6 Pediatric Accidental Traumatic Brain Injury: Evidence-Based Emergency Imaging

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Key Points

- The PECARN decision rule can help identify children in whom imaging after TBI is unnecessary (strong evidence).
- In the acute TBI setting, CT is the imaging modality of choice because of availability, speed, and importance in deciding emergent neurosurgical approach (moderate evidence).
- MRI is the preferred imaging modality in children with TBI who need additional imaging and in children with subacute or chronic TBI (moderate evidence).
- Advanced neuroimaging techniques are emerging as a potential tool for diagnosis, to guide management and to predict prognosis in pediatric patients with TBI (limited or insufficient evidence).

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Definitions and Pathophysiology

The definition of TBI used by the Centers for Disease Control is a disruption in the normal function of the brain that can be caused by a bump, blow, or jolt to the head or a penetrating head injury [1].

The pathomechanism in TBI relates to primary and secondary brain injury. Primary brain injury refers to effects that result directly from transfer of external mechanical forces to the contents of the brain. These include diffuse axonal injury (Fig. 6.2a–c), focal contusions (particularly in frontal and temporal lobes), and extra-axial hemorrhages (epidural, subdural, subarachnoid) (Fig. 6.3) [2]. Secondary brain injury is the result of a cascade of molecular mechanisms that are

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initiated at the time of initial trauma and continue for hours or days, such as excitotoxicity, oxidative stress, mitochondrial dysfunction, apoptosis, and inflammation [2]. In mild TBI, the underlying mechanism is usually an acceleration-deceleration event, not direct impact [3].

TBI can be classified based on clinical severity, mechanism of injury, and pathophysiology, each of which may impact prognosis and treatment. Most commonly TBI is classified based on the Glasgow Coma Scale (GCS) score, where a GCS of 9–12 is moderate TBI and a GCS of <9–12 is severe TBI [2]. Mild TBI is defined as a GCS of 13–15, loss of consciousness <30 min, and post-traumatic amnesia <24 h [4].

Computed tomography signs of focal injury (epidural and subdural hematomas, parenchymal contusions) or diffuse injury (axonal injury, diffuse cerebral edema) can be used as predictors for mortality after moderate or severe TBI. The two most commonly used systems for outcome prognostication are the Marshall classification [5] and the more recent Rotterdam scale [6]. The Marshall classification is a set of injury classes with fixed definitions, while the Rotterdam score accounts for individual patient differences in signs of cerebral edema, degree of midline shift, presence of epidural mass effect, and presence of intraventricular or traumatic subarachnoid blood [6]. The majority of patients with clinical criteria of mild TBI have no CT imaging findings, but it has been shown that a subset of 6–10% of these patients are CT positive [7] and another subset of 27% of these patients are CT negative and MRI positive [8].

Epidemiology

In the United States in 2010, there were 2.5 million patients with TBI; approximately 87% of these patients came to the emergency department, 11% were admitted, and approximately 2% died. These statistics likely underestimate the occurrence rate of TBI because outpatient visits and TBI in patients who did not seek medical care were not captured [1]. In a large European study, the incidence of TBI was reported as 235 per 100,000 per year [9]. Worldwide data show peak incidences in children, young adults, and in the elderly population [10].

Mild TBI totals 80–90% of all TBI cases, and it has been reported that one third of these patients experience prolonged physiological or neuropsychological complications and commonly take long times off work [11].

In the United States, the following etiologies are most commonly the cause of TBI: motor vehicle accidents (20–45%), falls (30–38%), occupational accidents (10%), recreational accidents (10%), and assaults (5–17%) [11]. TBI can also occur in contact sports, such as American football, ice hockey, soccer, boxing, and rugby.

Male gender doubles the risk for TBI. 50% of patients with TBI are between 15 and 34 years old, and age <5 years or >60 years are considered a moderate risk for TBI.

Other risk factors are lower socioeconomic status, lower cognitive function, and a history of hospital admissions for intoxications [11].

Overall Cost to Society

For the year 2000, it was reported that the cost for hospitalization of children with TBI was over $1.0 billion, ranking fifth of most expensive hospital diagnoses for children in 2000 [12]. The CDC reports that in 2010 estimated direct and indirect medical costs of TBI were approximately $76.5 billion [1].

Goals of Imaging

Neuroimaging is important for detecting and delineating extent of traumatic brain injury in children. Its main role is the timely detection of brain injuries that require further management. Advanced neuroimaging is used in the study of primary and secondary brain injuries and their relationship to outcomes after TBI.

In children it is particularly important to identify those with TBI who are at low risk and do not need to undergo CT brain imaging in order to avoid unnecessary radiation exposure to this vulnerable population.

Methodology

Information on definition, pathophysiology, risk factors, epidemiology, and goals of imaging were retrieved from the Centers for Disease Control 2015 Report to Congress "Traumatic Brain Injury in the United States: Epidemiology and Rehabilitations" and from UpToDate.

