Acute and Long-Term Outcomes Following Pediatric Traumatic Brain Injury

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Abstract

Keywords
► pediatric TBI
► health-related quality of life
► outcomes

Pediatric traumatic brain injury (TBI) is one of the leading causes of death and serious disability among children and adolescents. In this review, the neuropathology and pathophysiology of pediatric TBI will be briefly discussed, including the importance of advanced neuroimaging techniques to assist with acute management and diagnostic accuracy. Then, predictors of outcome and sequelae of injury will be highlighted, across TBI severities, including impact on health-related quality of life. Finally, a case study will be presented to highlight the unique trajectory and outcome in a teenager with a severe TBI.

Introduction

Pediatric traumatic brain injury (TBI) is one of the leading causes of death and serious disability among children and adolescents. Incidence and prevalence rates of pediatric TBI are often difficult to obtain and vary by injury severity as well as mechanism of injury. In a recent report, the Centers for Disease Control and Prevention (CDC) reported that children aged 0 to 4 years and adolescents aged 15 to 19 years display the highest incidence rates of TBI-related emergency department visits and/or hospitalizations.[1] A majority of pediatric TBI are mild (~80%), whereas a smaller percentage of injuries are moderate to severe.[2,3]

Despite physiological commonalities, the immature or developing brain likely responds differently to trauma than the mature adult brain.[4] Children are more likely to experience posttraumatic edema, ischemic insult, and diffuse rather than focal injuries, which may be due to differing biomechanical properties of the developing brain. This may be related to the fact that children have a greater head-to-body ratio, less myelination, and a greater relative proportion of water content and cerebral blood volume compared with adults.[5] The trajectory of recovery is known to be more variable in children compared with adults.

Neuropathology and Pathophysiology of Pediatric Traumatic Brain Injury

Depending on the mechanism of injury, pathophysiology, and regions of the brain impacted, pediatric patients will present with a variety of primary and secondary injuries. Primary injuries are a direct result of the traumatic impact and may include skull fractures, contusions, diffuse axonal shearing, and/or vascular injury.[6] Secondary injuries are insults that are triggered by the primary injury and include complications such as cerebral edema, elevated intracranial pressure, hypoxia, seizures, endocrine dysfunction, and/or autonomic instability.[7] The emergence of secondary injuries can further complicate recovery, particularly following moderate to severe TBI.[6]

The most common causes of pediatric TBI include falls and motor vehicle accidents, which often give rise to acceleration–deceleration injuries. Acceleration–deceleration injuries may result in tearing or bruising of blood vessels that leads to focal contusions or hemorrhage. These injuries are most likely to occur in the frontal and temporal regions given their close proximity to the bony prominences of the anterior and middle fossa of the skull.[8] Acceleration–deceleration injuries may also result in shearing of nerve fibers characteristic of diffuse axonal injury (DAI).

Previous studies have demonstrated that shearing lesions (hemorrhagic and nonhemorrhagic) associated with DAI occur in ~40% of pediatric TBI cases.[9] Subtle, microscopic injuries may also occur, which may not be seen with conventional neuroimaging modalities (e.g., computed tomography [CT] scans), yet contribute to functional lesions and suboptimal outcomes. DAI is characterized by damage to axons, commonly located in the gray–white matter junctions, the basal ganglia, periventricular white matter, corpus callosum,

and parasagittal white matter, and they can affect fiber tracts of the cerebral cortex and brainstem.[7]

Following injury, medical professionals use various diagnostic tools to determine severity of injury. The Glasgow Coma Scale (GCS) is one of the most commonly used screening tools, which allows clinicians to assess an individual's level of consciousness and responsiveness immediately following an injury.[10] Scores range from 3 to 15. Traditionally, scores between 13 and 15 represent a mild TBI, scores between 9 and 12 represent a moderate TBI, and scores of 8 or less represent a severe TBI. Research has highlighted additional indictors of severity that should be considered, including duration of loss of consciousness (LOC), time to emerge from a minimally conscious state (MCS), length of posttraumatic amnesia, and time to follow commands[6] (see ►Table 1).

