Diffusion-weighted Magnetic Resonance Imaging in Shaken Baby Syndrome

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• PURPOSE: To evaluate the role of diffusion-weighted magnetic resonance imaging (DWIMRI) in the diagnosis and management of children with suspected or confirmed Shaken Baby Syndrome (SBS).

• METHODS: This was a retrospective interventional case series of all infants and children younger than 2 years of age admitted to a children's hospital. We retrospectively reviewed medical records and neuroimaging findings of all children younger than 2 years of age with confirmed or suspected SBS admitted to a children's hospital. Inclusion criteria were documented ocular examination by an ophthalmologist and a brain MRI with DWI. Twenty-six infants and children were included. Other children were excluded. Children with proven SBS were diagnosed with "confirmed SBS," while children in whom the diagnosis of SBS remained uncertain were diagnosed with "suspected SBS."

• RESULTS: Twenty-six infants and children with mean age of 7.1 months (range, 6 weeks–24 months) were included, 18 with confirmed SBS. All 26 patients had a subdural hematoma, 10 had associated occult bone fractures, and 18 had retinal hemorrhages. Seven of the eight cases without retinal hemorrhages had isolated subdural hematoma without parenchymal brain lesions on both conventional MRI and DWIMRI. SBS was confirmed in only one case with a normal fundus. Among the 18 patients with retinal hemorrhages, SBS was confirmed in all but one case. All 18 patients with confirmed SBS had an abnormal DWIMRI. In 13 patients, DWI showed lesions that were larger than on conventional MRI. In patients with brain parenchymal lesions, the DWIMRI characteristics suggested cerebral ischemia, which appears to play a major role in SBS.

• CONCLUSIONS: In all patients with confirmed SBS, DWIMRI was abnormal and suggested diffuse or posterior cerebral ischemia, in addition to subdural hematomas in the pathogenesis of this disorder. (Am J Ophthalmol 2002;133:249–255. © 2002 by Elsevier Science Inc. All rights reserved.)

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NONACCIDENTAL HEAD INJURY RELATED TO THE Shaken Baby Syndrome (SBS) is the most common cause of head trauma in infants and young children in the United States.[1] It is a major cause of neurological and visual impairment. Shaken baby syndrome is characterized by subdural hematoma, occult bone fractures, and retinal hemorrhages.[2] However, none of the abnormalities is pathognomonic of SBS and the diagnosis of abuse is usually difficult and based on a constellation of clinical and radiological findings.[2–12] Moreover, because the exact types of injury are hidden by the perpetrators, the mechanisms of head injury and retinal hemorrhages remain debated.[2] Violent shaking and secondary acceleration-deceleration forces can cause traumatic axonal injury and subdural hematoma. Shaking may cause retinal and vitreous hemorrhages through vitreo-retinal traction or via acute elevation in intracranial pressure.[2,6,7] Direct impact to the head is now considered part of SBS and is responsible for skull fractures and cerebral cortical contusions.[2–5] Cerebral hypoxia and ischemia resulting from apnea are also postulated as important causes of brain injury.[13–17]

The wide use of head computed tomography (CT) in the evaluation of infants with suspected SBS has helped to elucidate the mechanisms of head injury and to establish prognosis. However, CT scan usually underestimates the severity and extent of cerebral damage acutely at a time when appropriate diagnosis and management are crucial to the child's survival.[2,15,18] Furthermore, its poor sensitivity to detect acute ischemia has led to underestimation of

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cerebral ischemia as a mechanism of brain damage in SBS. For these reasons, magnetic resonance imaging (MRI) of the brain has been used in addition, or as an alternative, to CT scan in numerous centers over the past decade. Indeed, in the recently revised guidelines for "imaging the child with suspected physical abuse" published by the American College of Radiology,[18] it was suggested that a MRI of the brain should be performed if the CT is negative or undeterminant, or to help determine timing of injury. It was also recommended that the MRI include three sequences: T1, T2, and gradient echo, the last a sequence very sensitive to blood products. In 2000, the American Academy of Pediatrics[19] recommended that CT scan should be obtained immediately after the injury and that the MRI should be delayed between 5 to 7 days after the injury to facilitate the detection of blood which may be difficult to image acutely on the MRI. In 2001, the American Academy of Pediatrics revised these recommendations[20] and suggested that the MRI should be obtained as early as 2–3 days after the trauma. Unfortunately, this timing of testing still does not allow the clinician to fully appreciate the extent and nature of the cerebral lesions acutely.

