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The New Science of Concussion and Mild Brain Injury in Children

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Abstract Concussions occur frequently in children and adolescents. Physicians are often faced with this common clinical problem and several decisions, such as when a patient needs to go to the emergency department or obtain additional imaging, must be made. Appropriate diagnosis and treatment is required to prevent post-concussive physical, cognitive, and emotional symptoms. Over the last decade there has been increasing attention and understanding of concussions. The purpose of this article is to provide a general review on literature regarding concussions in children and adolescents with a focus on (1) initial evaluation of concussion in children and adolescents; (2) decision-making guidelines for identifying children who are at very low risk of having a clinically significant injury and in whom neuroimaging can be avoided; (3) the use of assessment tools for baseline testing, diagnosis, and monitoring; (4) review of return-to-school and return-to-play guidelines; and (5) post-concussive symptoms and their management.

Keywords Concussion · Children · Traumatic brain injury · Pediatric · Sports · Pittsburgh

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Introduction

Traumatic brain injury (TBI) accounts for almost half a million annual emergency department (ED) visits by children aged 0–14 years. This includes 35,136 hospitalizations and 2174 deaths. TBI-related ED visits are the highest for children aged 0–4 years and the leading cause of death for children 1 year and older (Fig. 1) [1]. Injury can be mild, as in the case of a concussion, or severe, with coma and devastating consequences including death. Approximately 75–90 % is mild TBI (mTBI) or concussion and the terms are used interchangeably [2••, 3–5].

The main causes of TBI in the USA are falls, motor vehicle accidents, unintentional struck by/against events, assaults, and sports [6]. Blasts in military personnel account for most mTBI seen in this group [7]. Football consistently causes the highest number and percentage of concussions at the high school and college levels, as high as 75 %. Most concussions present after player-to-player contact (75 %) and nearly 78 % occur during competition [8].

Sport-related concussions resulting in over 200,000 ED visits with 65 % of TBI's occurring among children aged 5–18 years [9]. The incidence of concussions appear to be increasing from 2001 to 2009, the number of annual TBI-related ED visits increased significantly, from 153,375 to 248,418, with the highest rates among males aged 10–19 years. This increase may be partly attributed to increased awareness and diagnosis [10].

In addition, there has been increased public recognition of concussions in the last decade. This is due in part to media attention to high profile and young athletes suffering severe disability, including death, epilepsy, and motor and cognitive disorders.

Concussions present with acute symptoms; however, the long-term cognitive changes can have subtle but with long-

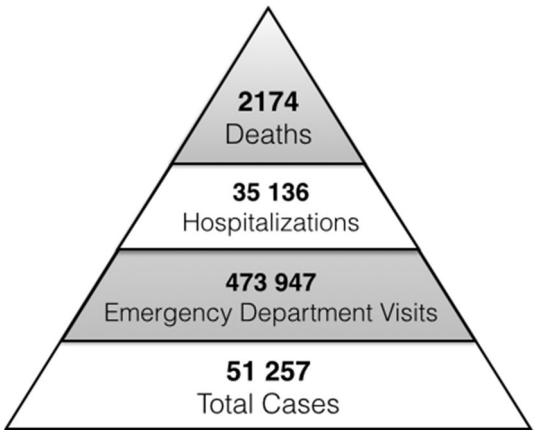

Fig. 1 Estimated average annual numbers of traumatic brain injury-related emergency department visits, hospitalizations, and deaths, in children aged 0–14 years, United States, 2002–2006 [1]

lasting effects. Studied populations of athletes include sports such as football, boxing, wrestling, rugby, hockey, lacrosse, soccer, and skiing. Recently, the research focus on TBI is predominantly concussions and severe TBI treatment [11].

