Nonaccidental Pediatric Head Injury: Diffusion-weighted Imaging Findings

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OBJECTIVE: **Diffusion-weighted imaging (DWI) reveals nonhemorrhagic posttraumatic infarction hours to days before conventional computed tomographic scanning or magnetic resonance imaging (MRI). We evaluated the diagnostic utility of DWI in children with nonaccidental head trauma.**

METHODS: **The medical records and imaging examinations obtained between January 1998 and May 2000 for all children less than 2 years of age with presumed or suspected nonaccidental head injury were reviewed retrospectively. Twenty children who had undergone DWI within 5 days of presentation were included in the study. Computed tomographic scans, conventional MRI sequences, and DWI combined with apparent diffusion coefficient (ADC) maps were evaluated.**

RESULTS: **Eleven girls and nine boys (median age, 5 mo) were studied. Eighteen children had presumed nonaccidental head trauma, and two children had suspected nonaccidental head trauma. Of the 18 children with presumed nonaccidental trauma, 16 (89%) demonstrated abnormalities on DWI/ADC, as compared with neither of the two children with suspected nonaccidental trauma. In 13 (81%) of 16 positive cases, DWI revealed more extensive brain injury than was demonstrated on conventional MRI sequences or showed injuries not observed on conventional MRI. DWI combined with ADC maps allowed better delineation of the extent of white matter injury. DWI/ADC abnormalities in the nonaccidental head-injured children were likely to involve posterior aspects of the cerebral hemispheres, with relative sparing of the frontal and temporal poles. Severity on DWI correlated significantly with poor outcome (*P* < 0.005).**

CONCLUSION: **DWI has broad applications in the early detection of infarction in children with nonaccidental head injury and enhances the sensitivity of conventional MRI. In the patients in this study, early DWI provided an indicator of severity that was more complete than any other imaging modality. The use of DWI may help to identify children at high risk for poor outcome and to guide management decisions.**

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Key words: Child abuse, Diffusion-weighted imaging, Magnetic resonance imaging, Traumatic brain injury

Inflicted head injury is a major cause of mortality and morbidity in young children (5, 7–11, 13, 15, 19, 22). A unique pattern of findings on imaging is widely recognized to be associated with abuse-related head injury in infants and young children; certain findings are considered highly suggestive markers for child abuse (6, 11, 14, 28, 44). Computed tomographic (CT) scanning is the diagnostic study of choice for evaluating acute traumatic head injury; however, a major disadvantage of CT scanning is its relative insensitivity for the detection of acute nonhemorrhagic infarction and white matter shear injuries. Magnetic resonance imaging (MRI) offers increased sensitivity for detecting and characterizing small intra-axial and extra-axial lesions as well as for identifying nonhemorrhagic infarction. MRI is especially helpful when CT findings are equivocal. Despite the sensitivity of CT scanning and MRI, the findings may underestimate the severity of injury because of a failure to delineate either diffuse brain injury not associated with vascular disruption or minute lesions not associated with hemorrhage or edema. Recognition of diffuse cortical infarction is especially difficult in very young children with immature white matter who are most at risk for nonaccidental head trauma (NAHT).

Diffusion-weighted imaging (DWI) can detect changes in the random motion of H_2O protons. The apparent diffusion coefficient (ADC) is an approximate measure of the rate of this random motion. This imaging technique has been extensively evaluated in the setting of acute ischemia, with numerous studies demonstrating that DWI is more sensitive than conventional MRI in detecting acute ischemic changes as well as in differentiating cytotoxic from vasogenic edema (2, 4, 10, 27, 29, 31, 34–39, 41–43). Recently, DWI changes have been described in experimental models of head injury and among patients with traumatic brain injury (2, 4, 24–26, 32, 42). In addition to acute ischemic injury, findings on DWI may be abnormal in contusion, hemorrhagic contusion, and penetrating injuries. More importantly, findings on DWI may reveal posttraumatic ischemic injury hours to days before CT scanning or MRI. Because areas of restricted diffusion as a result of cellular injury from any cause are revealed, DWI combined with ADC mapping has broad applications in children with accidental and nonaccidental brain injury, particularly for infants and very young children with immature white matter. In infants and young children, the delineation between normal and ischemic tissue is less obvious on conventional MRI because of the relatively high water content of the immaturely myelinated brain. The contrast between immature brain and injured tissue is improved with the use of DWI, because DWI capitalizes on the differences in diffusion. On DWI, the increased extracellular water content of immature white matter has a less restricted diffusion pattern than that of mature brain, whereas processes associated with ischemic injury result in greater diffusion restriction. The result is dramatic improvement in tissue contrast between immature brain and ischemic or infarcted tissue.

To define the diagnostic utility of DWI and ADC mapping in young children with abuse-related head injury, we analyzed diffusion-weighted images in addition to findings on conventional CT scanning and MRI obtained in children less than 2 years of age admitted to our institution with presumed or suspected NAHT.

PATIENTS AND METHODS

Patients

The medical records of all children admitted to the Children's Hospital of Atlanta–Egleston between January 1998 and May 2000 with a diagnosis or suspicion of child abuse or neglect were reviewed retrospectively. This institute is a tertiary referral center and is certified as a Level I trauma center by the American College of Surgeons. Medical records were cross-referenced with records from the Child Protection Program and the radiology department to identify all patients with presumed or suspected NAHT who had undergone DWI within 5 days of presentation (mean, 2 d; range, 1–5 d). The clinical history was determined by detailed examination of all information contained in the medical record.

Determination of nonaccidental versus accidental head injury

In the absence of a confession by the perpetrator, the determination of nonaccidental versus accidental head injury was based on an algorithm initially proposed by Duhaime et al. (13) and used by others in a modified form (*Fig. 1*) (11).

