Neuroimaging of pediatric abusive head trauma

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Abusive head trauma (AHT) is a major cause of morbidity and mortality in children subjected to abuse, accounting for nearly one-third of all deaths caused by child abuse.[1] Those children who do survive AHT are often left with significant and permanent disabilities, including motor and visual deficits, language abnormalities, seizures, and behavioral problems.[2-4] Despite the severe consequences of AHT, no standard criteria or objective tests exist for differentiating AHT from accidental trauma.[5] Clinical histories and presentations are often unclear and contribute to unrecognized cases or delays in diagnosis. Recent studies suggest healthcare providers had previously seen nearly one-third of children who subsequently died from AHT in the time leading up to their death.[6,7] In some cases, delay in diagnosis has been attributed to misinterpretation of radiologic studies, highlighting the need for improved education and awareness of the appropriate imaging techniques in the evaluation of AHT as well as common radiologic findings.[6-10]

Efforts continue to be made to understand the underlying pathogenesis and mechanisms of AHT. The two major categories of AHT include shaking mechanisms, in which repetitive acceleration-deceleration forces typically result in subdural hematomas (SDH), retinal hemorrhages and global parenchymal damage; and direct impact trauma, which may result in skull fractures and focal coup/contrecoup parenchymal injuries. However, the exact mechanisms of injury are often unknown and may result from a combination of forces. Parenchymal damage further can be multifactorial; for example, intracranial hemorrhage, hypoxic-ischemic injury and axonal disruption may all result in cytotoxic edema.[11-13]

Noncontrast head computerized tomography (CT) followed by conventional magnetic resonance imaging (MRI) is widely considered to be the first step in evaluating suspected AHT, with diffusion-weighted imaging (DWI) and susceptibility-weighted imaging (SWI) being critical MR sequences.[14-20] Diffusion tensor imaging (DTI), magnetic resonance spectroscopy (MRS) and arterial spin labeling (ASL) perfusion imaging of the brain also may be utilized, though these sequences are not typically included in routine protocols. In addition to evaluating brain injury, increasing emphasis has been placed on imaging of the orbits, olfactory tracts, and cervical spine. We outline current imaging techniques appropriate for the evaluation of AHT, highlighting their unique contribution to obtaining an accurate

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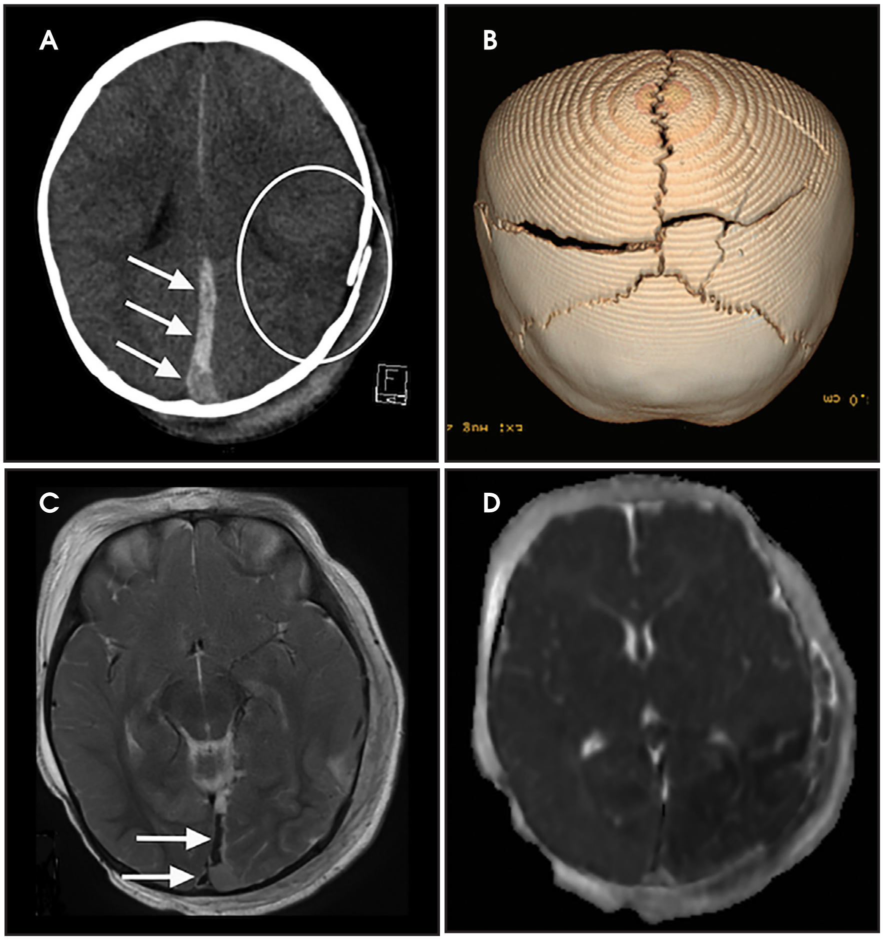

