resulting from violent shaking. Therefore, our results may suggest that the utility of spinal MR imaging is extremely helpful in patients with suspected AHT. A recent study reported that whole-spine MR imaging is helpful in AHT diagnosis and may be superior to cervical spine MR imaging to avoid missing, isolated thoracolumbar injuries.[22]

We also analyzed the association of neuroimaging findings with critical acute clinical data, including survival, GCS on admission, LOS, and length of ICU stay. We found that HII is the most important neuroimaging finding associated with critical clinical variables. We found that HII was significantly higher (89% versus 38%) in deceased children, and the median GCS on admission was significantly lower if HII was present on brain MRIs. HII represents severe and possibly irreversible injury to the brain.[23] Previously, Gencturk et al[23] reported a significant association between outcome severity and the presence of HII in their study, in which they evaluated clinical outcome based on abuse specialists' clinical assessment for the 6-month follow-up scoring. Therefore, in surviving children with AHT, the presence of HII has critical clinical prognostic value and emphasizes the need for neuroimaging in the evaluation of infants and children with suspected abuse. Most interesting, spinal ligamentous injury was associated with a lower GCS score and thus more severe injury. In AHT, spinal ligament injury is believed to be secondary to rigorous shaking of the child, which has been the most commonly reported (50%–63%) injury mechanism in AHT, resulting in hyperextension/flexion of the craniocervical junction.[24-26] Neuropathology literature suggested that damage to the lower brainstem (likely direct injury to the medulla) and upper cervical cord could be responsible for apnea events and may lead to HII and brain swelling.[27,28] Our results match the suggested hypothesis.

Kadom et al[19] reported that bilateral HII occurred more frequently in AHT, and almost half of bilateral HIIs in their cohort were among children who also had cervical soft-tissue injury on MR imaging. Our results show a higher incidence of HII in deceased children and also a lower GCS score when HII is present on neuroimaging. The similarity of the correlation between HII and mortality and markers of clinical severity emphasizes the critical importance of brain MR imaging evaluation for HII in the evaluation of AHT. Most interesting, although less sensitive than brain MR imaging, CT showed a similar incidence with a combination of CT and MR imaging. We also found a significantly higher LOS and/or ICU stay for IVH, DAI, HII, AS, and/or ligamentous injury in the initial neuroimaging studies in our patient cohort. This may suggest that a combination of these neuroimaging findings may be used as prognostic indicators and should be explored further in future studies of AHT and long-term developmental outcomes.

The strengths of this study include the large number of patients in a quaternary children's center. Additionally, this is the first study focused solely on classic and nonclassic neuroimaging findings in AHT with systematic completion of detailed imaging analysis of all patient studies. Limitations of this study are the following: 1) Clinical information was obtained through retrospective chart review; however, as the main focus of the study, the neuroimaging was re-read by 2 expert readers; 2) the children included had a confirmed diagnosis of AHT, which may have introduced bias in the reading of images, though 2 expert readers re-read images to mitigate this limitation; 3) although expected considering the high mortality of AHT, there was a discrepancy in number of children between the deceased and surviving patient groups, which has the potential to affect analyses; 4) CT is less sensitive than MR imaging for certain diagnoses, and not all patients had brain MR imaging available for the analysis; therefore, this limitation may have affected the statistical analysis and results; 5) a limited number of spinal MR imaging studies might have affected the statistical analysis and results; 6) this was a single-center evaluation of patients; and 7) heterogeneity of the imaging protocols performed may have an impact on the detection of subtle pathologies.

CONCLUSIONS

AHT is a leading cause of preventable mortality and significant morbidity for children. Given the difficulty in making this diagnosis often with incomplete history, head CT, brain MR imaging, and spine MR imaging are each critical tools in the evaluation of a child with suspected abuse. In this notably large cohort study for AHT, we found that SDH is the most common classic neuroimaging finding, and BVT is the most common nonclassic neuroimaging finding. Most important, ligamentous injury is seen in almost half of the spinal MRIs. HII is the most severe neuroimaging finding associated with higher mortality and other markers of clinical severity. Finally, we propose that the simultaneous presence of IVH, DAI, HII, AS, and/or ligamentous injury on the initial neuroimaging studies may be used as potential poor prognostic indicators, but prospective studies assessing the association between these neuroimaging findings and long-term developmental outcomes are needed to further support this conclusion.

ACKNOWLEDGMENTS

We would like to thank Haleh Sangi-Haghpeykar, PhD, from the Edward B. Singleton Department of Radiology and Department of Obstetrics and Gynecology, Texas Children's Hospital and Baylor College of Medicine, Houston, Texas, for the excellent and professional statistical support.

Disclosure forms provided by the authors are available with the full text and PDF of this article at www.ajnr.org.