Diffusion-weighted MRI (DWIMRI) has recently proven useful in the diagnosis of acute cerebral ischemia and may be more sensitive than conventional MRI in the detection of diffuse axonal injury from head trauma.[21,22] This noninvasive imaging technique is now widely used and can be performed in addition to conventional MRI in most imaging centers. It demonstrates cerebral ischemia within minutes of onset and the temporal evolution of diffusion characteristics enables differentiation of acute from chronic infarction.[21,23–25] It also allows differentiation of infarction from immature white matter.[21] For these reasons, diffusion weighted imaging (DWI) sequences have been added to all MRIs ordered for the evaluation of possible nonaccidental head injury since available at our institution. In this study, we evaluated the role of DWIMRI in the diagnosis and management of children with suspected SBS.

METHODS

• **PATIENTS:** We retrospectively reviewed the medical records of all infants and children younger than 2 years of age with confirmed or suspected SBS admitted to Children's Healthcare of Atlanta at Egleston Hospital between 1998 and 2000. Medical records were obtained from the Department of Neurosurgery and from the Department of Pediatric Ophthalmology registry data banks and were cross referenced with the records of the Child Protection Program and neuroradiology referral records to identify suspected cases of nonaccidental head injury. Inclusion criteria were (1) suspected or confirmed SBS (including extensive evaluation to rule-out medical conditions that can mimic SBS, skeletal survey, ocular evaluation, evaluation of patients and their families by the pediatric social service team and by a pediatrician from the Children's Protection Program), (2) ocular examination performed by an ophthalmologist, (3) head CT and brain MRI with DWI performed within 5 days of presentation. Twenty-six children were included in the study.

In the absence of a confession of child abuse, the diagnosis of SBS was based on the criteria defined by Duhaime and associates.[4] A nonaccidental head injury was confirmed when the history was insufficient to explain injuries, as indicated by a disparity between the suggested mechanism of injury and the injuries observed. The presence of other injuries present in child abuse, such as occult bone fractures detected by the skeletal survey and not explained by the reported mechanism, was also suggestive of SBS. These patients were classified as "confirmed child abuse." Patients with injuries for whom the diagnosis of child abuse was suspected but could not be proven, were classified as "suspected child abuse."

• **NEUROIMAGING:** All patients had a head CT obtained upon admission to the hospital. Magnetic resonance imaging included sagittal and axial T1-weighted sequences, an axial T2-weighted sequence, a T2-weighted gradient echo sequence, and a DWI sequence, as previously reported.[26] Magnetic resonance angiography was also obtained on all patients. A neuroradiologist (P.C.D.) retrospectively reviewed all CT and MRI scans. The location and extent of the parenchymal brain lesions seen on conventional MRI were compared with those seen on DWIMRI.

RESULTS

A TOTAL OF 26 INFANTS AND CHILDREN WERE INCLUDED. There were 14 boys and 12 girls with a mean age of 7 months (range, 6 weeks to 24 months). Among these 26 children, 18 had confirmed SBS, and 8 had suspected SBS. All patients had acute subdural hematoma as revealed by CT scanning. Skeletal survey demonstrated long bones or rib fractures in ten cases (38.5%). Retinal hemorrhages were found in 18 patients (69%) (unilateral in 3, bilateral in 15). One case had associated vitreous hemorrhage. All children had at least one head CT scan with bone windows performed on the day of admission. The DWIMRI was performed within 5 days of presentation in all cases (mean, 2 days). The details of the CT and MRI findings in 18 of our 26 cases have been previously reported.[26]