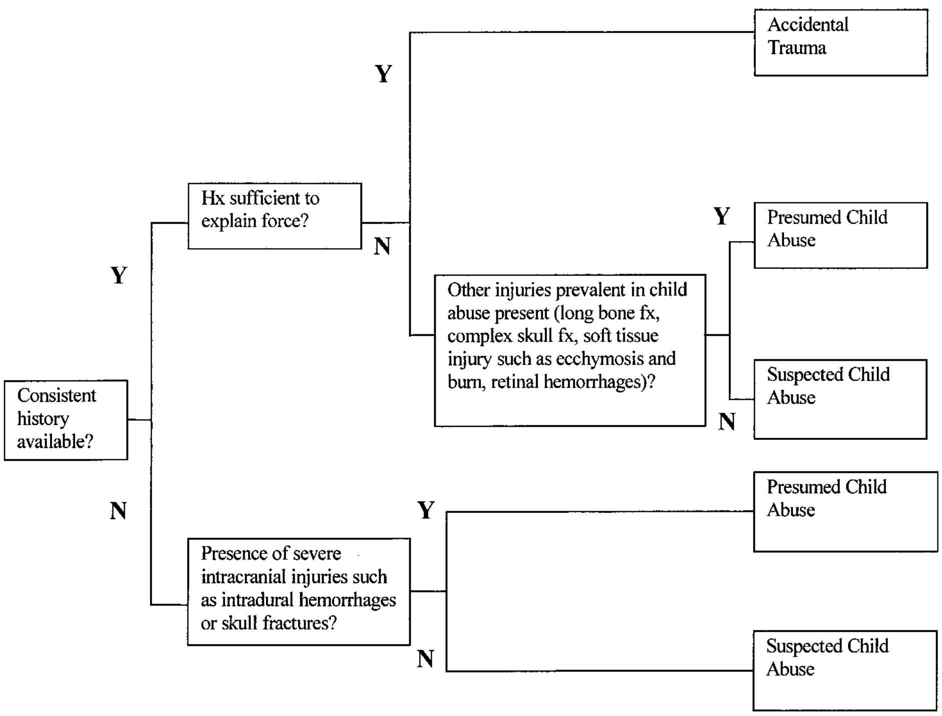

FIGURE 1. The determination of abuse-related head injury was based upon a finding of either a significant disparity between the suggested mechanism of injury and the actual observed injuries or the presence of other injuries prevalent in child abuse that were not accounted for by the purported mechanism. Patients who sustained injuries as a result of neglect were not included in this study. Patients with severe injuries who did not meet criteria for presumed child abuse were classified as suspected child abuse. *Hx*, history; *fx*, fracture; *Y*, yes; *N*, no.

Patients with nonaccidental head injury were classified as having "presumed" or "suspected" NAHT. Presumed NAHT was predicated on a finding of "history insufficient to explain injuries." When a consistent history was available, presumed NAHT was indicated by the presence of other injuries prevalent in child abuse but not explained by the purported mechanism. Patients with severe injuries for whom the diagnosis of presumed child abuse was suspected but could not be proven were classified as suspected NAHT. Patients who sustained injuries as a result of neglect were not included in this study.

A multidisciplinary team of clinicians, including a pediatric social services consultant and a pediatrician trained in child abuse investigation, examined all patients. Other medical conditions that can present with findings that mimic inflicted head injury, such as coagulopathy, osteogenesis imperfecta, and glutaric aciduria type I, were ruled out. A children's advocate from the Department of Family and Children's Services was involved based on the findings of the child abuse evaluation. An ophthalmoscopic examination by a pediatric ophthalmologist was conducted on all patients except one. Skeletal surveys were completed on all patients. In addition, all patients underwent noncontrast CT scanning of the head on the day of presentation using a protocol presented in *Table 1*. Conventional MRI sequences of the brain and DWI with ADC maps were obtained on all patients. A neuroradiologist (PCD) retrospectively reviewed all CT and MRI scans for lesion presence and location.

Diffusion images and ADC maps

Isotropic echo-planar DWI was performed with a commercially available software package (Echoplus; GE Medical Systems, Milwaukee, WI) with a *b* value of 1000 and mapping to a fluid-attenuated inversion recovery image. After image acquisition, the diffusion images were post-processed off-line by the use of an investigational software package for ADC mapping (GE Medical Systems) with Investigational Review Board approval.

RESULTS

A total of 84 children were referred to the Child Protection Program at the Children's Hospital of Atlanta–Egleston for evaluation of suspected physical child abuse or neglect between January 1998 and May 2000. Of these children, 20 (24%) were identified who were less than 2 years of age, had presumed (n = 18) or suspected (n = 2) NAHT, and had completed DWI within 5 days of presentation. In 15 children (75%), DWI was obtained within 48 hours of admission (range, 1–5 d). Eleven girls and nine boys were identified, with a median age of 5.0 months (range, 1–22 mo). Nine children were African-American, eight were Caucasian, two were Hispanic, and one was of mixed race. Nine patients (45%) were from single-parent families, and the primary caretakers of 11 patients (55%) were unemployed. Two of the primary caretakers had attended college. A confession by the perpetrator was obtained in 2 (10%) of 20 patients. An arrest warrant for the suspected perpetrator was issued on behalf of five additional patients.

Table 2 presents a summary of the relevant clinical information on admission. The reported mechanisms of injury for our sample are listed in *Table 3*. In the group in which the mechanism of injury was unknown, patients presented with a reported history of lethargy, apnea, nonspecific constitutional symptoms, or new-onset seizures. Eight (40%) of the 20 patients presented with a history insufficient to explain the

TABLE 1. Trauma Computed Tomography Protocol

- Scan plane parallel to the hard palate and foramen magnum
- 2.5- to 3-mm collimation in the posterior fossa
- 5- to 10-mm collimation to the vertex, depending on head size and age
- Image review with bone and soft tissue algorithms

TABLE 2. Summary of Clinical Findings on Admission

Admission Data	No.	Value
Children's Coma Scale score[a]	9 (median)	3–11 (range)
Presenting complaint		
History of impaired or loss of consciousness	16/20	80%
Lethargy	14/20	70%
Seizures	10/20	60%
Physical examination findings		
Tense or bulging fontanelle	10/15	67%
Positive skeletal survey	12/20	60%
Cranial fracture	6	30%
Long bone fracture	6	30%
Metaphyseal fracture	4	20%
Rib fracture	3	15%
Bruising	8/20	40%
Cephalohematoma	4/20	20%
Motor deficit	4/20	20%
Pupillary irregularity	2/20	10%
Comatose	2/20	10%
Acute management		
Intubation in field	9/20	45%
Cardiopulmonary resuscitation	3/20	15%

[a] **Children's Coma Scale Score, from Raimondi AJ, Hirschauer J: Head injury in the infant and toddler: Coma scoring and outcome scale. Childs Brain 11:12–35, 1984 (40).**

TABLE 3. Mechanism of Injury on Presentation

Mechanism Type	No. of Cases (%)
Unknown	11 (55%)
Minor fall	7 (35%)
Blunt object	1 (5%)
Witnessed assault	1 (5%)

injuries. One patient sustained an injury after a witnessed assault by a teenage sibling. *Table 4* lists the types of head injuries demonstrated on imaging studies. All 20 patients had acute subdural hematoma, with 85% of the patients demonstrating acute perifalcine and tentorial hemorrhages. Of the 20 patients, seven also had chronic subdural collections. Of note, 12 children (60%) demonstrated parenchymal hypodensity on serial CT scanning, with hypodensity present on the initial scan in 11 of the 12.