The remaining information was obtained through a comprehensive Medline search (United States National Library of Medicine database) for original articles published between January 1, 2005 and May 24, 2015 using the PubMed search engine. The search was limited to English-language articles and human studies. Additional relevant articles were selected from the references of reviewed articles and published guidelines. The following search terms were used: "pediatrics," "brain injuries," "traumatic brain injury," "TBI," "costs and cost analysis," "costs," "analysis," "costs and cost analysis," "guideline," "guidelines [as topic]," "decision rule," "PECARN," "CATCH," "CHALICE," "applicability," "implementation," "compliance," "research," "CT protocol," and "MRI protocol."

Discussion of Issues

What Clinical Practice Guidelines Are Available to Determine Which Children Do Not Need Imaging After Traumatic Brain Injury (TBI)?

Summary of Evidence The PECARN (Pediatric Emergency Care Applied Research Network) guideline has the highest sensitivity (100%) in identifying children with TBI who are at low risk for brain injury and do not need to undergo CT brain imaging (strong evidence). The use of this guideline reduces CT utilization, which may result in a decrease of radiation-induced malignancy rates, cost of care, and lower net quality-adjusted life-year loss (strong evidence). The CATCH (Canadian Assessment of Tomography for Childhood Head injury) and CHALICE (Children's Head injury Algorithm for the prediction of Important Clinical Events) decision tools also demonstrated very high sensitivities (98 and 98.1%) in identifying high-risk children who require brain CT imaging (strong evidence).

Supporting Evidence

PECARN (Pediatric Emergency Care Applied Research Network)

The PECARN guidelines (Fig. 6.1) were published in 2009 [13] and are the results of a prospective cohort study performed in patients <18 years old across 25 emergency departments. The goal of this study was to determine a set of predictive criteria for clinically important TBI (ciTBI) and to identify children at low risk for ciTBI in whom CT imaging could be avoided. The PECARN rule was shown to have a 99.95–100% negative predictive value [13, 14], 100% positive predictive value [15], and 100% sensitivity [16]. Children with a GCS <14 are not included in this rule.

Two studies compared PECARN, CHALICE, and CATCH [17, 18]. It was shown that PECARN had the highest sensitivity (100%) and that CHALICE was most specific (84–85%) [17, 18]. CHALICE was applicable to most patients (97%), followed by PECARN (76%) and CATCH (26%) [19].

A study using decision analytic modeling in a hypothetical cohort of 1000 children with minor blunt head trauma, the PECARN strategy missed slightly more children compared to hypothetical "usual" care, but there was deceased utilization of cranial CT scans. This could theoretically cause fewer radiation-induced malignancies and cost less, and there could be a lower net quality-adjusted life-year loss (strong evidence) [20].

There is variability in adherence rates to the PECARN rule. An Italian tertiary care academic pediatric emergency department implemented the PECARN rule and achieved a 93.5% adherence [15], while an implementation across four hospital emergency departments in Spain showed that only one hospital achieved compliance in >50%, of patients, and the other hospitals complied in <50% [21].