FIGURE 1. *An 11-month-old girl presented to the emergency department; her mother reported that the "child woke up with bruises." The Glasgow Coma Score (GCS) was 11-14. Axial noncontrast head CT with soft tissue window (A) and 3D reconstruction (B) demonstrate displaced and partially depressed skull fractures of bilateral parietal, occipital, and left temporal bones with significant soft-tissue swelling overlying the left calvarium and occiput. A wedge-shaped area of hypodensity underlying the fractures in the high left parietal lobe is consistent with evolving contusion (circle in A). Hyperdense subdural hematoma is seen along the left interhemispheric falx (arrows in A). Axial T2W image (C) shows that the hematoma has mixed characteristics of early and late subacute blood (arrows in C). Axial image from the ADC map (D) shows scattered areas of diffusion restriction consistent with ischemia/infarction, including within the left greater than right parietal lobes and corpus callosum splenium.*

and timely diagnosis, as well as common radiologic findings.

Imaging modalities

Computerized tomography

Noncontrast head CT is considered the appropriate primary study for children who present with signs and symptoms of head trauma including loss of consciousness, confusion, vomiting, irritability, seizures, or respiratory difficulties. CT is rapid, cost effective, widely available, and able to reveal injuries that may need rapid surgical intervention, including hemorrhage, midline shift, and herniation. Contrast should generally be avoided, as it can obscure high-density acute hemorrhage often found in AHT. Although the risk of ionizing radiation associated with CT should always be a consideration, it is widely accepted that the benefits of obtaining a CT in substantial trauma far outweigh the risks. Furthermore, in cases of suspected trauma when clinical evaluation may be difficult or indeterminate, or in cases when abuse is strongly suspected even without major neurological symptoms, head CT should be obtained, as studies have shown CT can detect occult head trauma even in cases of children with normal exams.[14,21] While older studies suggest the use of facial or skull radiographs to detect fractures associated with AHT, recent evidence suggests CT is superior to skull or facial radiographs for detecting fractures, and should be obtained with three-dimensional reconstructions to distinguish fractures from enlarged sutures in children less than two years of age[15,16] (Figure 1A-B). Thus, facial or skull radiographs are often not necessary and may only serve as a source of supplemental information.

Noncontrast CT can reliably identify substantial SDH (Figure 1A). This is critical, as SDH are significantly associated with AHT,[17,18] with estimates suggesting that SDH may be present in up to 90% of children who experience AHT.[19] However, SDH can also be a consequence of the birthing process,[20,22] benign enlargement of the subarachnoid spaces,[23] intracranial congenital malformations,[24] coagulation and hematologic disorders,[25] and certain metabolic disorders, most commonly glutaric aciduria.[26] Therefore, in addition to clinical history, SDH location and pattern is important. In particular, interhemispheric, convexity, and posterior fossa hematomas are individually associated with AHT[17] and significantly elevated in AHT versus accidental trauma[27] (Figure 1A). Mixed-density SDH are also more frequent in AHT (67% vs 18%), while homogenous hyperdense SDH were more frequent in accidental trauma (74% vs 33%).[28] It is important to note that spontaneous rebleeding into chronic SDH in infants is less likely than adults, and thus some suggest that mixed SDH in infants should raise further suspicions for repetitive head injury.[28] As blood attenuation is often multifactorial, especially in the acute setting, follow-up CT or MRI exams are usually necessary in order to reliably determine the age of a hematoma.[28]

Noncontrast CT is also useful for detecting the reversal sign, a phenomenon in which there is an inversion of the normal attenuation relationship between gray and white matter where gray