The patients were divided into two groups depending on the funduscopic findings. In the group of patients without retinal hemorrhages (8/26 patients), seven cases had isolated subdural hematomas without parenchymal lesions on both conventional MRI and DWI (Figure 1). Shaken baby syndrome was confirmed in only one case with a normal fundus and remained suspected in the other seven cases. In

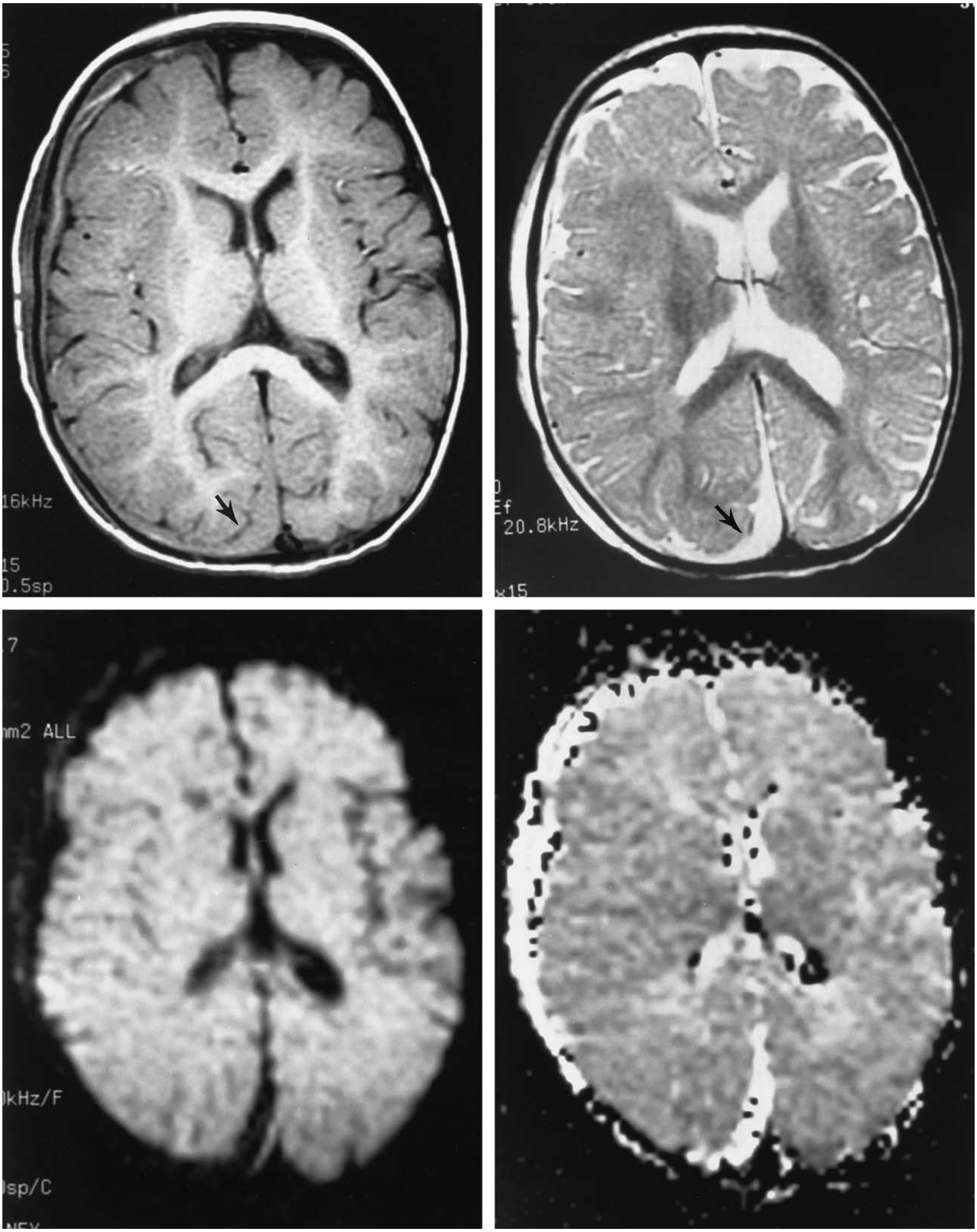

FIGURE 1. Axial MRI-T1-weighted image (top left), T2-weighted image (top right), diffusion-weighted image (bottom left), and the calculated ADC map (bottom right) obtained 1 day after head trauma in a 7 month-old child with suspected Shaken Baby Syndrome (SBS). There is a subdural hematoma, isointense on the T1-weighted image (arrow) and well seen on the T2W image (top right). The T2-weighted image does not show any associated parenchymal lesion nor do the DWI (bottom left) and ADC map (bottom right), which are unremarkable.

the patient with confirmed SBS and no retinal hemorrhages, the brain MRI showed parenchymal lesions in addition to the subdural hematoma. This patient had extensive lesions on DWIMRI that were larger than on the conventional MRI (Figure 2). In the group of patients with retinal hemorrhages (18/26 patients), SBS was confirmed in all, but one case. All 17 patients with retinal hemorrhages and confirmed SBS had parenchymal brain lesions on conventional and DWIMRI. In 13 of these 17 patients, DWIMRI showed parenchymal lesions that were larger than on conventional MRI (Figure 2). In five patients with retinal hemorrhages, DWI did not enhance the sensitivity of conventional MRI and showed lesions that were already seen on conventional MRI. The patient with retinal hemorrhages in whom the diagnosis of SBS could not be confirmed had small, bilateral, multiple intraretinal, and preretinal retinal hemorrhages without vitreous hemorrhage or disk edema. This patient had a negative skeletal survey. His CT scan showed bilateral subdural hematomas and his conventional MRI and DWIMRI did not reveal any associated parenchymal lesions.