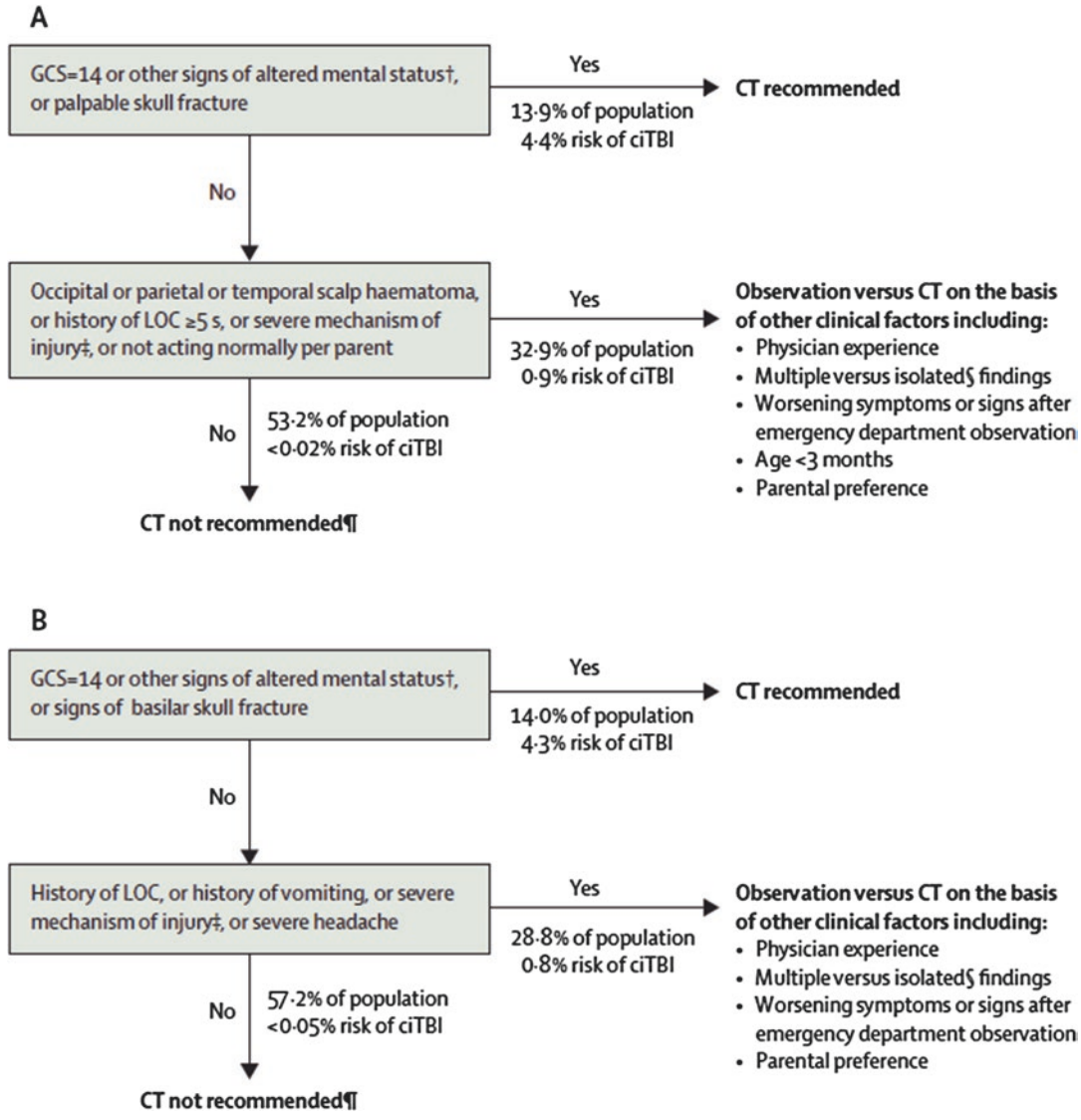

Fig. 6.1 PECARN criteria for TBI in children <2 years of age. (Used with permission from Kuppermann N, Holmes JF, Dayan PS, et al. Identification of children at very low risk of clinically important brain injuries after head trauma: a prospective cohort study. Lancet. 2009 Oct 3;374(9696):1160–70). *Altered mental status: other signs of altered mental status: agitation, somnolence, repetitive questioning, or slow response to verbal communication. **Severe mechanism of injury: motor vehicle crash with patient ejection, death of another passenger, or rollover; pedestrian or bicyclist without helmet struck by a motorized vehicle; falls of more than 0.9 m (3 feet); or head struck by a high-impact object. ***CT not recommended: risk of ciTBI exceedingly low, generally lower than risk of CT-induced malignancies. Therefore, CT scans are not indicated for most patients in this group. ****Patients with certain isolated findings such as isolated LOC, isolated headache, isolated vomiting, and certain types of isolated scalp hematomas in infants older than 3 months have a risk of ciTBI substantially lower than 1%

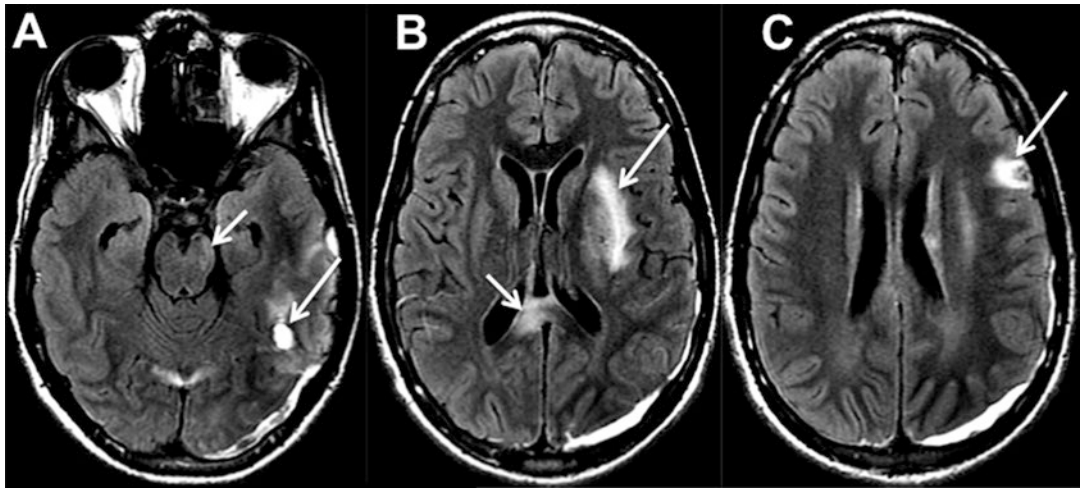

Fig. 6.2 (**a–c**) Grading of diffuse axonal injury (DAI). Axial FLAIR images in a 14-year-old girl with TBI after rollover motor vehicle accident. DAI is graded based on regional involvements: Grade 1 is used for injuries of the gray-white matter junction (**a**, **b**, **c**, *long arrows*). Grade 2 involves the corpus callosum (**b**, *short arrow*) in addition to the gray-white matter junction. Grade 3 refers to brainstem involvement (**a**, *short arrow*) in addition to the gray-white matter junction and the corpus callosum. This patient has DAI grade 3. In addition, this patient has a left subdural hemorrhage