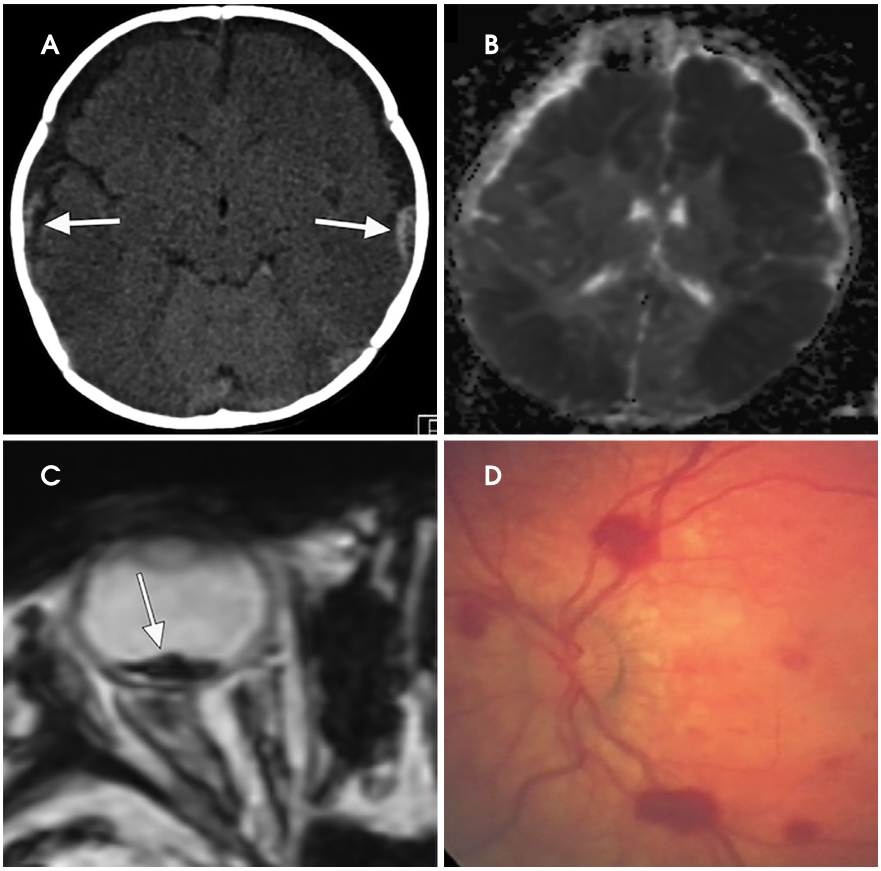

FIGURE 2. *An 18-month-old boy presented with status epilepticus after father reported the boy accidentally hit his head against a door frame. Axial noncontrast head CT (A) demonstrates bicerebral low-attenuation and loss of gray-white differentiation with relative hyperattenuating basal ganglia, brainstem and cerebellum, consistent with a 'reversal sign.' Mixed-density subdural hematomas overlie both cerebral hemispheres; high attenuating components are seen (arrows). Axial images from ADC map on MRI obtained the following day (B) show widespread patchy areas of diffusion restriction in both hemispheres consistent with global anoxic/ischemic injury. Magnified view of the right orbit on SWI sequence (C) from MRI obtained the next day shows an area of blooming in posterior right globe (arrow). An image from funduscopic exam (D) confirms diffuse retinal hemorrhage.*

matter has lower attenuation than white matter and there is an increased attenuation of the thalami, brainstem, and cerebellum.[29] The reversal sign is often a marker of diffuse cerebral edema, a common finding in AHT (Figure 2A). Positive cases of acute trauma on CT should be evaluated in conjunction with head MRI within 24-48 hours to better define extent of injury. Additionally, if the head CT is negative but trauma is strongly suspected by clinical evaluation, MRI should be obtained, as CT is often negative in the acute setting.

Magnetic resonance imaging

Conventional —Conventional MRI including gradient echo (GRE), T1-weighted, T2-weighted, and fluid-attenuated inversion recovery (FLAIR) is routinely performed in suspected cases of AHT in order to better characterize intraparenchymal injuries.[24] While MRI is more technically challenging, time-consuming and often requires anesthesia, the additional insight obtained from a head MRI is crucial for both initial and follow-up imaging for AHT. Conventional sequences in particular are better able to demonstrate recurrent episodes and evolution of injury by helping to date subacute and chronic hematomas, combating one of the challenges of CT (Figure 1C). T1-weighted imaging will often demonstrate hyperintensity of the cortical ribbon, identifying hemorrhagic cortical contusions or laminar necrosis. Identifying ischemia on T2-weighted imaging is challenging in infants and young children due to the high water content of unmyelinated white matter; however, loss of gray-white distinction along cortex and in deep nuclei can be a clue.

Conventional MRI sequences have also been shown to detect additional injuries not initially detected by CT including SDH, shearing injuries, ischemia, and parenchymal hemorrhages.[30,31] One study reported new findings in 25% (95% CI: 18.3 – 33.16%) of children when an MRI was conducted after an abnormal early CT.[30] An example of such a finding not well seen on CT is parenchymal lacerations; a retrospective review of 165 cases of pediatric accidental and abusive head trauma found that only half of the lacerations detected on MRI were appreciable on CT.[31] Parenchymal lacerations in this study were only seen in AHT cases.[31] Isolated subdural hygromas and those associated with subacute hematomas are also better detected by MRI and can be associated with AHT[32] (Figure 3A-B). In order to avoid the use of anesthesia, as well as potentially eliminate the need for an initial CT, the use of rapid MRI sequences has gained recent attention in evaluation of intracranial pathology in the pediatric population; however, a recent study suggests ultrafast MRI, even in combination with noncontract CT, has lower sensitivity compared to conventional MRI in patients with suspected AHT[33] and therefore is not generally used in this setting.