In all 18 patients with parenchymal brain lesions on DWIMRI, lesions were suggestive of cerebral ischemia (Figure 2).[23–25] DWI abnormalities were multifocal and bilateral in 17/18 patients. The topography of restricted diffusion was diffuse affecting both cerebral hemispheres in 5 cases, or suggested bilateral watershed infarctions predominating in the posterior part of the cerebral hemispheres in 12 cases. In only one case were the DWI abnormalities restricted to the area of the brain parenchyma underlying a skull fracture. In some patients there were areas of abnormal signal suggesting traumatic axonal injury in addition to ischemia.[25] All patients had normal venous sinuses on conventional MRI and normal intracranial arteries on magnetic resonance angiography. None of our patients had evidence of distal occlusion or diminished flow in the intracranial circulation to suggest cervical carotid or vertebral artery dissection in the context of head trauma.

DISCUSSION

THE DIAGNOSIS OF SBS REMAINS EXTREMELY CHALLENGING. Although recent successful murder prosecutions have increased public and professional awareness of SBS,[27] the syndrome is still missed by physicians.[28] Conversely, it is also sometimes overdiagnosed, and some children with subdural hematomas from other causes are erroneously suspected of having SBS and their parents or caregivers falsely accused of assault.[27] The consequences of such an error may be grievous.

Injuries to the head pose special diagnostic difficulties, especially in the absence of any external sign of violence. No imaging or clinical investigations can differentiate with certainty between accidental and inflicted injury. Even though retinal hemorrhages are highly suggestive of nonaccidental injury in the setting of head trauma, they are not specific to SBS and their absence does not rule out the diagnosis.[2–12] One of our patients with confirmed SBS had a normal funduscopic examination, while in another patient with bilateral retinal hemorrhages, the diagnosis of SBS could not be confirmed. In the preverbal child, in the absence of witnesses or confession, imaging studies are critical in the assessment of head injury and they also may be the first indication of abuse in a child who is seen with an apparent natural illness.