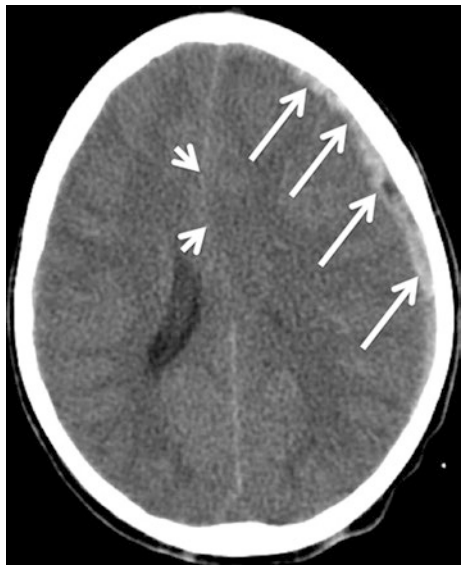

Fig. 6.3 Extra-axial hemorrhage. Axial non-contrast CT in a 4-year-old boy with traumatic brain injury after fall from a balcony. Note the mixed density, crescentic extra-axial collection on the left (*long arrows*). There is associated mass effect with diffuse sulcal effacement and midline shift (*short arrows*)

CATCH (Canadian Assessment of Tomography for Childhood Head Injury)

The CATCH guidelines were published in 2010 [22] and are the results of a prospective multicenter cohort study performed in patients <16 years with a GCS of 13–15. The goal of this study was to develop a decision tool for identifying children with minor TBI who should undergo CT imaging [22]. The CATCH rule was shown to have a sensitivity of 98.1% [22]. A validation study is pending [16].

CHALICE (Children's Head Injury Algorithm for the Prediction of Important Clinical Events)

The CHALICE guidelines were published in 2006 [23] and are the results of a prospective multicenter cohort study in England, performed in patients <16 years. The goal of this study was to derive a decision rule to aid in identification of children at high risk who should undergo CT imaging of the brain. The rule was applied to

children, regardless of GCS, and was shown to have a sensitivity of 98% [23]. A validation study is pending [16].

Which Imaging Modality Should Be Used in Children with TBI?

Summary of Evidence The benefits of non-contrast brain CT imaging include availability and speed of imaging, its ability to detect hemorrhages, mass effects, and fractures. The major disadvantage is radiation exposure. In children of any age with minor head injury, with a GCS of 14–15, and without neurologic signs or high-risk factors, the PECARN rule (Fig. 6.1) can be applied to determine who can safely be observed and who needs to undergo CT brain imaging (strong evidence).

In children <2 years of age, axonal injury is more common, and therefore brain MRI plays a greater role, although non-contrast CT brain remains the modality of choice in the initial evaluation (moderate evidence). In children of any age with minor head injury who are symptomatic or in children with moderate and severe head injury, non-contrast CT brain is most appropriate in detection of any acute traumatic injuries that require monitoring or treatment interventions (strong evidence). In this patient population, it is unlikely that MRI will detect neurosurgically relevant lesions, but MRI may detect axonal injury that could be missed by CT [24].

MR imaging is useful in patients with acute TBI and neurological findings and negative CT. MR imaging is superior in the detection of brain pathology in patients with mild, subacute, and chronic TBI (moderate evidence). CT criteria in patients with moderate and severe TBI play a role in predicting mortality (moderate evidence) [6].

In children of any age with subacute or chronic TBI, MRI is the imaging modality of choice (moderate evidence).

The use of various imaging modalities in pediatric traumatic TBI should be in agreement with the American College of Radiology (ACR) Appropriateness Criteria® Head Trauma – Child, last updated in 2014 [24].

Supporting Evidence The American College of Radiology (ACR) Appropriateness Criteria® Head Trauma – Child, last updated in 2014, give an overview of study results on which recommendations are based upon [24].

In non-accidental head injury, there is considerable debate regarding the selection of appropriate imaging techniques. More details can be found in Chap. 34 on non-accidental injury of infants and children.

What Is the Role for Advanced Neuroimaging in Pediatric TBI?

Summary of Evidence Magnetic resonance spectroscopic (MRS) imaging can help in predicting outcome after TBI. Single-photon emission computed tomography (SPECT) hypoperfusion abnormalities may be an indicator of a worse outcome in children (limited evidence). Brain positron emission tomography (PET) metabolic abnormalities may also predict outcome (limited to moderate evidence). Data about functional MRI (fMRI), MR perfusion, and diffusion tensor imaging (DTI) are limited in the adult population, even more so in the pediatric population. Susceptibility weighted imaging is helpful in detecting microhemorrhages related to shearing injury (or diffuse axonal injury) not seen on conventional MRI. DWI has been shown to improve detection of non-hemorrhagic shearing lesions, although there are only a few small studies describing sensitivity in adults; please see Chap. 5 on acute traumatic brain injury in adults for more details. The role of advanced neuroimaging in pediatric patients is not entirely clear for many of its applications, but some prognostic information is obtained as will be described below. Large studies are required with these advanced imaging modalities to determine the role and outcome after TBI.