In infants and young children abusive head trauma (AHT) is a major cause of mild and severe TBI. Therefore, this should always be incorporated in our differential diagnosis. Failure to appropriately diagnose abuse as the underlying etiology puts the child at increased risk of further injury and continues to expose other children in the home to violence. AHT causes an estimated lifetime burden that averaged 4.7 disability-adjusted life-year (DALY) for mild AHT, 5.4 for moderate AHT, 24.1 for severe AHT, and 29.8 for deaths. On average, DALY loss per 30-day survivor includes 7.6 years of lost life expectancy and 5.7 years lived with disability [12].

The pathophysiology of concussion is thought to be more related to a metabolic disruption rather than nerve cell damage. Structural and nerve cell damage is seen in more severe TBI [13]. After a hit to the head, a "neuronal metabolic crisis" with efflux of sodium and influx of calcium occurs, the proposed mechanism by which several neural pathways are affected resulting in symptoms. The mechanisms identified include neuronal depolarization, release of neurotransmitters, ionic changes, axonal dysfunction, and compromised cerebrovascular regulation [14].

Definition of Concussion

The Glasgow Coma Scale (GCS) is a score that is used for clinical assessment of unconsciousness, is also used to classify brain injury into mild, moderate, and severe [15]. However, the GCS does not take into account cognitive, somatic, and emotional factors. Age also limits the utility of this tool. The real value of GCS is as a prognostic tool in the initial evaluation of more severe forms of TBI. The motor component is most predictive value [16]. mTBI is defined as having a GCS of 13 or above. This type of injury includes concussion; positive CT findings are found in 5 % of these patients. Moderate TBI is defined as having a GCS between 9 and 12 or 13. Positive CT findings are found in 37 % of these patients. Severe TBI is defined as having a GCS of 8 or less. These patients have a high rate of positive findings in CT. (62–75 %) [17, 18].

According to the 2012 Zurich international consensus statement, concussion is a brain injury and is defined as a pathophysiological process affecting the brain, induced by biomechanical forces. It is usually caused by a direct blow to the head, face, or neck or with impulsive force to the head. Concussion has a typical onset of short-lived impairment of neurologic function that resolves spontaneously and the acute clinical picture seems to reflect a metabolic and functional disturbance rather than a structural injury [19••].

Notably, neither positive loss of consciousness nor a direct blow to the head is required for concussion. Previously used grades for concussion have fallen out of favor, and they have been replaced for more individualized management. A grade 3 concussion (with LOC) was thought to be more severe, but for example, we have learned that a concussion with no LOC and dizziness as a main symptom may have protracted symptoms lasting several months and be more difficult to treat.

There is evidence that female athletes may be at greater risk for concussion and present with different symptoms than their male counterparts. When genders compete in similar sports, females have almost twice the rate of concussion and longer duration of symptoms [20, 21]. Soccer is the most common cause of concussion in female athletes and is implicated in nearly 50 % of cases [22]. Girls also report more symptoms at baseline and different symptoms such as drowsiness and sensitivity to noise and males reported more confusion, amnesia, and disorientation [23, 24]. Tone hypothesis to explain these differences is the weaker neck musculature and lower head-to-ball ratio. Females also have higher rates of migraine than males, which may contribute to the gender differences seen in concussion [25], this is believed to be due to increased excitability of neurons and hormonal changes [26].

Reporting bias is important as there can be underreporting of symptoms, this can be due to fear of not being able to play or admitting weakness and vulnerability. In one study, approximately 50 % of high school athletes do not report their concussions. The reasons for underreporting included not thinking the injury warranted medical attention (66.4 % of unreported injuries), being withheld

from competition (41.0 %), and lack of awareness of probable concussion (36.1 %) [27].