Seventeen of the 18 patients with presumed NAHT and both patients with suspected NAHT underwent an ophthalmoscopic evaluation. Neither of the patients with suspected inflicted head injury had retinal hemorrhaging. Bilateral or unilateral retinal hemorrhaging was present in 15 (88%) of 17 patients with presumed NAHT. The findings of the ophthalmoscopic examination for patients with presumed NAHT are presented in *Table 5*.

All patients in the study survived and were discharged from the hospital with a median hospitalization of 13.0 days (range, 4–43 d). *Table 6* presents the data regarding in-patient treatment and disposition at the time of discharge from the acute care hospital. Of the 18 patients in the NAHT group, 11 (61%) required ventilatory support for a median duration of 5 days. Neither of the patients with suspected NAHT required ventilation. In 6 (30%) of the 20 patients, some form of medical therapy for raised intracranial pressure was required. Three patients underwent craniotomy for evacuation of acute subdural hematoma.

TABLE 4. Types of Head Injury Demonstrated on Imaging Studies

Injury	No. of Cases (%)
Acute subdural hematoma	20 (100%)
Hypodensity	12 (60%)
Chronic subdural hematoma	7 (35%)
Cerebral contusion	7 (35%)
Cerebral edema	6 (30%)
Cranial fracture	6 (30%)
Midline shift	3 (15%)
Shear-type injury	3 (15%)
Intraparenchymal hematoma	1 (5%)
Epidural hematoma	1 (5%)

TABLE 5. Ophthalmoscopic Examination Findings for 17 Patients with Presumed Nonaccidental Head Trauma

Findings	No. (%)
Retinal hemorrhage	15/17 (88%)
Bilateral	12/15 (80%)
Preretinal	11/15 (73%)
Intraretinal	10/15 (67%)
Pre- and intraretinal	10/15 (60%)
Perimacular folds	6/15 (40%)

TABLE 6. Treatment and Disposition of 20 Patients at the Time of Discharge[a]

	No. (%)
Treatment	
Ventilation	11 (55%)
Craniotomy	3 (15%)
Management for raised intracranial pressure	6 (30%)
Hyperosmolar therapy	6 (30%)
EVD or ICP monitor	5 (25%)
Hyperventilation	4 (15%)
Pressors	3 (15%)
Pentobarbital coma	3 (15%)
Gastric tube placement	5 (25%)
In-patient rehabilitation	11 (55%)
Out-patient therapy	15 (75%)
Anticonvulsant regimen	19 (95%)
Discharge status	
DFACS custody	16 (80%)
Disposition	
Foster care	13 (65%)
Custody of parent(s)	5 (25%)
Custody of nonparental family member	2 (10%)

[a] EVD, external ventricular drainage; ICP, intracranial pressure; DFACS, Department of Family and Children's Services.

Table 7 presents the Children's Outcome Scale (COS) score (40) for children with presumed inflicted head injury at the time of discharge. Both patients with suspected abuse-related head injuries made a full recovery (COS I). In the group of 18 children with presumed inflicted head injury, only 1 (5%) made a full recovery and 5 (28%) had "moderate but nondis-

TABLE 7. Outcome by Age in 18 Patients with Presumed Inflicted Head Injury[a]

Age (mo)	No. (%)		
	COS I	COS II	COS III
1–5	0 (0)	1 (5%)	9 (50%)
6–22	1 (5%)	4 (23%)	3 (17%)
Total	1 (5%)	5 (28%)	12 (67%)

[a] **COS, Children's Outcome Score.**

abling deficits" (COS II) at the time of discharge. Twelve children (67%) in the nonaccidental head injury group had "severe motor or cognitive deficits" at the time of discharge. Nine (90%) of 10 patients less than 6 months of age had severe deficits (COS III) at the time of discharge, as compared with 3 (37%) of 8 patients aged 6 months and older (age range, 6–22 mo).

The findings on DWI are presented in *Table 8*. In 16 (80%) of the 20 patients studied, DWI demonstrated lesions with increased signal intensity and decreased ADC (*Fig. 2*). No abnormalities on DWI were found in the 2 of 16 patients with suspected child abuse or in 2 patients with presumed inflicted head injury. When abnormalities on DWI were demonstrated, they tended to be multifocal and involve multiple lobes of the brain. In 4 of 16 patients, abnormalities on DWI were so widespread as to be considered global (*Fig. 3*). In more than two-thirds of patients (68%), DWI/ADC abnormalities involved the posterior aspects of the cerebral hemispheres with relative sparing of the anterobasal frontal lobes or anterior aspects of the temporal lobes. DWI/ADC abnormalities were restricted to the area underlying a cranial fracture in one of five patients. Three lesions were identified that seemed characteristic of diffuse axonal injury based on conventional MRI sequencing or DWI. ADC mapping revealed an additional diffuse axonal injury located in the corpus callosum of one patient that was not apparent on MRI or DWI. In 81% of positive cases, DWI revealed more extensive brain injury than was demonstrated on conventional MRI sequences. DWI with ADC mapping disclosed additional findings that were not apparent on conventional MRI sequences in 25% of patients. Follow-up CT scanning was obtained in 12 of the 16 children

TABLE 8. Diffusion-weighted Imaging Findings[a]

DWI Findings	No. (%)
Suspected NAHT	0/2 (0)
Presumed NAHT	16/18 (89%)
Multifocal	15/16 (94%)
Global	4/16 (25%)
Associated with fracture	1/5 (20%)