Supporting Evidence

MR Spectroscopy (MRS)

MRS can detect subtle cellular abnormalities that may more accurately estimate the extent of brain injury, particularly in diffuse axonal injury (DAI)

(limited to moderate evidence). Makoroff and colleagues studied 11 children with TBI and documented elevated lactate and diminished N-acetylaspartate (NAA) in several brain regions, in four children with global ischemic injury (limited evidence) [25]. Holshouser and colleagues performed MRS in 40 children with TBI 1–16 days after injury and correlated this with neurologic outcome 6–12 months after TBI [26]. A logistic regression model demonstrated a significant decrease in the NAA/creatine and increase in the choline/creatine ratios in normal-appearing ($P < 0.05$) and visibly injured brain ($P < 0.001$). In normal-appearing brain, NAA/creatine decreased more in patients with poor outcomes (1.32 ± 0.54) than in those with good outcomes (1.61 ± 0.50) (limited evidence). Babikian and colleagues studied 20 children and adolescents and demonstrated a moderate to strong correlation of decreased NAA and worse cognitive scores (limited evidence) [27]. Ashwal and colleagues demonstrated in 38 children with TBI that the occipital glutamate/glutamine in the short-echo MRS was significantly increased in TBI when compared with controls (limited evidence) [28]. They also demonstrated that occipital gray matter myoinositol in 38 children with TBI was increased (4.30 ± 0.73) compared with controls (3.53 ± 0.48; $P = 0.003$). In addition, patients with poor outcomes 6–12 months after injury had higher myoinositol levels (4.78 ± 0.68) than patients with good outcomes (4.15 ± 0.69; $P = 0.05$) (moderate evidence) [29], indicating that myoinositol elevation after pediatric TBI is associated with a poor neurologic outcome. Ashwal and colleagues also demonstrated significant decreases in NAA-derived ratios and elevation of Cho/Cre measured in occipital gray matter within 13 days of neurological insult. These metabolite changes correlated with poor neurological outcome at 6–12 months after injury ($n = 52$) (limited evidence) [30]. In a subgroup of these patients ($n = 24$), neuropsychological evaluations were performed at 3–5 years after neurological insult. It was found that these metabolite changes strongly correlated with below average functioning in multiple areas including full-scale IQ, memory, sensorimotor, and attention/executive functioning (limited evidence) [31].

Diffusion Tensor Imaging (DTI)

DTI requires special software that maps the degree and direction of water diffusion along major fiber bundles based on diffusion-weighted imaging (DWI). DTI can detect the impaired connectivity of white matter tracts, even in normal-appearing tissue. Few studies have studied the role of DTI in pediatric patients with TBI. Treble and colleagues studied 74 children with TBI and 49 controls with DTI tractography of eight callosal subregions in relation to measures of verbal and visuospatial working memory [32]. They found that lower fractional anisotropy (FA) and higher radial diffusivity in callosal subregions connecting anterior and posterior parietal cortical regions predicted poorer verbal working memory. Additionally, higher radial diffusivity in callosal subregions connecting the anterior and posterior parietal as well as temporal cortical regions predicted poorer visuospatial working memory. They concluded that reduced microstructural integrity of the corpus callosum might act as a neuropathological mechanism contributing to long-term working memory deficits in TBI. This may help early identification of children at higher risk of working memory deficits and earlier intervention (limited evidence). Oni and colleagues examined DTI in 46 children with moderate-to-severe TBI and 47 children with orthopedic injury 3 months post-injury [33]. Significant group differences in frontal lobe white matter DTI metrics (FA, apparent diffusion coefficient, and radial diffusivity) were identified that were predictive of later Glasgow Outcome Scale (GOS) ratings (limited evidence). Therefore, DTI could serve as an index of white matter integrity in TBI and as a potential biomarker for the outcome. Levin and colleagues studied DTI in 32 children with moderate-to-severe TBI, compared to 36 children with orthopedic injury [34]. They found that fractional anisotropy and apparent diffusion coefficient (ADC) values differentiated the groups and that both cognitive and functional outcome measures were related to DTI findings. Dissociations were present wherein the relation of FA to cognitive performance differed between the TBI and OI groups. A DTI composite measure of white matter integrity was related to global outcome in

children with TBI (limited evidence). McCauley et al. evaluated incentive effects in prospective memory after TBI with DTI in 40 children with TBI and 37 children with orthopedic injury [35]. Children underwent an event-based prospective memory test under two motivational enhancement conditions (low and high motivation) and had concurrent DTI 3 months after injury. The FA of the left cingulum bundle, left orbitofrontal white matter, and bilateral uncinate fasciculi predicted performance in the high-motivation condition. They concluded that these white matter structures are important in mediating event-based prospective memory responses following moderate-to-severe TBI in children (moderate evidence).

Mayer et al. examined FA, axial diffusivity, and radial diffusivity in 15 pediatric patients with mild TBI and in 15 healthy controls [36]. Results showed that patients with TBI had increased anisotropic diffusion and a higher number of clusters with increased anisotropy. Measurements of increased anisotropy differentiated TBI patients from controls with 95% accuracy but were not associated with neuropsychological deficits (limited evidence). Wozniak and colleagues studied 14 children with TBI and 14 controls aged 10–18 years who had DTI studies and neurocognitive evaluations at 6–12 months [37]. The TBI group had lower FA in three white matter regions: inferior frontal, superior frontal, and supracallosal. Supracallosal FA is correlated with motor speed and behavior ratings (limited evidence). Parent-reported executive deficits were inversely correlated with FA. A few other small studies (insufficient to limited evidence) have shown decreased anisotropy in brain parenchyma of TBI patients [38–40].