Diffusion-weighted imaging—In addition to conventional MRI series, DWI and the apparent diffusion coefficient (ADC) map have a well-established role in evaluating AHT, being crucial in evaluation of parenchymal injury.[34-36] Broadly, DWI and ADC mapping have been shown to be very sensitive in detecting early nonhemorrhagic infarction and subsequent acute cytotoxic edema, often hours to days before changes on CT.[30,37-39] These types of injuries are common in AHT and often result in

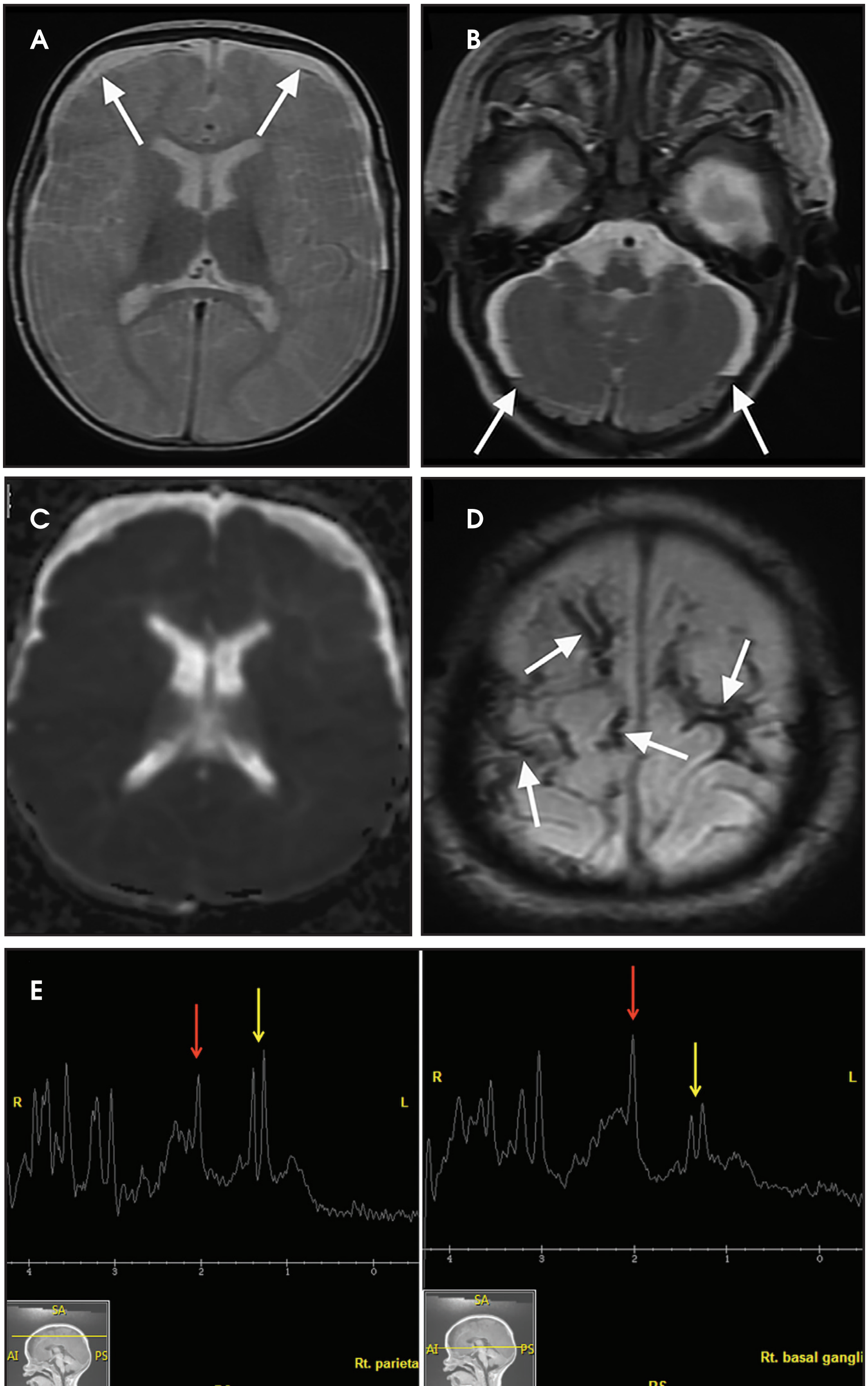

FIGURE 3. *A 2-month-old boy presented to ED with altered mental status and poor feeding. GCS was 9, pupils were fixed, and his anterior fontanelle was full. Axial T2W image at the level of the lateral ventricles (A) demonstrates bifrontal fluid collections, which are isointense to CSF, indicating these represent subdural hygromas (arrows). Axial T2W image at the level of the posterior fossa (B) shows additional mixed intensity fluid collections about the bilateral cerebellar hemispheres thought to represent hematoma layering within hygroma (arrows). Axial ADC map from the same exam (C) shows global cerebral diffusion restriction. Axial SWI image at the vertex (D) demonstrates evidence of cortical vein injury (arrows). MR spectroscopy (E) with selected voxels in right parietal lobe and right basal ganglia shows a pronounced lactate doublet and decreased NAA consistent with anoxic injury and neuronal dysfunction, respectively.*

poor outcomes including seizures, intubation, neurosurgical procedures, and inpatient rehabilitation.[34,40,41] DWI can help recognize these injuries in a timely manner, and can also be particularly helpful in children under two years of age in whom it is difficult to distinguish ischemic injury from normal immaturely myelinated white matter.