[a] **DWI, diffusion-weighted imaging; NAHT, nonaccidental head trauma.**

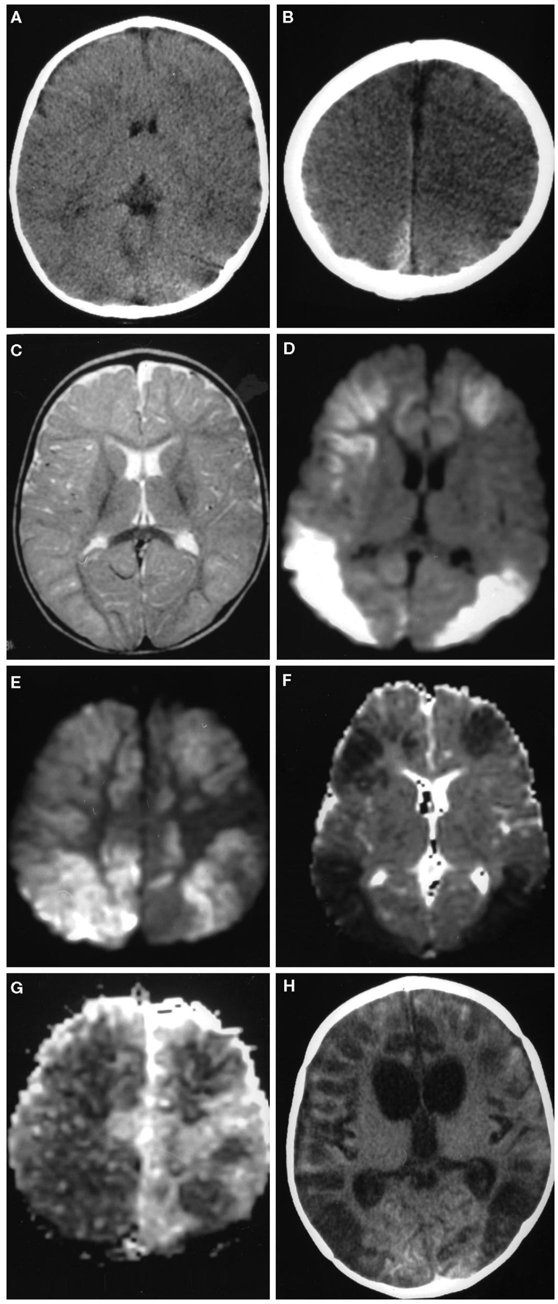

FIGURE 2. CT and MRI scans obtained from a 7.5-month-old boy who reportedly fell off the bed onto a carpeted floor. *A* and *B*, noncontrast head CT scans demonstrating an acute interhemispheric subdural hematoma on the right. *C*, T2-weighted MRI scan obtained 1 day after presentation. Note subtle cortical hyperintensity with gyral swelling and sulcal effacement predominantly in the posterior aspects of both cerebral hemispheres. *D* and *E*, DWI scans showing multifocal, bilateral watershed hyperintensities, posterior more so than anterior, compatible with infarction. *F* and *G*, ADC mapping confirming extensive signal abnormality. *H*, 1-month follow-up CT scan documenting the evolutionary changes of bilateral cerebral cortical infarction.

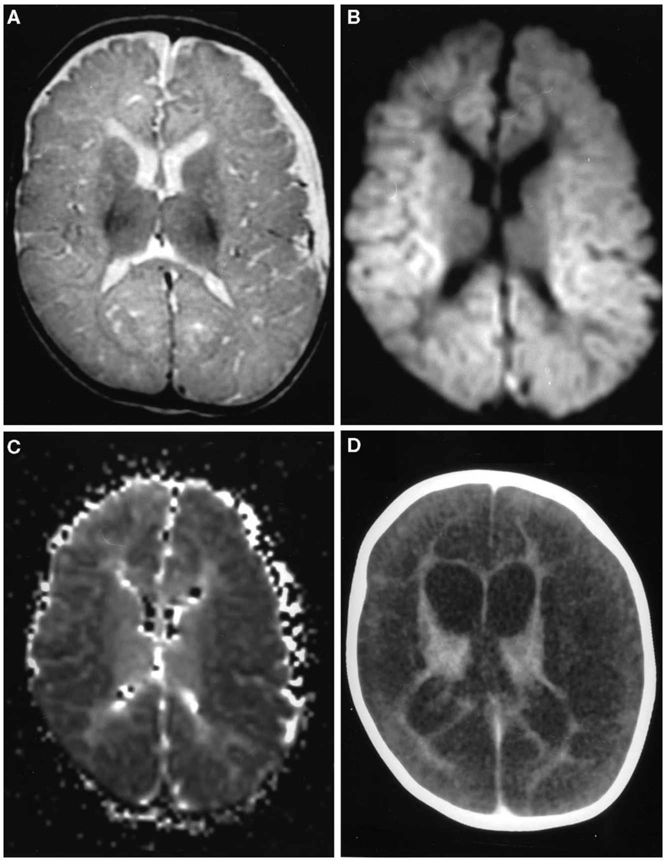

FIGURE 3. MRI and CT scans obtained from a 1.5-month-old girl. *A*, T2-weighted MRI scan at 1 day after presentation demonstrating no focal lesion. Note that the white matter myelin is immature. A subtle loss of contrast between immature white matter and cortex is noted. *B*, DWI scan demonstrating symmetric and uniform signal intensity in both hemispheres. Note the contrast between the abnormal white matter and cortex as compared with the relatively normal signal of the deep gray nuclei. *C*, subtle findings on the T2-weighted sequence and DWI scan are much more apparent on ADC mapping. *D*, CT scan at follow-up examination documenting severe encephalomalacia.

with DWI changes, with CT scanning in 10 of the 12 patients completed more than 1 week from the time of admission (range, 3 d–6 mo). Follow-up CT findings were consistent with the pattern and extent of injury depicted on the DWI in 11 of the 12 children, including injuries that were observed only on DWI and not initially demonstrated on conventional MRI sequences.

We performed a nonparametric statistical analysis by using Spearman rank correlation (r_s) to determine whether the severity of injury as depicted on DWI was associated with outcome as measured by the COS score using a formula that corrected for tied observations. Severity on DWI was graded on a scale of 1 to 4 that reflected the DWI findings (*Table 9*).

TABLE 9. Grading Scale for Diffusion-weighted Imaging Severity[a]

Grade	DWI Severity
1	*Unilateral and focal* (limited to only one lobe or the parieto-occipital junction)
2	*Unilateral and multifocal* (involving the posterior aspect of a cerebral hemisphere and another discrete region of focal injury), or *Bilateral and restricted* (limited to the posterior aspects of both cerebral hemispheres)
3	*Bilateral and multifocal* (involving the posterior aspects of both cerebral hemispheres in addition to other discrete region(s) of focal injury but not diffuse)
4	Diffuse

[a] DWI, diffusion-weighted imaging.