Functional MRI (fMRI)

Functional MRI (fMRI) can provide noninvasive serial mapping of brain activation, such as with memory tasks. This form of imaging can potentially assess the neurophysiological basis of cognitive impairment, with better spatial and temporal resolution than SPECT or PET. However, it is susceptible to motion artifact and requires extremely cooperative subjects and therefore is more successful in mildly injured rather than moderate or severely injured patients as well as in older children and adolescents. There have only been a few small studies (insufficient evidence) with adults and even less with pediatric patients, attempting to correlate fMRI with outcomes. Fourteen pediatric subjects with mild TBI who underwent fMRI to investigate its effects on auditory orienting had decreased activation within the bilateral posterior cingulate gyrus, thalamus, basal ganglia, midbrain nuclei, and cerebellum, with spatial topography of hypoactivation similar to previous studies in adults [41]. These patients showed no significant deficits in other measures of attention. The findings suggest that fMRI could potentially serve as a biomarker for subtle injury caused by mild TBI and documenting the course of recovery (limited evidence).

A pilot study by Krivitzky et al. examined 13 children with symptomatic mild TBI using fMRI during tasks of working memory and inhibitory control [42]. Children with mild TBI showed greater activation in the posterior cerebellum and addition of a demand for inhibitory control in comparison with the control group (limited evidence). These findings suggest that children with mild TBI may experience disrupted neural circuitry. Newsome and colleagues studied eight children with moderate-to-severe TBI and eight matched, uninjured control children with fMRI using an N-back task to test effects of TBI on working memory performance and brain activation [43]. Two patterns in TBI patients were seen: Patients whose criterion performance was reached at lower memory loads than control children demonstrated less extensive frontal and extrafrontal brain activation than controls; patients who performed the same highest memory load as controls demonstrated more frontal and extrafrontal activation than controls (limited evidence). These were small series, and further longitudinal studies are needed.

Susceptibility Weighted Imaging (SWI)

Susceptibility weighted imaging (SWI) is a modified gradient echo (GRE) high-spatial resolution 3D MR technique that accentuates the paramag-

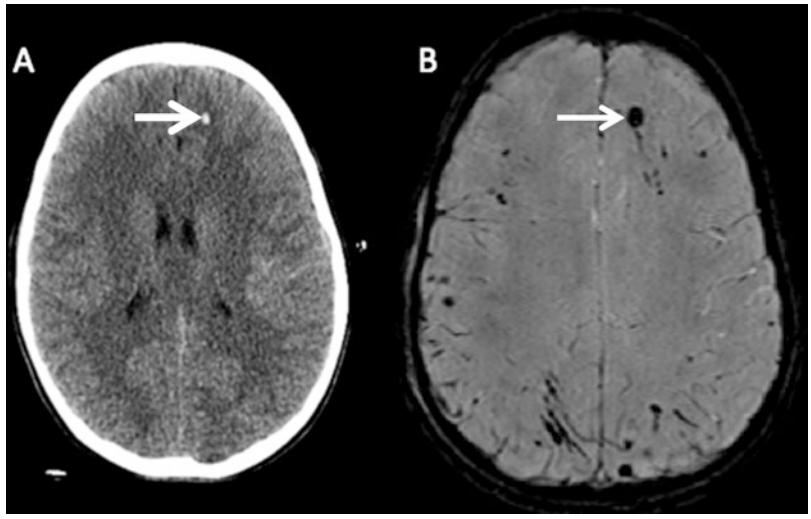

Fig. 6.4 DAI in CT versus SWI; both exams were performed the same day. An 11-year-old female with altered mental status after motor vehicle accident, thus fulfilling PECARN criteria for imaging. Axial head CT (**a**) shows a hyperattenuating focus at the gray-white matter junction in the left frontal lobe in keeping with a focus of hemorrhagic axonal shearing injury (*black arrow*). Axial MRI using susceptibility weighted imaging (**b**) shows the focus with low signal intensity representing susceptibility artifact. This sequence proves that this dominant focus is only the tip of the iceberg as there are several other hypointense foci representing bilateral microhemorrhages related to diffuse axonal injury. For the astute viewer, linear areas of hyperattenuation in the left subarachnoid space on CT have no hypointense correlate in susceptibility weighted imaging and are thus favored to represent vascular congestion rather than subarachnoid hemorrhage. *DAI* diffuse axonal injury, *SWI* susceptibility weighted imaging

netic properties of blood products, which disturb the magnetic field and result in a loss of MRI signal. This technique is particularly helpful in detecting cerebral microhemorrhages related to DAI that are not seen on CT or conventional MRI, and SWI has been shown to detect more hemorrhagic lesions than GRE (Figs. 6.4a, b and 6.5a, b) [44–46].