Neuroimaging plays an important role in identifying the sequelae of injury and determining the acute management of pediatric TBI.[11] Recent advances in neuroimaging have helped in the clinical care and management of children and adolescents with TBI.[12] Conventional imaging modalities are often used acutely following hospital admission; however, these modalities may be relatively insensitive to detecting microstructural injuries that are characteristic of DAI. More sensitive techniques, such as magnetic resonance imaging (MRI), diffusion-weighted imaging, and diffusion tensor imaging, provide high spatial resolution, which increases sensitivity for the detection of DAI.[12] With advances in imaging modalities, targeted treatment and rehabilitation therapies may be administered.

Global, more diffuse, burden associated with DAI may be more important than localized injury with regard to outcomes following pediatric TBI. Over time, severe TBI may result in gradual and prolonged white matter degeneration and cortical thinning, with associated cerebral atrophy and ventricular dilation. Emerging literature focuses on identifying imaging biomarkers of tissue injury as predictors of functional outcomes.[11,12] Therefore, following a moderate-to-severe TBI in children and adolescents, advanced neuroimaging techniques should be considered in conjunction with conventional modalities.

Predictors of Outcome

When monitoring recovery following pediatric TBI, it is important to consider predictors of functional recovery post-injury. Various factors, including injury characteristics, non-injury-related factors, and developmental factors, have been shown to contribute to the rate and trajectory of recovery. Additionally, these factors influence one's independence with activities of daily living, or the routine activities that people actually do or can do every day without needing assistance (e.g., eating, bathing, dressing, toileting) as well as self- and parent-reported health-related quality of life (HRQL) such as children's physical, emotional, and social functioning.

Injury Severity

Injury characteristics, including severity, mechanism, and location of injury, have long been identified as predictors of morbidity and mortality in pediatric TBI. Past studies have found that severity of injury is related to several, both acute and chronic, physical, cognitive, and psychological issues.[13] Neuroimaging studies in children with brain insult have shown that more diffuse or bilateral injury, regardless of age at insult, with large lesion size or extent of pathology is associated with greater impairment.[14,15] Anderson and colleagues followed a large sample of children who sustained a brain injury, and found that those with severe injuries showed slower recovery rates and poorer cognitive outcomes at 5 years after injury compared with children with less severe injuries.[16] The greatest deterioration of function, specifically a reduction in verbal and perceptual domains on an IQ test, was seen in the first 30 months, and then was observed to stabilize from 30 months to 5 years after injury. More severe injury has also been shown to be associated with increased utilization of school support services following injury, including special education.[17,18]

Noninjury-Related Factors

Premorbid psychological, behavioral, and environmental risk factors have been associated with negative outcomes and poor recovery following pediatric TBI. In an early study by Brown and colleagues, children who sustained severe TBI and had high rates of premorbid psychosocial issues were at greater risk of developing psychiatric disorders after injury.[19] The presence of cognitive impairments prior to injury has also been associated with worse cognitive functioning following discharge up to 5 years postinjury.[14,20] Parent ratings of preinjury behavioral issues were more strongly related to behavioral problems at 1 and 2 years after injury.[21] More

Table 1 Severity classifications in traumatic brain injury

	GCS	PTA	LOC	Initial clinical presentation
Mild TBI	13 to 15	<1 d	0 to 30 min	Brief change in mental status, headache, dizziness, nausea/vomiting, trouble concentrating
Moderate TBI	9 to 12	>1 d to <7 d	>30 min to <24 h	Variable clinical presentation Cognitive and/or physical deficits
Severe TBI	3 to 8	>7 d	>24 h	Coma/unresponsive wakefulness; generalized responses to environment

Abbreviations: GCS, Glasgow Coma Scale; LOC, loss of consciousness; PTA, posttraumatic amnesia; TBI, traumatic brain injury.
Source: Adapted from Management of Concussion/mTBI Working Group.[60]

proximal risk factors, including family demographics (e.g., socioeconomic status, income, parent education level), environmental factors, and quality of treatments received (e.g., acute hospitalization, rehabilitation, school-related services), have also been found to be important predictors of long-term outcomes.[22–25]

Developmental Factors

Developmental factors (e.g., age at the time of injury, time since injury, age at testing) are also important.[25–28] For example, children who sustain a TBI earlier in childhood, prior to 5 years of age, demonstrate more persistent deficits over time and have a slower rate of recovery than injuries sustained during late childhood or adolescence.[25] Children generally show more rapid rate of recovery during the initial months and years following injury, particularly with severe versus mild injuries.