Two authors (PCD and DYS) were blinded to the clinical outcomes of the patients at the time that the scale was developed. The results of this analysis confirmed that severity on DWI was significantly associated with outcome ($r_s = 0.68$) at the $P < 0.005$ level.

We also retrospectively reviewed the DWI findings of five children less than 2 years of age who sustained traumatic head injuries after high-speed motor vehicle accidents (*Table 10*). As a group, these children were older (median age, 8.6 yr) and had a slightly higher Children's Coma Scale score on admission (median Children's Coma Scale score = 10) as compared with the NAHT group. Of the five children in the accidental head injury group, four demonstrated abnormalities on DWI, including all three with severe head injury. These injuries tended to be more focal and unilateral, either restricted to a vascular distribution or in proximity to a cranial fracture and/or they included white matter shear-type injuries.

DISCUSSION

The shaken baby syndrome represents the most common cause of traumatic head injury in young children in the United States (9, 11, 13, 14, 22). Inflicted head injury is the major cause

TABLE 10. Injuries Documented in Five Children with Accidental Head Injuries[a]

Injury	No.
Acute subdural hematoma	5
Cranial fracture	4
Focal intraparenchymal hemorrhagic contusion	4
Minor head injuries associated with short hospital stay	2
Severe injuries with poor outcome (COS III)	3

[a] COS, Children's Outcome Scale Score.

of traumatic death in infancy and carries a high risk of permanent neurological and visual impairment (7, 8, 15, 19). Despite increasing recognition of abuse-related injury, the pathophysiology of the unique pattern of focal and diffuse intracranial injuries observed in inflicted head injury remains incompletely understood. Multiple factors, all occurring in the setting of an immature, incompletely myelinated brain, are likely to be involved and include mechanical forces resulting in hemorrhage, focal contusions, or diffuse axonal injury; secondary hypoxic-ischemic injury after apnea, hypotension, strangulation, suffocation, or seizures; vascular occlusion from direct trauma leading to more focal infarction; and superimposed cytotoxic edema. These factors combine to account for the severe brain swelling and subsequent extensive tissue loss observed in infants who survive severe abuse-related head injury, with the particular pattern of injury dependent on the level of brain development. A key pathophysiological factor may be cerebral hypoperfusion. Cerebral hypoperfusion is associated with poor outcome after severe head injury (1, 19, 20), and evidence of bilateral or unilateral cerebral hypodensity has been identified as an acute factor that is highly predictive of poor long-term outcome in infants with the shaking-impact syndrome (15).

In the series presented here, both the pattern and the severity of injury as indicated by measures of gross neurological functioning were consistent with other reported studies (6, 8, 11–14, 21, 23). Acute subdural hemorrhage was found in all of our patients, with a propensity for subdural blood to be localized to the interhemispheric fissure. More than a third of the patients also presented with chronic subdural hematoma suggestive of previously inflicted injuries. On a skeletal survey, 60% of our patients had a positive finding. As in previous studies of children with the shaken baby syndrome (8, 11, 13, 14, 21), the majority of our patients presented with retinal hemorrhage (79%) that involved perimacular folds (40%) or multiple levels (60%). Although retinal hemorrhage is not specific to inflicted head injury, it is generally accepted that the finding of severe retinal hemorrhage with folds or of hemorrhages involving multiple levels is virtually diagnostic of nonaccidental trauma (14, 21). Finally, nearly two-thirds of our patients demonstrated early signs of parenchymal hypodensity, placing them at high risk for poor outcome (12, 15). Although all of the patients in our series survived, two-thirds were left with severe motor or cognitive deficits at the time of discharge from the hospital and nearly all patients required outpatient anticonvulsant therapy. These findings are consistent with results of other outcome studies in infants with the shaking-impact syndrome, indicating profound deficits in these children without evidence of meaningful neurological recovery despite aggressive medical management (15, 18, 19).

Findings on DWI

Nearly 90% of children with presumed nonaccidental head injury in our sample demonstrated diffusion abnormalities. The changes on DWI tended to be multifocal or involve multiple lobes in more than 90% of patients, indicating relatively diffuse injury. In more than two-thirds of patients, diffusion abnormalities involved the posterior aspects of the cerebral hemispheres with relative sparing of structures in the posterior fossa, the anterobasal frontal lobes, or the anterior aspects of the temporal lobes. Basal ganglia and hippocampal structures tended to be spared in nearly all of our patients, suggesting that profound anoxia or hypoperfusion could not be solely responsible for the demonstrated findings. Although conventional MRI frequently demonstrated regions of injury that corresponded to those detected by DWI, the findings either underestimated the extent of brain injury or missed injuries that were demonstrated on DWI in 81% of patients. In particular, DWI in combination with ADC mapping allowed better delineation of the degree of white matter involvement than did conventional MRI. Follow-up CT scanning obtained in 12 of the 16 patients with abnormalities on DWI confirmed the pattern of injury depicted by DWI.

Other authors have also described more extensive lesions on DWI as compared with T2-weighted imaging lesions in early ischemia (43). We observed additional areas of injury on DWI that were not apparent on conventional MRI sequences in 25% of patients but were confirmed on follow-up CT. Changes in DWI in regions without associated T2-weighted signal abnormality may represent zones of potentially salvageable tissue at risk for permanent damage (26). Our results also demonstrated a significant relationship ($P < 0.005$) between severity and outcome using DWI, with more extensive abnormality associated with poorer outcome. All of the patients in our series who demonstrated evidence of global abnormalities on DWI had severe cognitive or motor deficits (COS III) at the time of discharge. Although acute CT scanning demonstrated early signs of parenchymal hypodensity in nearly two-thirds of our patients, a finding that is highly associated with poor long-term outcome (15), six patients did not show evidence of parenchymal hypodensity on the initial CT scan but did demonstrate abnormalities on early DWI (within 48 h). Of these six patients, five had moderate to severe deficits at the time of discharge. Therefore, early DWI may also help to identify a group of patients at high risk for poor outcome.