In children with nonaccidental injury, the use of head CT,[9,18–20,29,30] and, more recently, of brain MRI,[9,18–20,31,32] helps to diagnose SBS, elucidate the mechanisms of head injury, and establish prognosis. However, although CT and conventional MRI are good at demonstrating subdural and parenchymal hemorrhages, they often do not acutely show other forms of parenchymal injury, such as that due to ischemia (Figure 2). The demonstration of associated cerebral ischemia acutely may be the key to the diagnosis of SBS, making DWI an extremely useful technique. Indeed, all our patients with confirmed SBS had an abnormal DWIMRI, while DWI was normal in all other cases in whom SBS could not be confirmed.

Diffusion-weighted MRI is a MRI sequence sensitive to the diffusion of water molecules, which is altered by cerebral lesions.[21,23–25] The detection of acute cerebral ischemia at the very earliest stages of stroke is by far the most significant application of DWI. Indeed, only a few minutes after the onset of symptoms, the apparent diffusion coefficient (ADC) is reduced and an area of ischemia appears hyperintense on DWI at a time when the conventional T2-weighted images still appear normal (Figure 2). Furthermore, the changes in the ADC and DWI vary with time and DWIMRI allows an estimate of the age of ischemic lesions and may prove of particular importance in cases of suspected SBS.

In addition to showing acute cerebral ischemia much earlier than conventional MRI, DWI also makes the diagnosis of ischemia easier in infants and young children with immature white matter.[21,23] Furthermore, DWI may help differentiate ischemia from traumatic axonal injury, thereby clarifying the specific mechanisms responsible for acute cerebral injury in SBS, with resultant important implications for the acute management of these children.[15–17,22]

Indeed, the mechanisms responsible for the cerebral injury remain debatable.[2] Subdural hematoma, which was present in all our cases, is likely caused by the shearing forces provoked by the acceleration-deceleration which disrupt the small bridging veins over the surface of the brain.[2,3,8,12] As recently demonstrated by Geddes and associates,[16,17] cerebral hypoxia and ischemia is the most common mechanism of intraparenchymal injury, while contusions, shearing injuries, and traumatic axonal injuries are found in only a minority of patients. Cerebral hypoxia/