Second-impact syndrome (SIS) is the development of significant TBI after a second hit to the head is received after a minor head injury. Several mechanisms such as abnormal brain auto-regulation and catecholamine surge-induced injury have been proposed [28]. The catastrophic clinical picture of young athletes with SIS having permanent sequelae or even death caused the attention of the public and major shift in law and sports regulations. In 2006, Zachary Lystedt suffered a concussion while playing football as an 8th grader. He played the rest of the game but collapsed on the field and developed permanent neurological damages. He was diagnosed with SIS and as a result of this case there is now legislation to prevent athletes from playing the same day after a concussion and from returning to play without medical release. In May 2009, the state of Washington passed the first concussion law named after Lystedt. Since then all 50 states and the District of Columbia now have some form of youth concussion sport law. The National Football League (NFL) was part of the initial coalition in Washington State and has strongly lobbied for national adoption of youth concussion laws.

These laws generally have three components: (i) immediate removal from play of a player suffering a concussion; (ii) the player may not return without medical clearance; and (iii) parent and athletes just demonstrate yearly concussion awareness. Unfortunately, most of these laws represent "unfunded mandates" and there is yet to be clear evidence of their effectiveness in reducing the incidence or severity of concussions.

Initial Evaluation and Management of Concussion

Immediately after a child or adolescent suffers a concussion, he must be removed from further activity and should have a medical evaluation to determine whether he needs further evaluation. The patient should be assessed by medical personnel and sent to the ED if there are symptoms such as headache, loss of vision/consciousness, altered mental status.

The diagnosis of concussion is based on the assessment of several domains including somatic (e.g., headache), physical signs (e.g., loss of consciousness), cognitive changes (e.g., slow reaction times), emotional or neurobehavioral changes (e.g., irritability), and sleep disturbances (e.g., insomnia). If any of these domains is altered a diagnosis of concussion should be suspected and appropriate management instituted.

Initial diagnosis and evaluation of TBI patient can be done with the acute concussion evaluation (ACE) form. This form is part of the "Heads Up: Brain Injury in Your Practice" tool kit developed by the centers for disease control and prevention (CDC). Figure 2 This tool assesses symptoms in the 4 domains, physical, cognitive, emotional, and sleep. It identifies risks factors for protracted recovery and red flags for patients that should go to the emergency department.

An interesting tool that has the potential to diagnose concussion is the Vestibular/Ocular Motor Screening or VOMS test. This test can be performed in the office in 5 min and has shown to identify concussed patients [29].

Vestibular symptoms also appear to have added clinical significance. Dizziness at the time of injury was associated with a 6.34 odds ratio of protracted recovery of more than 21 days. Headache is the most common observed symptom 95 % and loss of consciousness only 13 %. Interestingly LOC does not predict severity of concussion or duration of symptoms, this is of particular interest as we as clinicians learn to identify LOC and guide our decisions based on that finding [30].

Another useful tool is the standardized assessment of concussion (SAC), The Child Standardized Concussion Assessment Tool (Child SCAT-3) can be used to diagnose concussions. SAC or SCAT-3 are validated tools for identifying the effects of mild traumatic brain injury. In an observational study, SAC was able to reliably identify mTBI symptoms in children 6 years and older, amnesia or altered mental status were correlated with more symptoms and increased severity, and it was also noted the difficulty of assessing cognitive deficits in young children [31]. Child SCAT-3 can be used to diagnose children aged 5–12 years of age. Older children should be assessed with the adult SCAT-tool. Recent clinical updates from the 2005 and 2009 SCAT and SCAT-2 tools have been published [19••].

ED Evaluation and Clinical Prediction Rules

Those patients with no risk predictors of moderate or severe TBI can be managed without imaging by using clinical prediction rules such as the ones published by The pediatric emergency care applied research network (PECARN). Currently there are three decision-making guidelines for evaluating TBI in the ED. These rules are important since they reduce unnecessary CT imaging. This is of particular importance since 5 % of patients presenting to the ED will have TBI requiring admission but a third of the patients will have CT imaging performed. Neuroimaging has long-term effects on children due to radiation exposure.

It is estimated that the risk of fatal cancer resulting from one head CT in a 1-year old infant can be as high as one in 1500 and 1 in 5000 for a 10-year old [32]. One study estimates that one excess case of leukemia and one excess case of brain tumor per 10,000 head CT scans is estimated to occur [33]. One means to decrease medical imaging radiation exposure is through the use of clinical decision rules.