DWI often reveals more extensive injury than conventional sequences (Figure 1D).[38,39,42] Widespread areas of diffusion restriction are common in AHT (Figure 2B, 3C). Diffuse supratentorial or posterior cerebral are the most frequently reported patterns (Figure 4A). Arterial watershed hypoxic ischemia, venous hemorrhage/infarction, diffuse axonal injury (DAI), and contusions are less commonly encountered.[43] Although the shaking mechanism predisposes to DAI, incidences are overall less common in AHT compared to accidental trauma.[18,27] Low ADC values have also been found in several studies to be associated with poor long-term neurodevelopmental outcomes, offering additional prognostic value.[44-48] Importantly, DWI can also identity new areas of injury on repeat scans weeks after initial injury.

DTI, a form of DWI, is another imaging modality with growing applications. DTI is currently considered a useful technique in the evaluation of microstructural white matter abnormalities, as it is a direct measure of injury to axonal fibers.[49] While DTI has most commonly been used to assess myelination during maturation,[50] new investigations have focused on application of DTI to head trauma in children, demonstrating correlation of changes on DTI with injury severity, functional outcome, and long-term recovery.[49,51] One study directly assessing DTI in cases of AHT demonstrated unique widespread reduced axial diffusivity (AD) in white matter regions in AHT compared to controls, with localization to white matter tracts that meditate neurocognitive domains including auditory, visual, and executive functions. These findings suggest that DTI is able to detect additional