Microhemorrhages can cause long-term deficits, and detecting them is important for the treatment and prognosis in patients with TBI, particularly in those who have no ominous findings with conventional imaging (moderate evidence). Tong et al. studied 40 children with TBI using SWI to detect hemorrhage (moderate evidence) and found that children with lower GCS scores (≤8, $n = 30$) or prolonged coma (>4 days, $n = 20$) had a greater average number ($P = 0.0007$) and volume ($P = 0.008$) of hemorrhagic lesions [47]. Beauchamp et al. evaluated the relationship of SWI to the outcome after TBI in 106 children with varying levels of TBI who underwent SWI [48]. Subjects completed an assessment of intellectual functioning, processing speed, and behavioral and adaptive skills 6-month post-injury. The number and volume of SWI lesions were significantly correlated with clinical outcome variables including GCS, surgical intervention, length of hospital stay, and length of intubation, as well as with intellectual functioning. SWI and GCS accounted for significant proportion of the variance in IQ. They concluded that SWI shows promise in the prediction of cognitive outcomes in the initial stages post-injury (moderate evidence) [48]. Babikian and colleagues studied 18 children and adolescents 1–4 years after injury using susceptibility weighted imaging showing negative correlations between lesion number and volume with neuropsychological functioning (limited evidence) [49].

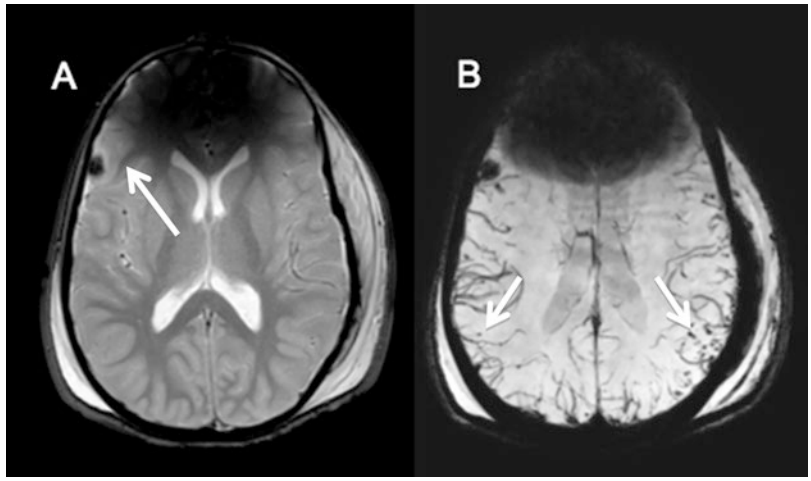

Fig. 6.5 DAI in MRI: GRE versus SWI in a 14-year-old male following a motor vehicle accident. Axial GRE sequence (**a**) shows a hypointense focus in the periphery of the right frontal lobe (*white arrow*) representing hemorrhage of diffuse axonal injury. Axial SWI (**b**) shows several other foci of microhemorrhage (*white arrows*) that were not seen in the conventional GRE sequence, thus better depicting the severity of injury. *DAI* diffuse axonal injury, *GRE* gradient recalled echo, *SWI* susceptibility weighted imaging

Positron Emission Tomography (PET)

Positron emission tomography (PET) can measure regional glucose and oxygen utilization, cerebral blood flow (CBF) at rest, and CBF changes related to performances of different tasks. Spatial and temporal resolution is limited, although better than with SPECT. PET is not widely available, uses high ionizing radiation, and requires patient cooperation. A few PET studies evaluating patients of different ages have reported various areas of decreased glucose utilization, even without visible injury. Bergsneider and colleagues prospectively studied 56 patients with mild to severe TBI, evaluated with 18F fluorodeoxyglucose (FDG)-PET within 2–39 days of injury, 14 of which had subsequent follow-up studies. They found that TBI patients demonstrate a triphasic pattern of glucose metabolism changes that consist of early hyperglycolysis, followed by metabolic depression, and subsequent metabolic recovery (after several weeks) (limited to moderate evidence) [50]. Wu and colleagues evaluated gray and white matter with PET in 14 TBI patients, and 19 normal volunteers studied with a quantitative FDG PET, a quantitative $H_2{}^{15}O$-PET, and MRI acutely following TBI [51]. The gray to white matter ratios for both FDG uptake rate and changes of glucose metabolic rate were significantly decreased in TBI patients ($P < 0.001$) (limited evidence). The changes of glucose metabolic rate decreased significantly in gray matter ($P < 0.001$) but not in white matter ($P > 0.1$). The glucose to white matter ratios of changes in glucose metabolic rate correlated with the initial GCS of TBI patients with $r = 0.64$. Patients with higher changes in glucose metabolic rates (>1.54) showed good recovery 1 year after TBI. Another study by Lupi and colleagues examining PET in 58 consecutive patients (age range 14–69 years), with 44 having TBI, demonstrated a relative hypermetabolic cerebellar vermis as a common finding in the injured brain regardless of the nature of the trauma (limited evidence) [52]. A recent clinical validation study of FDG PET and fMRI in disorders of consciousness was performed by Stender and colleagues in 126 patients (48 of whom had TBI) with unresponsive wakefulness syndrome (vegetative state), locked-in syndrome, or in a minimally conscious state [53]. The validation of cerebral FDG PET and fMRI used the

Coma Recovery Scale-Revised (CRS-R) as a reference for diagnostic accuracy. Outcome after 12 months was assessed using the GOS-Extended. FDG PET was more sensitive for identification of patients in a minimally conscious state than fMRI (95% versus 45%, respectively). In addition, FDG PET had higher congruence with behavioral CRS-R scores than fMRI (85% versus 63%, respectively). FDG PET correctly predicted outcome in 74% and fMRI in 56% of the patients. Therefore, they concluded that FDG PET could be used to complement bedside examinations and predict long-term recovery of patients with unresponsive wakefulness syndrome (moderate evidence).