ACUTE CONCUSSION EVALUATION (ACE)

PHYSICIAN/CLINICIAN OFFICE VERSION

Gerard Gioia, PhD[1] & Micky Collins, PhD[2]
[1]Children's National Medical Center
[2]University of Pittsburgh Medical Center

Patient Name:_____
DOB: _____ Age:_____
Date:_____ ID/MR#_____

A. Injury Characteristics **Date/Time of Injury**_____ **Reporter: __Patient __Parent __Spouse __Other**_____

1. Injury Description _____

1a. Is there evidence of a forcible blow to the head (direct or indirect)? __Yes __No __Unknown
1b. Is there evidence of intracranial injury or skull fracture? __Yes __No __Unknown
1c. Location of Impact: __Frontal __Lft Temporal __Rt Temporal __Lft Parietal __Rt Parietal __Occipital __Neck __Indirect Force
2. Cause: __MVC __Pedestrian-MVC __Fall __Assault __Sports (*specify*)_____Other_____
3. Amnesia Before (Retrograde) Are there any events just BEFORE the injury that you/ person has no memory of (even brief)? __Yes __No Duration
4. Amnesia After (Anterograde) Are there any events just AFTER the injury that you/ person has no memory of (even brief)? __Yes __No Duration
5. Loss of Consciousness: Did you/ person lose consciousness? __Yes __No Duration
6. EARLY SIGNS: __Appears dazed or stunned __Is confused about events __Answers questions slowly __Repeats Questions __Forgetful (recent info)
7. Seizures: Were seizures observed? No__ Yes___ Detail_____

B. Symptom Check List* Since the injury, has the person experienced any of these symptoms any more than usual today or in the past day?
Indicate presence of each symptom (0=No, 1=Yes). ***Lovell & Collins, 1998 JHTR***

PHYSICAL (10)		COGNITIVE (4)		SLEEP (4)	
Headache	0 1	Feeling mentally foggy	0 1	Drowsiness	0 1
Nausea	0 1	Feeling slowed down	0 1	Sleeping less than usual	0 1 N/A
Vomiting	0 1	Difficulty concentrating	0 1	Sleeping more than usual	0 1 N/A
Balance problems	0 1	Difficulty remembering	0 1	Trouble falling asleep	0 1 N/A
Dizziness	0 1	**COGNITIVE Total (0-4)** _____		**SLEEP Total (0-4)** _____	
Visual problems	0 1	**EMOTIONAL (4)**			
Fatigue	0 1	Irritability	0 1		
Sensitivity to light	0 1	Sadness	0 1		
Sensitivity to noise	0 1	More emotional	0 1		
Numbness/Tingling	0 1	Nervousness	0 1		
PHYSICAL Total (0-10) _____		**EMOTIONAL Total (0-4)** _____			
(Add Physical, Cognitive, Emotion, Sleep totals) Total Symptom Score (0-22) _____					

Exertion: Do these symptoms worsen with:
Physical Activity __Yes __No __N/A
Cognitive Activity __Yes __No __N/A

Overall Rating: How different is the person acting compared to his/her usual self? (circle)
Normal 0 1 2 3 4 5 6 Very Different

C. Risk Factors for Protracted Recovery *(check all that apply)*

Concussion History? Y ___ N___	√	Headache History? Y ___ N___	√	Developmental History	√	Psychiatric History
Previous # 1 2 3 4 5 6+		Prior treatment for headache		Learning disabilities		Anxiety
Longest symptom duration Days__ Weeks__ Months__ Years__		History of migraine headache __ Personal __ Family_____		Attention-Deficit/ Hyperactivity Disorder		Depression
						Sleep disorder
If multiple concussions, less force caused reinjury? Yes__ No__				Other developmental disorder_____		Other psychiatric disorder _____

List other comorbid medical disorders or medication usage (e.g., hypothyroid, seizures)_____