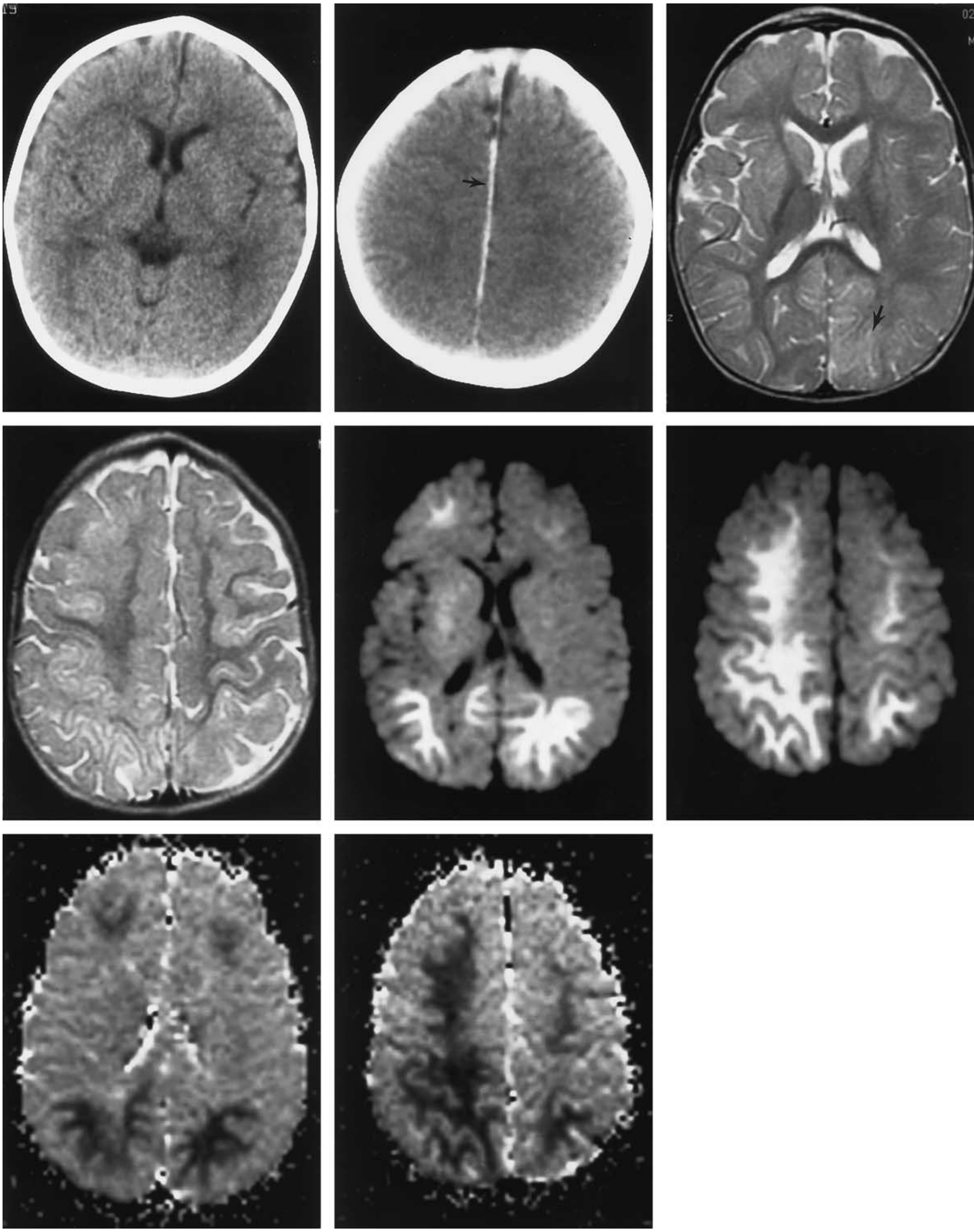

FIGURE 2. Noncontrast CT scan (top left and top middle), axial MRI-T2-weighted image (top right and middle left), diffusion-weighted image (middle middle and middle right), and the calculated ADC map (bottom left and bottom middle) in an 11 month-old child with confirmed SBS. The CT scan was obtained upon admission to the hospital and the DWI was performed 2 days later. There is an interhemispheric subdural hematoma (arrow) well seen on the CT scan (top middle). The T2-weighted images (top right and middle left) are remarkable only for possible cortical swelling involving the left occipital lobe (arrow). The DWI (middle middle and middle right) demonstrate symmetric hyperintensity involving the occipital lobes bilaterally, the right parietal lobe, and the posterior right frontal lobe. These hyperintensities on DWI correspond to decreased signal on the ADC map (bottom left and bottom middle), suggesting restricted diffusion. These abnormalities are consistent with bilateral watershed infarctions predominating in the occipito-parietal junctions. The magnetic resonance angiography showed normal intracranial arteries. The venous sinuses were normal on the conventional MRI.

ischemia in SBS may be explained by numerous factors such as reactive vasospasm adjacent to hemorrhagic lesions, strangulation, cervicomedullary injuries, and persistent crying and apnea.[3,16,17,33–35] Very few studies have investigated the role of cerebral ischemia in SBS, but there is evidence that it is one of the mechanisms leading to irreversible neuronal damage in SBS.[15–17,36,37]

DWIMRI was abnormal in all our patients with confirmed SBS. It suggested diffuse cerebral hypoxia/ischemia, in addition to subdural hematomas in all our patients. In most cases, the cerebral infarctions were subtle or not yet suspected on the head CT performed acutely and were either missed or underestimated on the conventional MRI. The intracranial vessels appeared normal on the magnetic resonance angiography obtained at the same time as the DWI, which reinforced the hypothesis of apnea and hypotension being mostly responsible for the cerebral hypoxia. Indeed, in a large majority of our patients the DWI abnormalities were either diffuse or predominantly in the distribution of the posterior watershed territories. As emphasized by Suh and associates,[26] this distribution of lesions is very atypical for head trauma in any situation other than SBS and may be responsible for some of the visual impairment frequently found in children with SBS.[7] Indeed, in the large series of patients with SBS recently published by Kivlin and associates,[6] one fifth of the survivors had visual impairment, most often the result of brain injury involving the occipital lobes. Similarly, McCabe and Donahue[11] found a correlation between visual unresponsiveness and the severity of cerebral edema, the latter most likely a result of cerebral infarction. They also found that the visual prognosis of patients with SBS was related to any requirement for ventilatory support, the latter correlated with the extent of cerebral injuries.[11]