Sequelae of Pediatric Traumatic Brain Injury

Children and adolescents who sustain a TBI may experience changes in physical, cognitive, and emotional/behavioral functioning, which can increase family burden and negatively impact quality of life.[29,30] As previously mentioned, several factors have been shown to influence the degree of impairment postinjury as well as the trajectory of recovery following injury, which vary depending on severity of injury. Numerous studies have also suggested that the combination of younger age at the time of injury and greater injury severity may be associated with negative outcomes over time.[31,32]

Mild Traumatic Brain Injury

After a mild TBI, individuals may experience a brief LOC and seek medical evaluation; however, conventional neuroimaging is unremarkable.[6] Children and adolescents may experience a constellation of symptoms including somatic complaints (e.g., headaches, nausea, vomiting, sensitivity to light or sound), cognitive changes (e.g., difficulties with focusing, concentration, and/or remembering new information), and emotional lability (e.g., increased irritability or anxiety), as well as sleep disturbance. Symptoms typically resolve within weeks to months.[3]

In a previous systematic review of outcomes following mild TBI, Satz and colleagues found no immediate or long-term effects on academic or psychosocial functioning.[33] Babikian and Asarnow conducted a meta-analytic review that revealed no statistically significant effects on overall neurocognitive functioning[34]; nevertheless, some adverse effects have been reported, including increased behavioral and learning difficulties up to 24 months postinjury.[31,35,36] Most recently, Lloyd and colleagues found 6.8% of reviewed studies indicated adverse academic outcomes, 17.8% of reviewed studies indicated adverse neuropsychological outcomes, and 48.9% of reviewed studies indicated adverse psychosocial outcomes following mild TBI.[3] Risk factors for protracted recovery may include previous history of repeated head injuries, headaches, attention difficulties, learning problems, or psychiatric concerns.[37]

Moderate to Severe Traumatic Brain Injury

Early cognitive deficits following moderate-to-severe TBI may range from severe and diffuse impairments (e.g., MCS and/or minimal responsiveness to environmental stimuli) to subtle, higher level concerns including impulsivity and/or poor safety awareness.[38] Children and adolescents presenting with a moderate-to-severe TBI are more likely to present with altered consciousness (coma, unresponsive wakefulness, MCS), fluctuations in arousal, disorientation, and/or confusion. As children and adolescents become more awake and alert, previously acquired knowledge, overlearned information, and automatized skills tend to be less affected. More difficulties are observed with speeded, novel, and/or integrative tasks that require new learning. Previous studies have demonstrated poor functioning 6 months postinjury on everyday ratings of executive function, showing greater difficulties associated with severe TBI.[39] The fastest rate of recovery following a moderate-to-severe TBI ranges from 6 months to 2 years following injury.[40]

Younger age at the time of injury (less than 5 years of age) increases the risk for experiencing difficulty in acquiring broad academic skills in school. Children and adolescents who sustain moderate-to-severe TBI are also at increased risk for needing special education services, academic performance problems, and failing grades.[41] In their systematic review of studies, Lloyd and colleagues found that 18.2% of reviewed studies indicated adverse academic outcomes, 31.8% of reviewed studies indicated adverse psychosocial outcomes, and 45% of reviewed studies indicated adverse neuropsychological outcomes following moderate TBI.[3]

Following TBI, children and adolescents may display a high incidence of behavioral disturbance, depression, and/or anxiety. Children with severe TBI have been shown to have greater overall behavioral problems 6 months postinjury compared with individuals with less severe injuries.[39] Additionally, severe TBI is associated with the emergence of new undesirable behaviors, such as aggression, impulsivity, personality change, and social difficulties.[23,42] Problems with social functioning have also been described after pediatric TBI. Previous research has found that children with severe TBI are rated as less socially competent, poorer social problem-solvers, and lonelier compared with healthy peers.[24,43]