D. RED FLAGS for acute emergency management: Refer to the emergency department with sudden onset of any of the following:

* Headaches that worsen	* Looks very drowsy/ can't be awakened	* Can't recognize people or places	* Neck pain
* Seizures	* Repeated vomiting	* Increasing confusion or irritability	* Unusual behavioral change
* Focal neurologic signs	* Slurred speech	* Weakness or numbness in arms/legs	* Change in state of consciousness

E. Diagnosis (ICD): __Concussion w/o LOC 850.0 __Concussion w/ LOC 850.1 __Concussion (Unspecified) 850.9 __Other (854) _____
__No diagnosis

F. Follow-Up Action Plan **Complete *ACE Care Plan* and provide copy to patient/family.**
___ **No Follow-Up Needed**
___ **Physician/Clinician Office Monitoring**: Date of next follow-up _____
___ **Referral:**
___ Neuropsychological Testing
___ Physician: Neurosurgery____ Neurology____ Sports Medicine____ Physiatrist____ Psychiatrist____ Other_____
___ Emergency Department

ACE Completed by:_____

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This form is part of the "Heads Up: Brain Injury in Your Practice" tool kit developed by the Centers for Disease Control and Prevention (CDC).

Fig. 2 Acute concussion evaluation form (ACE)

PECARN published a set of clinical prediction rules which were created using a large prospective cohort study of children with minor blunt head trauma. Table 1 two age-based TBI clinical prediction rules were derived to identify children who are at very low risk of having a clinically significant injury who may safely avoid cranial CT [34••].

On external validation done on 2400 children with TBI, 19 children (0.2 %) had clinically important TBI and none of these children were classified as very low risk, therefore the age-based PECARN TBI prediction rules accurately identified children at very low risk for a clinically significant TBI [35].

The Canadian assessment of tomography for childhood head injury (CATCH) and children's head injury algorithm for the prediction of important clinical events (CHALICE) are two other clinical prediction rules that can be used as well. These studies are different, they included different ages and hypothesis, CHALICE studied children with all grades of TBI severity, whereas PECARN and CATCH studied mTBI and included observation to determine which patient needs neuroimaging. Also of importance PECARN identifies those patients that do not need further testing as opposed to CATCH and CHALICE that identified those patients that need further imaging.

In a prospective study performed in an urban setting utilizing available clinical prediction rules, PECARN and physician estimation had the best sensitivity when detecting clinically important TBI [36]. In our pediatric ED we use the PECARN decision-making rules to decide which patients can be safely evaluated without neuroimaging.

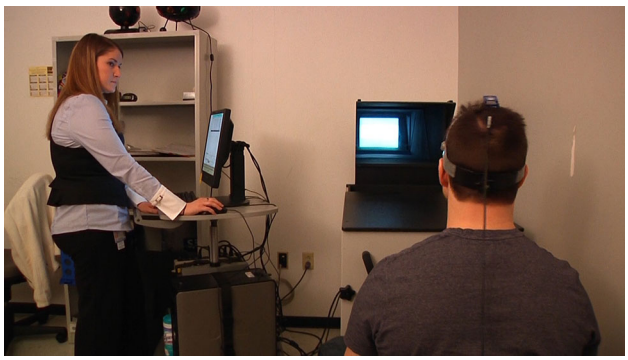

Fig. 3 Vestibular therapist Pamela Dunlap performs a computerized gaze-stability examination on minor-league hockey player Andrew Lord as part of the multi-disciplinary approach with the UPMC Concussion Program. Photo courtesy of UPMC

Post-concussive Symptoms and Its Management

While somatic and cognitive symptoms occur frequently after concussion, they usually resolve in a mean of 7 days [14, 37]. Post-concussive symptoms can be manifested by headache, dizziness, gait instability and deficits in attention, mental flexibility, processing speed, anterograde memory, and verbal fluency [38–40] Post-traumatic headache is one of the most common symptoms occurring after mTBI in children.