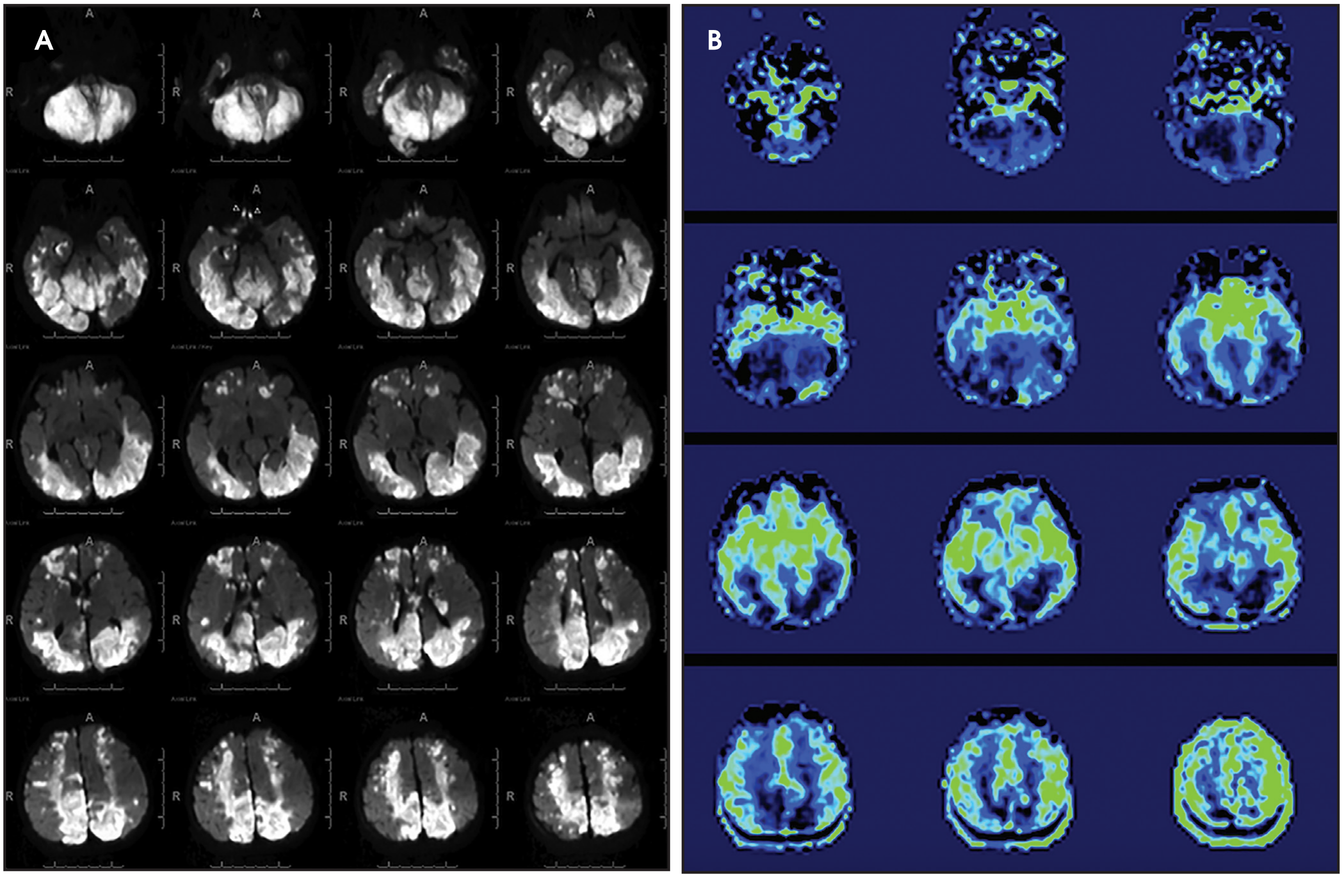

FIGURE 4. *A 9-month-old infant with complex medical history, presenting with extensive facial and body bruising, status post-reported unwitnessed fall from bassinet. Partially healed rib fractures were noted on chest radiograph. Serial axial diffusion-weighted imaging (A) reveals extensive areas of restricted diffusion throughout the cerebral and cerebellar hemispheres, with overlapping features of cortical contusions, shearing injuries, and hypoxic injury. Arterial-spin labeled perfusion images (B) demonstrate corresponding areas of marked hypoperfusion throughout the areas of injury.*

white matter changes that may be helpful in predicting long-term outcomes; however, it is also important to note that a negative DTI does not exclude AHT.

Susceptibility-weighted imaging—SWI is a 3D high-resolution MRI technique that accentuates the paramagnetic properties of blood products. SWI is more sensitive than conventional MRI, including GRE, in detecting hemorrhagic lesions. Examples of better visualized abnormalities include hemorrhagic foci associated with DAI,[52,53] clot formation within injured bridging veins, and hemosiderin deposition in superficial siderosis[32,54,55] (Figure 3D). Bridging vein thrombosis, in particular, is considered a sign of traumatic SDH in the context of AHT, as evidenced by blooming within bridging veins on SWI and often without signs of venous infarction.[56,57] In both accidental and AHT, the extent and number of hemorrhages is strongly correlated with initial severity of injury and long-term severity of neurologic outcome months after injury, as well as neuropsychological functioning several years after injury in AHT patients.[53,58,59] SWI is also increasingly utilized in conjunction with the funduscopic exam to identify retinal hemorrhages, a highly specific finding of AHT[56,57,60] (Figure 2C-D).

MR Spectroscopy—MRS is a noninvasive imaging technique that acquires concentration levels of various metabolites that are indicative of underlying neuronal dysfunction.[61] In processes that destroy brain tissue, N-acetyl aspartate (NAA), a neuronal marker, is reduced; likewise, choline, a cell membrane marker, is increased. Lactate elevation is widely known to result from hypoxic-ischemic damage as neurons switch to anaerobic metabolism.[62] While MRS is not routinely used in the acute trauma setting, it can help confirm the extent of neuronal injury in severe cases such as those resulting in hypoxic-ischemic injury and DAI. Several studies have shown that decreased NAA or NAA/creatine (Cr) ratios in children with AHT or TBI from other causes portend a worse outcome;[58,63-66] two of these studies found similar prognoses in patients with elevated lactate[64,66] (Figures 3E, 5A). Additional studies found increased rates of glutamate/glutamine[67] and myoinositol[68] to be associated with poor prognosis in children with TBI. Confirming diffuse brain injury with spectroscopy, if available, can aid in early management and intervention.