Social difficulties may be exacerbated by poor family functioning, lower socioeconomic status, and limited resources, as well as deficits in social information-processing and social problem-solving.[24,44–47] Caregiver and family burden may also emerge, especially among individuals with severe TBI.[48,49] Caregivers are more likely to report family burden when their child's functioning is poorer and health care needs are unmet.[50]

Health-Related Quality of Life

With the advances in treatment techniques and improved survival rates, the likelihood of long-term consequences and residual deficits in children with a history of TBI is greater and may negatively impact quality of life over time. HRQL is a multidimensional construct referring to the impact of a disease or injury on patients' physical, emotional, and social well-being.[51,52] HRQL may be a more salient outcome measure in

pediatric TBI given previous findings that severity and allocation of services following TBI do not account for variability in social adjustment and cognitive functioning.[53]

Previous studies addressing HRQL in pediatric TBI have considered the effects of injury severity; however, there is evidence to suggest recovery may occur at different rates for different HRQL domains.[54] Rivara and colleagues found that children with moderate-to-severe TBI showed reduced HRQL up to 24 months postinjury, whereas children with mild TBI were not affected.[55] Studies that have followed children for longer time periods have found reduced HRQL for children with TBI across severities at 1 to 5 years postinjury compared with healthy control groups.[56] A recent study by Brown and colleagues found that different dimensions of HRQL were affected differentially over time.[54] Children with moderate-to-severe TBI experienced greater initial dysfunction than children with mild TBI; however, this difference disappeared by 18 months following injury. Overall, research suggests that injury severity impacts overall HRQL; however, the impact on various domains may vary considering the focus of TBI recovery changes from the physical to psychosocial and family functioning over time.

Another important consideration is the method in which HRQL is measured in pediatric TBI. Currently, both parent and child reports of HRQL are used; however, they often can be discrepant. Studies have shown that, while both parents and children reported reduced HRQL following injury, parents appeared to report more difficulties compared with their children.[57,58] Specifically, parents rated their child or adolescent HRQL less favorably than the children or adolescents themselves. These findings may suggest that children and adolescents may be more prone to minimizing concerns about their own health and functioning and thus report higher HRQL compared with their parents. Alternatively, it could be that the cognitive and behavioral sequelae of TBI render children and adolescents less capable of providing insight into their social and emotional functioning.

Case Vignette: "Henry"

Background
Henry, a right-handed, Caucasian adolescent, sustained a severe TBI when he was almost 16 years old when he was involved in a dirt bike accident. Prior to his trauma, Henry's birth, developmental, and educational histories were largely unremarkable. Henry was a 10th grade student at a public high school who participated in the general education curriculum. He was described as a high-achieving, "straight A" student who was motivated to perform well. Henry was enrolled in accelerated courses and managed the demands of his course load independently. Henry's parents acknowledged that Henry had experienced the deaths of two close friends ~1.5 years prior to his accident. As such, he participated in group therapy services to facilitate his grieving process. In general, Henry was described as a likable, friendly, and funny teenager who was well liked by his peers. Henry's medical history was unremarkable, except for occasional migraine headaches.

In short, Henry was an otherwise healthy teenager until he sustained a TBI. He was riding his dirt bike on a wooded trail with a friend when he crashed. He was wearing a helmet and was found unconscious at the scene. His initial GCS score was a 6. He was intubated at the scene and transported to the hospital. Initial conventional neuroimaging (head CT) revealed no sign of intracranial injury or hemorrhage, but a subsequent MRI revealed a left subdural hemorrhage, left temporal lobe cortical contusions, and multiple shear injuries. Once medically stable, Henry was transferred to the inpatient rehabilitation unit for ongoing medical management and intensive therapies, including speech, occupational therapy, and physical therapy services (length of stay [LOS] = 6 days). During his inpatient admission, Henry displayed notable difficulties with higher level executive dysfunction (e.g., problem-solving, planning/organization, initiation), verbal memory, and deficit/safety awareness. Upon his discharge from the hospital, Henry transitioned to the Day Rehabilitation Program for intensive outpatient neurorehabilitation (LOS = 15 days).