Concussions can be managed initially in the primary care setting, but if the symptoms persist for more than 5–7 days, it is appropriate to refer the patient to a concussion specialist or clinic for evaluation and treatment.

Table 1 PECARN TBI age-based clinical prediction rules (high, intermediate, and very low TBI risk groups) for children with minor blunt head trauma and initial GCS ≥ 14 [29]

PECARN prediction rule for clinically important TBI in children Inclusion criteria	Age <2 years risk group High risk	Age >2 years risk groups High risk
Age <18 years of age	Altered mental status[c]	Altered mental status[c]
Non-trivial[a] head trauma within 24 h	Palpable skull fracture	Signs of basilar skull fracture[d]
Exclusion criteria	Intermediate risk	Intermediate risk
Neurological comorbidities bleeding disorders	Severe injury mechanism[b]	Severe injury mechanism[b]
Suspected child abuse previous neuroimaging	Loss of consciousness >5 s non-frontal hematoma	Any loss of consciousness vomiting
Outcome measure = clinically important TBI	Not acting right as per parents	Severe headache
Death, intubation > 24 h, neurosurgery, or two or more nights in the hospital for management of the head injury	Very low risk	Very low risk
	No predictors	No predictors

[a] Ground-level falls or running into stationary objects with no signs of TBI other than scalp abrasions and lacerations

[b] Motor vehicle crash with patient ejection, death of another passenger or rollover, pedestrian or bicyclist without helmet struck by motorized vehicle, falls (of >3 feet for children <2 years of age or >5 feet for children ≥2 years) or head struck by high-impact object

[c] GCS 14, agitation, sleepiness, slow response, or repetitive questioning

[d] Retroauricular bruising (battle sign), periorbital bruising (raccoon eyes), cerebrospinal fluid otorrhoea, or hemotympanum

Post-concussive syndrome (PCS) is usually defined as symptoms persisting for more than 6 weeks after the injury [41].

Post-concussive symptoms are evaluated using several methods. These domains can be assessed using a neuropsychological test battery [42–46]. A very useful tool is Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT), this is a computer-based neurocognitive tool that is used to evaluate a patient, it allow us to identify symptoms, assess neurocognitive function, document, and monitor progress. It also helps to establish a baseline level when a player is in a non-concussed or "normal" state. Figures 3 and 4 some schools use assessment tools to establish a baseline level before a concussion occurs on children that play sports. This has a disadvantage as children can underperform to have a safety margin in case they do not perform well in a subsequent examination. Postural deficits can be assessed using the Balance Error Scoring System [47].

Physical rest is paramount in the treatment of concussions. This is achieved through return-to-play (RTP) guidelines, which are based on expert recommendations. Table 2 cognitive rest is achieved by avoiding activities that require concentration, attention, and stress. It requires the patient to stop using a cell phone, video games, and computers for that period of time determined by RTP guidelines. Based on the Zurich 2012 concussion guidelines it was unanimously agreed that no RTP on the day of concussive injury should occur [19••]. Current guidelines recommend physical and cognitive rest after concussion. The rationale of rest is to allow the brain tissue to overcome a period of injury and recover. A graduated protocol has been developed to assist in RTP. The patient should move up the step in the logarithm every 24 h and should progress to full activity in 1 week, if symptoms exists the patient should drop back one step.