Findings on DWI in nonaccidental versus accidental head injury

Although changes on DWI occurred in the majority of children in both the nonaccidental and the accidental head injury groups, differences existed in the pattern of injury between the two groups. In general, children with presumed NAHT had more diffuse injuries that tended to involve the posterior aspects of the cerebral hemispheres but spared the anterior temporal lobes and the frontobasal aspects of the frontal lobes. Moreover, only 4 of 20 patients with presumed or suspected NAHT demonstrated evidence of white matter shear-type injury. In contrast, nearly all of the patients in the accidental traumatic injury group had white matter shear-type injury or had injuries that were either more focal or unilateral in nature and restricted to a vascular distribution or associated with an overlying cranial fracture. Diffuse white matter shear-type injury or intraparenchymal hemorrhage is typically described after accidental head injury (18).

Age-dependent vulnerability

Our results confirm earlier clinical studies of poor outcome in the youngest age groups after traumatic head injury from the shaking-impact syndrome (15, 30, 33). In our series, 90% of the patients less than 6 months of age had severe cognitive or motor deficits (COS III) as opposed to 37% of patients aged 6 months or older. Further study is required to determine whether this age-specific difference reflects an intrinsic vulnerability to mechanical trauma in the younger age group or, as suggested by Duhaime et al. (17), simply represents the outcome of an overwhelming injury that overcomes the potential resistance to injury that is conferred by the immature brain.

Potential concerns

The potential concerns of the study presented here include the small sample size and the retrospective nature of the review. Because we used a relatively restrictive inclusion criterion, cases of inflicted head injury were likely excluded. Perhaps of greater concern are questions regarding the potential reversibility of abnormalities seen on DWI. Although it is known that DWI "normalizes" within 10 to 14 days as the injury evolves, reversibility of acute DWI lesions associated with reperfusion after focal ischemia has been reported in a number of animal studies (35, 36) and among a subset of patients after transient ischemic attacks (27). Recent studies, however, have indicated that the reversal of acute DWI abnormalities is a transient phenomenon that does not reflect histological normalization (32, 39). Rather, abnormalities seen on DWI recur in a delayed fashion that is detectable both radiographically and histologically. These findings suggest that secondary damage associated with tissue injury occurs in ischemic regions despite an acute reversal of abnormalities seen on DWI. Transient reversibility of acute abnormalities on DWI may account for the evolution of DWI changes in one of our patients. This patient demonstrated evidence of subtle loss of gray-white differentiation as revealed by the initial CT scan; however, an MRI scan performed within 24 hours of admission did not show any diffusion abnormalities (*Fig. 4, A–C*). Because of continued neurological deterioration, including poorly controlled seizures, a repeat MRI scan with DWI obtained 2 days later revealed significant changes on DWI that were confirmed on follow-up CT scanning (*Fig. 4, D* and *E*). In our series, the overwhelming majority of children with diffusion abnormalities who had follow-up CT scans (11 of 12) demonstrated the pattern of injury on follow-up CT scanning that had been identified on DWI, indicating that abnormalities on DWI were associated with tissue injury. Nevertheless, given the controversy that exists regarding the potential reversibility of diffusion abnormalities, continued long-term follow-up with clinical correlation is needed.

Another concern surrounding MRI with DWI is whether the information provided is clinically relevant when compared with conventional imaging techniques, particularly in the acute setting. According to guidelines of the American Academy of Pediatrics regarding diagnostic imaging of child abuse, MRI should be delayed for 5 to 7 days in the abused

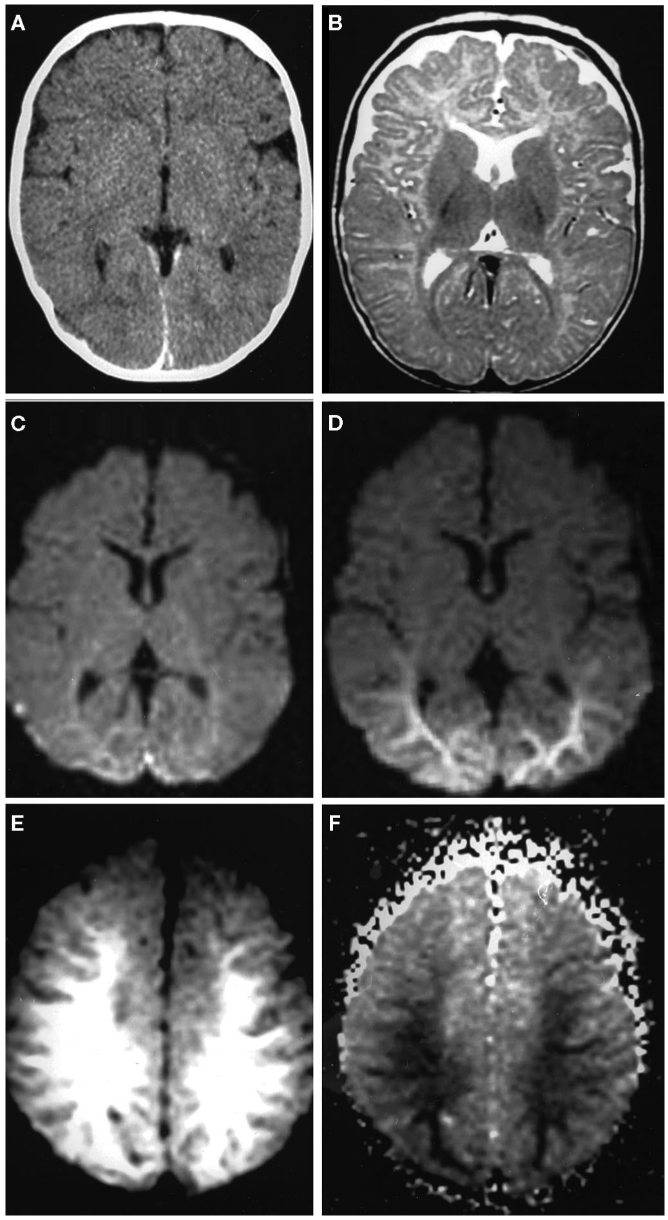

FIGURE 4. CT and MRI scans obtained from a 5-month-old girl. *A*, noncontrast head CT scan at presentation showing an acute smear subdural hematoma along the posterior falx with subtle loss of gray-white junction detail. *B*, T2-weighted MRI scan showing no evidence of parenchymal ischemia or traumatic injury. Note the age-appropriate immature white matter myelination pattern. *C*, the initial DWI scan. No definitive lesion is identified. *D* and *E*, because of recurrent seizures not well explained by imaging findings, repeat MRI was performed that showed interval development of extensive bilateral findings on DWI that were confirmed on ADC mapping (*F*).