REFERENCES

1. Spies EL, Klevens J. **Fatal abusive head trauma among children aged <5 years: United States, 1999-2014**. *MMWR Morbid Mortal Wkly Rep* 2016;65:505–09 CrossRef Medline
2. Orman G, Kralik SF, Meoded A, et al. **MRI findings in pediatric abusive head trauma: a review.** *J Neuroimaging* 2020;30:15–27 CrossRef Medline
3. Leventhal JM, Asnes AG, Pavlovic L, et al. **Diagnosing abusive head trauma: the challenges faced by clinicians.** *Pediatr Radiol* 2014;44 (Suppl 4):S537–42 CrossRef
4. Jenny C, Hymel KP, Ritzen A, et al. **Analysis of missed cases of abusive head trauma.** *JAMA* 1999;281:621–26 CrossRef Medline
5. Pollanen MS, Smith CR, Chiasson DA, et al. **Fatal child abuse-maltreatment syndrome: a retrospective study in Ontario, Canada, 1990-1995.** *Forensic Sci Int* 2002;126:101–04 CrossRef Medline
6. Pfeifer CM, Hammer MR, Mangona KL, et al. **Non-accidental trauma: the role of radiology.** *Emerg Radiol* 2017;24:207–13 CrossRef Medline

7. Choudhary AK, Servaes S, Slovis TL, et al. **Consensus statement on abusive head trauma in infants and young children.** *Pediatr Radiol* 2018;48:1048–65 CrossRef Medline
8. Choudhary AK, Bradford R, Dias MS, et al. **Venous injury in abusive head trauma.** *Pediatr Radiol* 2015;45:1803–13 CrossRef Medline
9. Hahnemann ML, Kinner S, Schweiger B, et al. **Imaging of bridging vein thrombosis in infants with abusive head trauma: the "tadpole sign."** *Eur Radiol* 2015;25:299–305 CrossRef Medline
10. Palifka LA, Frasier LD, Metzger RR, et al. **Parenchymal brain laceration as a predictor of abusive head trauma.** *AJNR Am J Neuroradiol* 2016;37:163–68 CrossRef Medline
11. Gunda D, Cornwell BO, Dahmoush HM, et al. **Pediatric central nervous system imaging of nonaccidental trauma: beyond subdural hematomas.** *Radiographics* 2019;39:213–28 CrossRef Medline
12. Zimmerman RA, Bilaniuk LT, Farina L. **Non-accidental brain trauma in infants: diffusion imaging, contributions to understanding the injury process.** *J Neuroradiol* 2007;34:109–14 CrossRef Medline
13. Ichord RN, Naim M, Pollock AN, et al. **Hypoxic-ischemic injury complicates inflicted and accidental traumatic brain injury in young children: the role of diffusion-weighted imaging.** *J Neurotrauma* 2007;24:106–18 CrossRef Medline
14. Orru E, Huisman T, Izbudak I. **Prevalence, patterns, and clinical relevance of hypoxic-ischemic injuries in children exposed to abusive head trauma.** *J Neuroimaging* 2018;28:608–14 CrossRef Medline
15. Zuccoli G, Khan AS, Panigrahy A, et al. **In vivo demonstration of traumatic rupture of the bridging veins in abusive head trauma.** *Pediatr Neurol* 2017;72:31–35 CrossRef Medline
16. Huang AH, Robertson RL. **Spontaneous superficial parenchymal and leptomeningeal hemorrhage in term neonates.** *AJNR Am J Neuroradiol* 2004;25:469–75
17. Jaspan T, Narborough G, Punt JA, et al. **Cerebral contusional tears as a marker of child abuse–detection by cranial sonography.** *Pediatr Radiol* 1992;22:237–45 CrossRef Medline
18. Khan NR, Fraser BD, Nguyen V, et al. **Pediatric abusive head trauma and stroke.** *J Neurosurg Pediatr* 2017;20:183–90 CrossRef Medline
19. Kadom N, Khademian Z, Vezina G, et al. **Usefulness of MRI detection of cervical spine and brain injuries in the evaluation of abusive head trauma.** *Pediatr Radiol* 2014;44:839–48 CrossRef Medline
20. Jacob R, Cox M, Koral K, et al. **MR imaging of the cervical spine in nonaccidental trauma: a tertiary institution experience.** *AJNR Am J Neuroradiol* 2016;37:1944–50 CrossRef Medline
21. Choudhary AK, Ishak R, Zacharia TT, et al. **Imaging of spinal injury in abusive head trauma: a retrospective study.** *Pediatr Radiol* 2014;44:1130–40 CrossRef Medline
22. Karmazyn B, Reher TA, Supakul N, et al. **Whole spine MRI in children with suspected child abuse.** *AJR Am J Roentgenol* 2022 Jan 12. [Epub ahead of print] CrossRef Medline
23. Gencturk M, Tore HG, Nascene DR, et al. **Various cranial and orbital imaging findings in pediatric abusive and non-abusive head trauma, and relation to outcomes.** *Clin Neuroradiol* 2019;29:253–61 CrossRef Medline
24. Christian CW, Block R; Committee on Child Abuse and Neglect; American Academy of Pediatrics. **Abusive head trauma in infants and children.** *Pediatrics* 2009;123:1409–11 CrossRef Medline
25. Starling SP, Patel S, Burke BL, et al. **Analysis of perpetrator admissions to inflicted traumatic brain injury in children.** *Arch Pediatr Adolesc Med* 2004;158:454–58 CrossRef Medline
26. Adamsbaum C, Grabar S, Mejean N, et al. **Abusive head trauma: judicial admissions highlight violent and repetitive shaking.** *Pediatrics* 2010;126:546–55 CrossRef Medline
27. Geddes JF, Hackshaw AK, Vowles GH, et al. **Neuropathology of inflicted head injury in children, I: patterns of brain damage.** *Brain* 2001;124:1290–98 CrossRef Medline
28. Geddes JF, Vowles GH, Hackshaw AK, et al. **Neuropathology of inflicted head injury in children, II: microscopic brain injury in infants.** *Brain* 2001;124:1299–1306 CrossRef Medline