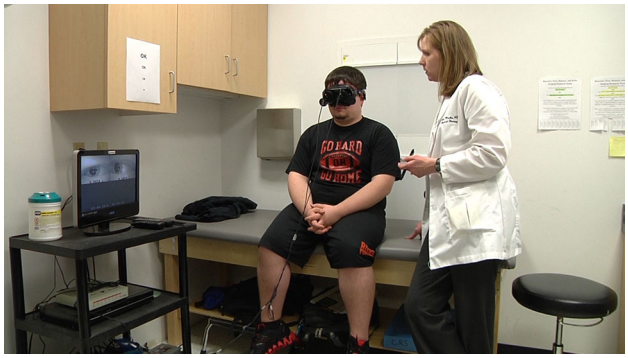

Fig. 4 Anne Mucha, the UPMC Concussion Program's clinical coordinator for vestibular therapy, places computerized infrared goggles over the head of high school athlete Baylee DeForest of Virginia to better examine the tracking and movement of the eyes of a concussion patient. Photo courtesy of UPMC

Return to school should occur after symptoms are controlled. It is important for the patient to return to regular activities, the school personnel needs to monitor for symptoms and if there is decreased attention, poor memory, irritability, medical evaluation should be undertaken. Students with permanent or prolonged disability may benefit from referral for special accommodations and services, in which environmental, methodological, and organizational changes can be made to their education curriculum.

One tool to help assess student's needs is the pediatric test of brain injury (PTBI). PTBI is a criterion-referenced, standardized test that assesses the skills children need to return to school and function in the general education curriculum.

Therapies that are available for post-concussive symptoms are aimed at rehabilitation of the patient. These include the use of medications to treat specific symptoms

Table 2 Graduated return-to-play protocol

Rehabilitation stage	Functional exercise at each stage of rehabilitation	Objective of each stage
No activity	Symptom limited physical and cognitive rest	Recovery
Light aerobic exercise	Walking, swimming, or stationary cycling keeping intensity <70 % maximum permitted heart rate no resistance training	Increase HR
Sport-specific exercise	Skating drills in ice hockey, running drills in soccer. No head impact activities	Add movement
Non-contact training drills	Progression to more complex training drills, e.g., passing drills in football and ice hockey May start progressive resistance training	Exercise, coordination, and cognitive load
Full contact	Following medical clearance participate in normal training activities	Restore confidence and assess functional skills by coaching staff
Return to play	Normal game play	

such as insomnia and anxiety by a physician with concussion treatment [48].

Chronic Traumatic Encephalopathy (CTE)

For almost 100 years it has been know that repetitive brain injury causes chronic symptoms. The term "dementia pugilistica," although initially coined to describe boxers who exhibit progressive neurodegenerative disease secondary to multiple concussions, has also been observed in many athletes and military personnel. Since the age of onset is outside the pediatric period (ranging from 25 to 76 years), awareness of the cumulative effects of multiple concussions suffered during childhood must be raised. CTE is characterized by accumulation of tau protein in the brain cortex [49]. At least 17 % of patients with repetitive concussion may develop CTE [50]. Patients may have cognitive findings, psychiatric symptoms, and ultimately parkinsonian symptoms as the disease progresses [51]. It is therefore important to prevent concussions in our patients, through education, appropriate use of helmets, restraints, and other sports gear.

Conclusions

Concussion is an important problem in our children and adolescents; this has a real impact on behavior and cognition. There is increased awareness of this condition in the last decade. Recent advances have been made to identify and treat concussion using set guidelines.

Patients should be evaluated by medical personnel after concussion has occurred, determination for ED evaluation should be made. Patients should be evaluated for the need of neuroimaging. Prediction rules are useful to identify patients in which neuroimaging can be avoided and therefore limit the use of ionizing radiation in the ED.

Return-to-play guidelines provide a pathway to safely integrate the patient to regular activities. Patients should not be allowed to RTP on the day of injury unless cleared by medical personnel.

Post-concussive symptoms and their management are extremely important to rehabilitate injured children, it is difficult to predict which patients will have prolonged symptoms. Patients may exhibit prolonged symptoms several weeks after the injury has occurred, and therefore, appropriate recognition and management is fundamental to avoid negative effects in performance and quality of life of our patients.

Concussion future advances will focus on gathering evidence to refine clinical assessment tools and develop effective treatment approaches and management of post-concussive symptoms.

Compliance with Ethics Guidelines

Conflict of Interest Drs. Calisto and Gaines declare that they have no conflicts of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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