child because MRI lacks sensitivity to more acute processes that are better visualized by CT scanning (3). Although our results underscore the prognostic importance of acute CT, particularly when parenchymal hypodensity is observed, they also indicate that early MRI with DWI (i.e., completed within 24–48 h) may help to identify a subset of children at risk for poor outcome who were not identified by acute CT. Moreover, given that treatment decisions are best guided by a full knowledge of the nature and scope of the injury, early DWI provides a rapid assessment of the degree and severity of injury that seems to be more complete than other imaging modalities. A complete and timely assessment of the extent and severity of injury is especially important with regard to medicolegal issues that arise in cases in which child abuse is suspected. Early DWI may help to identify regions of at-risk tissue for permanent damage and/or identify patients at high risk for poor outcome. Such information can help to guide management and inform treatment, particularly as interventions are developed to address the underlying pathophysiological processes and delayed secondary injury that contribute to abuse-related head injury. Early DWI may also further clarify diagnostic and prognostic issues in children with neurological deterioration or in patients who seem more clinically impaired than would be predicted on the basis of the radiographic studies. Because of the potential for reversibility of acute abnormalities seen on DWI, DWI may need to be repeated if the initial study was negative, especially in cases of unexplained neurological deterioration or in patients who demonstrate more impairment than predicted on the basis of conventional imaging.

CONCLUSIONS

Abuse-related head injury represents a major cause of mortality and morbidity in young children. Child abuse victims in our institution demonstrated a constellation of intracranial and extracranial injuries that were consistent with the patterns of injury reported in other series. Significant diffusion abnormalities were found in children with NAHT. Early DWI provided an indicator of severity that was more complete than any other imaging modality. DWI was especially helpful in the detection of tissue injury in very young children with immature myelination, the group most at risk for NAHT. Abnormalities in abused children observed on DWI/ADC documented few cases of white matter shear-type injuries and revealed a high proclivity to involve the posterior aspects of the cerebral hemispheres with relative sparing of the frontal or temporal poles, a pattern of injury that is different from that described in accidental head trauma. DWI has a broad application in the early detection of infarction in children with abuse-related head injury and enhances the sensitivity of conventional MRI. The use of early DWI may help identify patients at high risk for poor outcome and potentially guide management decisions. Because DWI sequences require only a few minutes to obtain and are technically straightforward to interpret, these images should complement the routine MRI examination in cases when child abuse is suspected.

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COMMENTS

Suh et al. have published data to support the use of diffusion-weighted imaging (DWI) as an excellent technique for defining pathology after nonaccidental head trauma in infants and toddlers. More information is required to fully establish the value of this technique; however, this article can be used to support the use of magnetic resonance imaging (MRI) with the addition of DWI as a primary imaging modality in suspected child abuse.

How early can the changes be observed? The authors suggest very early, although one infant had a normal study and then developed seizures; on repeat examination, this infant had evidence of severe injury. Was this an inevitable result of the trauma, or did the seizure contribute to secondary damage? More studies are required before this question can be answered. How reliable is DWI in predicting outcome? Apparently, quite reliable; however, more patients must be studied before this technique can be used to predict outcome. MRI spectroscopy is now an easily acquired additional piece of information, and it will be interesting to see what further insights into the pathophysiology of this type of injury can be gained from this imaging technique. Does ischemia occur in the period between the injury and the arrival at the hospital in the majority of children, making the outcome decided at a very early stage, or is there ongoing secondary injury that may lend itself to therapy? Finally, it will be very important to time the occurrence of the cerebral imaging changes in the hope that this may be a more accurate way of defining when the traumatic injury occurred. This is still a major forensic problem and one that must be clarified for a full understanding of the process of injury to the brain that occurs as a result of child abuse.

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This study used the relatively accessible technique of DWI to delineate nonhemorrhagic ischemia in children with presumed nonaccidental and accidental head trauma. The significance of this article is that it graphically illustrates how this simple technique can uncover infarction earlier than conventional computed tomographic (CT) scanning and MRI. How could that possibly be helpful? In children with nonaccidental head trauma, we often are called to gauge the severity of the injury as well as confirm the diagnosis with collaborative radiological data. This technique does both to some degree, with less delay (2–3 d) compared with conventional MRI (6–7 d). This modality will be successful in identifying the children who will fare poorly after their injury because of the extent of their ischemic insult. In some patients, it is theoretically possible that treatment paradigms could be altered as determined by the availability of this new and early information. Will the data be clinically useful? The concept that new treatments can halt the secondary injury that plagues these children remains an untested hypothesis. The fact that DWI revealed ischemic changes not observed in 81% of the patients undergoing MRI sheds light on why these children often do so poorly despite relatively unimpressive conventional scans. That is, the mechanism of injury is severe enough to compromise local and global vascular delivery. As this technique is used more, we are likely to learn of its clinical applicability and prognostic ability. The authors have presented a convincing demonstration of how DWI can be a simple but useful adjuvant to conventional MRI in the detection of infarct in children with various types of head injury.

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Seattle, Washington

From the viewpoint of external agencies, timing is critical after beginning the investigation of the circumstances that surround an infant or small child who may have been the victim of nonaccidental head trauma. As the analysis becomes more detailed, the pediatric neurosurgeon may feel disadvantaged, as, often, the best he or she can do is to provide a dissection of the clinical scenario that resulted in the infant's hospital admission. What happened and when, and what evidence can one offer in support of one's conclusions? Sooner or later, the phrase "exclusive opportunity" pops up, at which time the physician is challenged as to how much the imaging features and clinical outcome relate to the actual nonaccidental event and/or to what degree the rescue and ongoing medical therapies are responsible. Additionally, in the case of the infant or small child, the immaturely myelinated brain is thrown into the mix when one attempts to analyze regions of suspect ischemic tissue on CT and MRI studies.

This article examines the historical features, the accepted clinical markers for nonaccidental head injury, and the imaging characteristics of 20 patients. Patients with nonaccidental head trauma demonstrated diffuse injuries on DWI that tended to involve the posterior aspects of the cerebral hemispheres, whereas the anterior temporal and orbital surfaces of the frontal lobes were spared. Additionally, in six patients, initial CT scanning did not reveal evidence of parenchymal hypodensity, whereas "early" DWI did (within 48 h). Interestingly, even an MRI scan performed within 24 hours of admission may not pick up on diffusion abnormalities, but, as was shown in the case represented by *Figure 4*, the DWI findings were abnormal when obtained 48 hours later. In response to a question the authors pose concerning the ability of MRI with DWI to provide additional information that is "clinically relevant," I would agree that, in the early setting, MRI does provide clinically relevant information. It then has an impact on both early therapies and anticipated outcomes, as well as providing ammunition for the investigating personnel.