Neuropsychological Evaluation 1 Month after Traumatic Brain Injury
Henry functioned in the average to high-average range. Specific areas of weakness included verbal memory, higher level executive functioning, visual-motor integration skills, and fine motor speed. Parent ratings did not endorse any clinically significant concerns with executive or behavioral-emotional functioning in the everyday environment. The recommendation was made for Henry to return to school with a 504 Intervention Plan and accommodations to address his current areas of weakness.

Neuropsychological Evaluation 1 Year after Traumatic Brain Injury
From a medical standpoint, Henry remained stable; however, he and his parents reported frequent headaches, which were typically managed with over-the-counter medication. Given the persistence of his headaches, despite pharmacologic intervention, his parents explored additional treatment options. As per the suggestion of a family member, Henry had recently undergone hyperbaric oxygen therapy (HBOT) in the weeks prior to the evaluation, with qualitative improvements noted. Of note, previous research has been inadequate to support or refute the use of HBOT for migraine prevention.[59] Henry also endorsed ongoing problems with sleep as well as increased concerns with stress and mood. Henry gradually returned to the school environment following his discharge from the Day Rehabilitation Program. A 504 Intervention Plan was established, which outlined specific supports and accommodations, including extended time, taking tests in a smaller group setting, and reduced homework. Henry maintained a full course load, although he was required to make up classwork from the 6 weeks that he was absent due to his hospitalization; as such, he withdrew from his honors courses. On follow-up, Henry's parents indicated that his 504 Intervention Plan was not consistently followed and implemented by teachers. Henry continued to work hard at his studies and earn straight As. Despite his high level of academic achievement, Henry and his parents acknowledged

that it takes "much more time and effort" for him to complete his work as well as maintain his grades compared with before his injury. Due to the stress of his current course load, teachers eventually agreed to limit the amount of time spent on homework to 30 minutes each night. Henry and his parents reported more notable concerns with his mood (anxiety, depression) following his return to school. Henry was reported to have high expectations for himself and work until he "reaches his limit." He worried about pushing himself too hard and prolonging his recovery due to his involvement in extracurricular activities. Henry also thought that he was "terrible at everything" and displayed decreased enjoyment in previously preferred activities. While he had not withdrawn from social interactions, parents observed that it requires "much more energy" than before his TBI. Henry was recently prescribed Prozac by a psychiatrist to assist with mood management. Henry continues to participate in individual therapy on an as-needed basis.

Results of the updated evaluation revealed a largely stable to improved neurocognitive profile compared to his previous assessment. Specific areas of weakness included processing efficiency, higher-level executive dysfunction, and aspects of memory. While Henry continued to demonstrate nice improvements in his cognitive and physical recovery, he and his family were endorsing more significant concerns with his mood and emotional functioning in addition to frequent headaches and ongoing sleep disturbance, which appeared to be negatively impacting his quality of life. The recommendation was made to increase the level of individualized support he received at school, to prioritize psychological intervention to include regularly scheduled weekly sessions, and to receive ongoing medication management with his psychiatrist.

Conclusion

The neuropsychological, psychosocial, and academic outcomes following child and adolescent TBIs vary by a multitude of factors. Like many, including Henry, outcomes depend on various factors, including injury severity, noninjury factors, and developmental history. Furthermore, although many cognitive and physical difficulties may resolve in the years following a TBI, emotional and behavioral functioning in addition to mood and somatic concerns may become exacerbated over time, which can negatively impact the quality of life of the child. During the initial months following a severe TBI, it is important to participate in intensive rehabilitation therapies, if indicated, and obtain appropriate supports in the academic and community settings to facilitate ongoing recovery. A patient's level of functioning should be reassessed over time since the needs may differ based on their initial constellation of difficulties and stage of recovery. The case of Henry is a good example of how recovery following pediatric TBI is multifaceted. Children and adolescents may often display positive cognitive and physical recovery following a severe TBI while also experiencing persistent and lingering difficulties, which may negatively impact HRQL for both the patient and family.

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