Suh and associates[26] evaluated in detail the neurologic outcome of 18 of our 26 patients and suggested that DWIMRI, performed in addition to head CT and conventional MRI, may provide useful information regarding prognosis. Extensive DWI abnormalities correlated with a poor neurologic prognosis in these patients.[26] Although it is likely that patients with bilateral posterior watershed infarctions involving the retrochiasmal visual pathways have a poor visual prognosis, we do not have long-term data regarding the visual outcome in our patients. It has been shown that the duration of the hypoxic injury is proportional to the severity of the brain injury and is a major determinant of clinical outcome, including visual function.[10] Being able to assess acutely the presence and extent of an ischemic insult to the brain with DWIMRI would have profound implications for the acute management of children with suspected SBS. Indeed, findings suggesting diffuse cerebral ischemia would prompt the use of treatments aimed at protecting the brain from the effects of acute ischemia, rather than treating traumatic axonal injury and posttraumatic cerebral edema.

Since the history is often unreliable in cases of SBS, information about timing of injury must be extrapolated from clinical and radiological findings. Indeed, the timing of changes in the clinical and radiographic appearance of various injuries following child abuse is critical from a medicolegal viewpoint, as it provides a legal framework for establishing the time of the alleged abuse.[2,38] Retinal hemorrhages, for example, cannot be dated with precision. Since approximately 50% of abused children are victims of repeated episodes, acute traumatic neuroradiographic findings may be superimposed on those of prior injury. Several studies have demonstrated the superiority of MRI over CT in SIBS in establishing the timing of injury, because of its ability to identify parenchymal blood of various ages.[18,31,38] The change in signal of the intraparenchymal hematoma due to transformation of hemoglobin degradation products makes MRI a sensitive method of detecting the age of hematoma. However, the evolution over time of subdural hematoma or extradural hematoma is still poorly known. The change in signal of ischemic regions on DWI over time is exquisitely sensitive and it is likely that DWI may provide better information about the timing of cerebral ischemia in SBS. The combination of findings on head CT and both conventional and DWIMRI may prove useful in determining the sequence of events and helping the police identify potential perpetrators.

Our study suggests that DWI, which is an excellent technique for the detection of acute cerebral ischemia and injury, may be helpful in the diagnosis of SBS. Indeed, by demonstrating cerebral ischemia in addition to subdural hematomas in all our patients with confirmed SBS, and in none of our patients with only suspected SBS, DWIMRI was more sensitive and specific than funduscopic examination. Furthermore, DWIMRI helps elucidate the mechanisms of the neurologic deficit acutely, which may be the key to the diagnosis of SBS. Indeed, only very few diseases can produce at the same time and in the same patient, retinal hemorrhages, subarachnoid, subdural and parenchymal hemorrhages, cerebral edema, and cerebral infarction. Severe head trauma from motor vehicle accidents, venous sinus thrombosis, severe coagulopathies, and leukemia may rarely show such findings in association, but these disorders are usually ruled out by history, conventional brain MRI, and simple blood tests. DWI findings also correlate with neurologic prognosis and it is likely that the bilateral posterior watershed infarctions found in these patients may explain the high frequency of visual loss in SBS. Improved understanding of the mechanisms of injury in SBS and its prognosis should better direct the acute management of these infants and children.

We agree with the new American Academy of Pediatrics Guidelines[20] suggesting that a brain MRI should be obtained systematically in addition to CT scan in children with suspected inflicted head injury. However, our results suggest that this MRI should not be delayed after the injury, but should be obtained as soon as possible, with additional DWI sequences.

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