Cost-Effectiveness Analysis

The advanced imaging modalities are not readily available in many of the clinical settings. Additionally, they can be expensive and time-consuming and require patient cooperation. At present, the role of advanced imaging modalities in evaluating pediatric patients with TBI is uncertain from an evidence-based standpoint. More data is necessary in order to define what contribution these modalities can add to the diagnosis, management, and/or prognosis of the patients.

Take-Home Figure

Figure 6.2a–c presents PECARN criteria to be used for TBI in children less than 2 years old.

Imaging Case Studies

Case 1

Figure 6.3 presents the grading of a diffuse axonal injury (DAI) in a 14-year-old girl with TBI.

Case 2

Figure 6.1 presents an extra-axial hemorrhage in a 4-year-old boy with traumatic brain injury.

Case 3

In Fig. 6.4a, b, a diffuse axonal injury is presented in CT and SWI images of an 11-year-old girl who experienced a motor vehicle accident and altered mental status thereafter.

Case 4

Figure 6.5a, b presents diffuse axonal injury as imaged by MRI (GRE and SWI) in a 14-year-old male who experienced a motor vehicle accident.

Case 5

Figure 6.6a, b presents a parietal skull fracture as imaged by CT 3D skull reconstruction and maximum intensity projection.

Suggested Imaging Protocols

CT Brain

When using CT imaging in children, in order to decrease radiation exposure, (1) the kVP and mA should be adjusted for each size and age group, (2) the area should only be scanned once, and (3) only the area of interest should be included in the field of view [Image Gently: CT]. A typical trauma head CT acquisition includes helical 5 mm axial images with axial 2.5 mm reformatted images in bone and soft tissue algorithm, 2.5 mm coronal soft tissue reformats, and 3D bone reconstruction and maximum intensity projections (MIPs) of the skull (Fig. 6.6a, b) [54, 55].

MRI Brain

The use of brain MR imaging in children may require procedural sedation. Access to MRI in the emergency setting may be difficult, and image acquisition times are long. The major benefits of

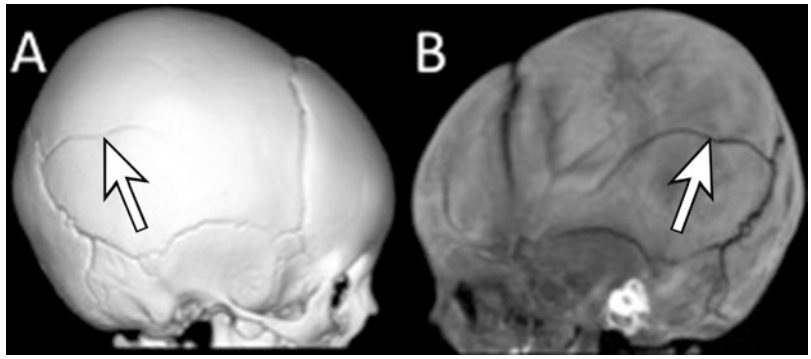

Fig. 6.6 Computed tomography: 3D skull reconstruction and maximum intensity projection (MIP) of a parietal skull fracture. This right parietal skull fracture in a 9-month-old patient was not identified on axial CT images due to its orientation parallel to the axial imaging plane. 3D reconstruction (**a**) and MIP (**b**) were instrumental in identification of this fracture (*arrows*)

MRI are (1) the lack of radiation exposure and (2) the ability to detect axonal injuries and small bleeds with higher sensitivity compared to CT. For children the routine brain imaging protocol includes sagittal T1 (5 mm or isometric 1.5 mm with multiplanar reconstructions), 5 mm axial T2 with fat saturation, 5 mm axial FLAIR, 3 mm axial DWI, 5 mm axial susceptibility weighted imaging, and 5 mm coronal T2.

Research Imaging

Advanced imaging techniques that have been used in the study of TBI include susceptibility weighted imaging (SWI), diffusion tensor imaging (DTI), diffusional kurtosis imaging (DKI) cerebral perfusion/permeability MR imaging, MR spectroscopy, resting-state functional MR imaging, positron emission tomography, and magnetoencephalography. These techniques allow for quantitative rather than qualitative imaging assessments and may facilitate statistical correlations to enhance knowledge of TBI and its prognosis [56].

Future Research

- Validation of PECARN in abusive head trauma
- Determination of actual cost savings related to the use of PECARN criteria
- Multicenter studies to assess prognostic value of various advanced neuroimaging methods
- Imaging predictors of outcomes after TBI
- Define the role of advanced neuroimaging techniques in pediatric patients with TBI

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