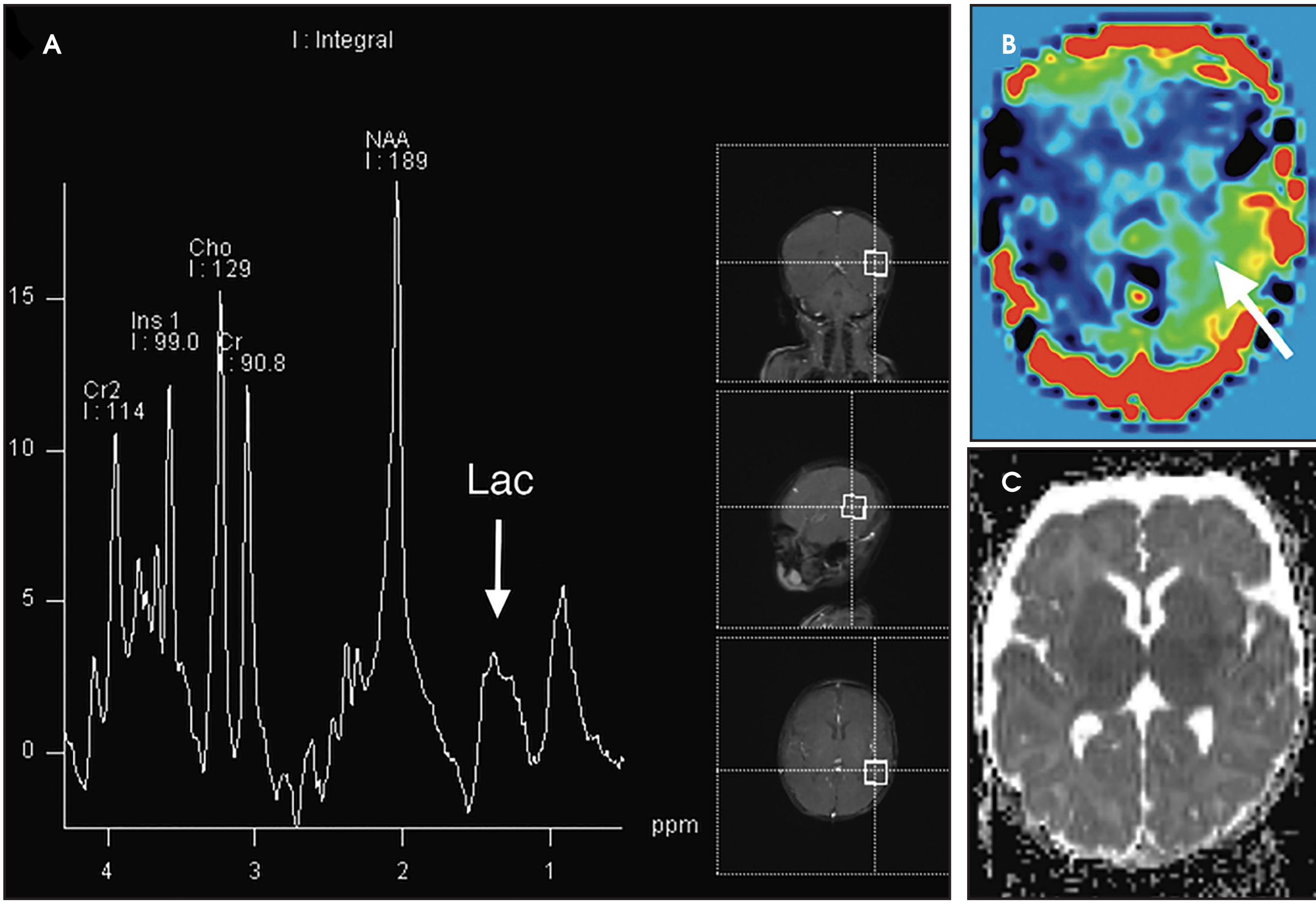

FIGURE 5. *Abusive head injury victim scanned shortly after recurrent seizures. Single-voxel MR spectroscopy (A) performed at TE=30 ms reveals an elevated lactate peak. On arterial-spin labeled perfusion imaging (B), there is a large area of hyperperfusion throughout the left temporoparietal region (arrow), despite lack of apparent abnormality in this region of the corresponding ADC map (C).*