Robin P. Humphreys
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This is a retrospective review of 20 young children who were the presumed victims of child abuse. The major finding was that abnormalities on DWI performed within 5 days correlated with poor outcome. The authors make a strong case that their patient population, in fact, was composed of abused children. This is often a weak point in studies of this type, because the perpetrators rarely confess.

It is well known that very young victims with shaking-impact syndrome often present with a picture of hypoperfusion on acute CT scanning. These findings may be quite subtle, especially within the first few hours, and consist of loss of the gray-white border of the cortex and generalized hypodensity of one or both cerebral hemispheres. Acute conventional MRI is particularly unhelpful. Because the patients are often infants, the neurological examination may underestimate the severity of the injury. An infant with "bicycling" movement of the legs who seems alert but does not cry is often considered to be intact, whereas subsequent imaging reveals severe damage to both hemispheres. Thus, both imaging and neurological assessment may be falsely reassuring in the acute period after injury.

This study suggests that acute DWI may provide a rapid method for determining the true extent of injury in these cases. The authors cautiously allude to the fact that "such information can help to guide management and inform treatment." They only claim a correlation between abnormalities seen on DWI and poor outcome at this point, but it is logical to assume that an infant with extensive bilateral holohemispheric infarctions will be neurologically devastated, and consideration should be given to withholding heroic interventions, such as craniotomy, intracranial pressure monitoring, and cardiopulmonary resuscitation. Practitioners are often reluctant to withhold these measures because the perpetrator and his/her legal team may attempt to claim medical malpractice as a defense. DWI seems to provide an objective measure of the true extent of injury. Future studies should attempt to further define acute changes on DWI that reliably predict poor outcome and follow-up imaging studies to follow the evolution of abnormalities seen on DWI and correlate them with subsequent parenchymal loss.

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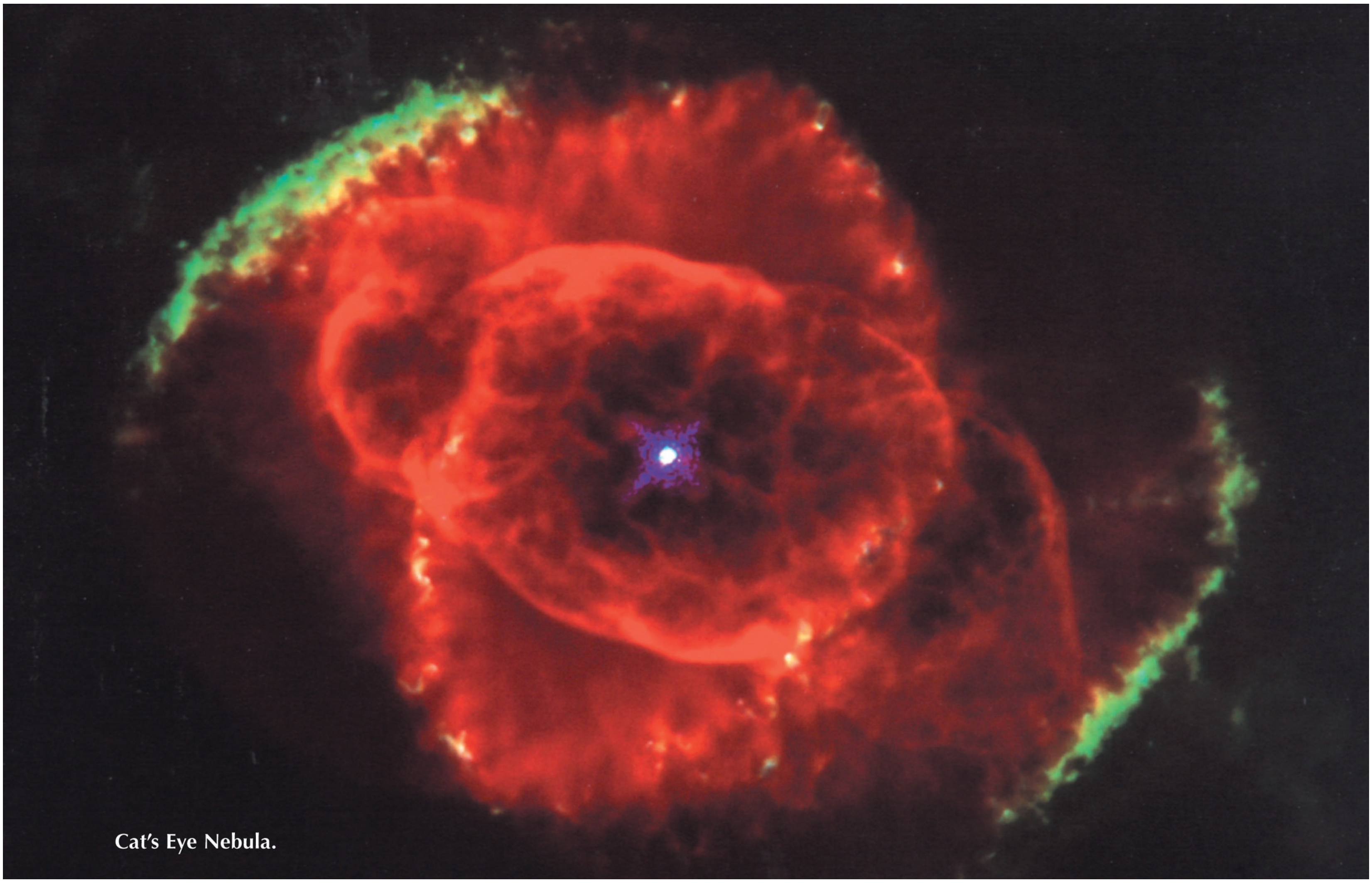

Cat's Eye Nebula.

William Beecher Scoville Prize
World Federation of Neurosurgical Societies

The secretariat of the World Federation of Neurosurgical Societies (WFNS) in Geneva, Switzerland, has announced that Michael L.J. Apuzzo, M.D., will be the recipient of the William Beecher Scoville Prize at the Opening Ceremonies of the September 2001 World Congress in Sydney, Australia.