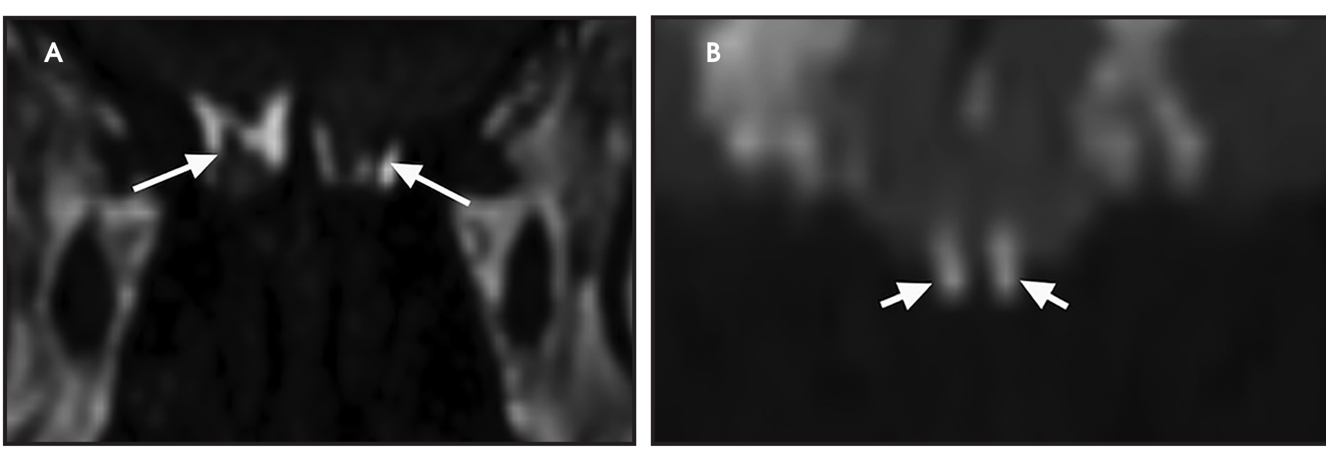

FIGURE 6. *Volumetric balanced coherent steady-state free precession (bSSFP) image reformatted in the coronal planes (A) demonstrates irregularity and asymmetry of the olfactory bulbs (arrows), secondary to traumatic injury. 20-directional diffusion weighted imaging in the reformatted coronal plane (B) reveals restricted diffusion within the olfactory bulbs (short arrows), confirming the acuity of the injury.*

Arterial spin labeling—As one of the two most common MRI perfusion-imaging methods, along with dynamic susceptibility contrast (DSC), ASL can also be utilized to evaluate TBI. Instead of contrast, ASL uses magnetically labeled water molecules in arterial blood as an endogenous tracer, making ASL a noninvasive technique for quantifying cerebral blood flow. Studies on ASL in mild accidental brain trauma have described diminished cerebral blood flow in certain brain regions in acute/subacute stages which was later restored in the chronic stage[69] and have shown that hypoperfusion may be seen in mild TBI in the context of an otherwise negative MRI, both acutely and months after injury.[69,70] In chronic TBI, encephalomalacia is the main contributor to alternation in absolute cerebral blood flow.[71] ASL may also detect additional injury in cases of AHT which are not as evident on other sequences (Figure 5B-C) or may help to confirm areas of restricted diffusion on DWI (Figure 4B). An investigation of perfusion using ASL in patients with AHT found children with AHT had more perfusion abnormalities compared to those without AHT and children with the most significant hypoperfusion had the poorest clinical outcomes.[72] Further studies using ASL should be pursued in order to solidify its role in initial and subsequent evaluation of AHT.

Other imaging considerations

When AHT is suspected, special attention should be paid to the retina and other orbital structures. As noted above, retinal hemorrhages are considered highly specific for AHT. They are often bilateral, extensive and multilayered in this context, and their presence indicates an acceleration-deceleration type mechanism. Intravitreous and optic nerve sheath hemorrhage and/or optic atrophy are other ophthalmologic findings of AHT that may be visible on imaging. In addition, trauma to the cisternal olfactory tracts and bulbs are frequently encountered as the result of severe coup/contrecoup injury or shearing across the cribriform plate,[73,74] which can be sustained from either a direct head strike or shaking (Figure 6). High-resolution imaging of the orbits, olfactory bulbs, and other cisternal structures can be readily performed with balanced coherent steady-state free precession (bSSFP) imaging. This sequence provides superior contrast for fine structures that are profiled by fluid or fat, making it ideal for delineating the small anatomic structures of the orbits, skull base, and exiting craniospinal nerves.

Finally, as small children typically lack the neck strength and head control to protect themselves against sudden hyper-extension/flexion forces, they are more prone to cervical spine injury, including spinal subdural hematomas and ligamentous injury.[75-79] Increasing evidence suggests cervical spine injury is more common AHT and is associated with more severe brain injury and poor outcomes; thus, cervical spine MRI is also now generally warranted.[75,77,79-81]

Conclusion

The evaluation of pediatric AHT is an ongoing diagnostic challenge as there are currently no standard criteria for differentiating AHT from accidental trauma. Clinical presentation and histories are often nonspecific, and thus investigations always warrant a thorough, multidisciplinary approach including skeletal surveys and ophthalmologic exam. Neuroradiologic imaging is vital in the evaluation of suspected cases, potentially offering insight into the mechanisms of injury and long-term prognosis. With the use of more advanced imaging such as DWI, DTI, SWI and MRS, prediction of long-term outcomes and identification of those at high risk is becoming more feasible, offering an opportunity to intervene earlier.

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