Neuroimaging of Sports Concussions

Teresa G Odle, BA, ELS

Concussions resulting from sports activities have received attention in recent years, and failure to prevent head injury has undergone scrutiny. Although many factors contribute to sports concussion incidence, determining when an athlete can return to play is crucial to minimizing long-term effects of concussion. To date, neuroimaging plays a limited role in concussion evaluation, but conventional and advanced neuroimaging techniques are contributing to the body of research on their future use in evaluation.

After completing this article, the reader should be able to:
- Discuss sports concussion incidence and reasons for increased attention to these injuries in children and adults.
- Describe the biomechanics of concussion and common signs and symptoms.
- List long-term complications and late sequelae from sports concussions.
- Articulate the related laws, programs, and initiatives aimed at decreasing sports concussion occurrence and effects.
- Discuss treatment recommendations for sports concussion.
- Explain the role of conventional and advanced imaging in diagnosis, management, and research of sports concussions.

In 2004, University of North Carolina researchers mounted sensors on football helmets and determined that some collisions during football games are similar in intensity to an automobile hitting a wall at 25 mph. These collisions can result in a concussion, a transient disturbance in brain function caused by trauma. An estimated 1.6 million to 3.8 million sports concussions occur each year in the United States.

In the past, concussions also have been called mild traumatic brain injuries (mTBIs). Most recent recommendations reported that people with concussions usually fully recover, but because mTBI can cause persistent symptoms, the 2 terms are not synonymous. Concussions are a subset of mTBI, but not all mTBIs are concussions. Another reason the terms are not synonymous is that mTBIs exist along a TBI severity spectrum, causing a pathological injury to the extent that damage is perceived on neuroimaging. In contrast, concussions show symptoms of functional disturbances that do not appear on computed tomography (CT) or magnetic resonance (MR) imaging examinations. Despite the benign findings, concussion can lead to long-term effects, some severe.

Patients with symptoms of concussion can have significant pathology that is difficult to diagnose. Evidence shows potential long-term functional and psychiatric complications after concussion in adult athletes. Sports concussions are unique in that athletes return to the same setting that put them at risk for initial concussion; often, they return to the sport too soon. A study of 170 patients in an Ontario, Canada, practice reported that in 43.5% of cases, patients who had received a sports concussion returned to play too soon.

As a result, sports concussions can have more serious consequences than apparent from a single
mild head injury. Studies have shown a link between number of head impacts and impaired cognition, even within a single sporting season.

The long-term implications of sports concussion, and particularly of repeat concussions, has increased interest in studying and treating these injuries. Most notably, concerns about long-term sequelae from repeat concussions and returning to play too soon have led to increased public attention, programmatic and guideline recommendations, and regulations. Addressing sports concussions is difficult, considering the culture of sports, sideline assessment, and the financial stakes in professional sports. Research on long-term implications of concussions continues, and advanced medical imaging plays an important role in the study of sports concussion and possibly in prevention, diagnosis, and treatment efforts.

**Mechanisms of Injury and Biomechanics**

Studies of the pathophysiology of concussion show that a complex series of events takes place in the brain. Acute functional problems following a concussion arise mostly from the primary brain injury and the neurometabolic events that follow, often called a *secondary brain injury.* The primary and secondary injuries interact, because the primary injury triggers the subsequent processes.

Biomechanics of concussion are similar to those of all TBI. Mechanical injury from a force disrupts cellular membranes, releasing a stream of intracellular potassium. The depolarizing (switch in charges) effects on neurons lead to a loop that causes additional potassium and adds to neuronal effects. Neurotransmitters (amino acids) are released in the form of glutamate, which stimulates receptors and further exacerbates the potassium release. Activation of proteases and mitochondrial impairment are among other metabolic results of unchecked neurotransmitter release. Following the excitatory cascade, neuronal depression occurs in diffuse areas of the brain. In severe trauma, cells struggle to maintain metabolic balance and activate the lactic acid glycolysis, which accumulates in the brain. The accumulation eventually causes acidosis and breaks down the blood-brain barrier, which can cause cerebral edema.

Changes to cerebral blood flow can cause symptoms such as migraine headaches. When axons are involved (particularly following acceleration from impact), diffuse white matter lesions arise. The effects of the multifocal lesions vary based on the brain regions injured. Focal damage to axonal cytoskeletons occurs and, combined with loss of elasticity, can cause breakage of microtubules, preventing the tubules from realigning. Inflammation can promote demyelination of axons. The role of inflammation in axonal regeneration is uncertain but might be linked to later neurodegenerative disease following brain injury.

The 2 primary forces that lead to concussions are direct impact to the head and deceleration or acceleration forces. A forceful direct blow causes direct injury at the point of contact and is called a *coup injury.* Direct injury typically is represented by contusions. Examples of direct force sports injuries include instances such as a baseball strike to the head, head-to-head collisions, and the head striking the floor.

Acceleration and deceleration lead to shear forces and both tensile and compressive strain on tissue; the forces typically are represented as *contrecoup injuries,* which affect the contralateral side of the brain from forcing the brain against the skull. The forces damage the brain’s white matter by causing diffuse and vascular injury from stretching. At times, an injury involves combined coup-contrecoup mechanisms, leading to damage to the impacted side of the brain and the opposite side as the brain lags immediately following acceleration.

Sports injury biomechanics vary from 1 sport or type of injury to another. Compression of the head causes injury at the point of contact, but tensile forces can lead to contrecoup injury. The brain can more easily endure a brief, compressive force than it can tension and shearing forces. A violent impact can lead to shearing injury of white matter fibers. In some cases, an athlete is injured by both direct and rotational forces. In general, the forces lead to a cascading injury of neurometabolism that involves ionic, metabolic, and pathophysiological effects.

Biomechanics of concussion affect men and women differently. The kinetics involved in head strikes vary...
between the sexes. Men have larger heads, which can lower acceleration of the head on impact. Women have 43% less mass in their heads and necks than men, and 23% less neck girth. Women’s head-neck segments also are less stiff than men’s (by about 29%) and have 59% less isometric strength. Still, studies relating kinetics to physical differences between the sexes are not conclusive, likely because of the variables involved (eg, use of head protection, type and velocity of force) and the complex nature of concussion injuries and pathophysiology. Studies of the role of hormones in sex-related differences of concussion effects suggest that estrogen could be involved in the brain’s reaction to trauma, but results across studies are not consistent.9

The term concussion can be used to describe the distinct pathophysiological entity or a group of symptoms that appear following some types of TBI19 and as a separate designation from the term mTBI.3 No defined biomechanical threshold exists for clinical concussion.3 For the purposes of this article, concussion refers to a clinical syndrome represented by altered brain memory and orientation function, and sometimes loss of consciousness. The syndrome is caused by biomechanical-induced changes in the brain.18

Second Impact

One of the greatest concerns following a sports concussion is susceptibility to another concussion.8 Athletes who have had a concussion are at higher risk for future concussions, and in general, athletes in many sports are at higher risk of head trauma.19 A prior concussion increases the risk for another concussion as much as 3-fold to 6-fold.20 Sustaining a second, albeit minor, impact while still experiencing effects and symptoms of a first concussion is particularly troublesome.8,19

Athletes’ reaction times, balance, and cognition usually are impaired following concussion, which places them at higher risk for a second injury and even a severe injury.21 Typically, more significant injuries occur because the first concussion was not recognized or diagnosed or because an athlete returned to play too soon, typically within a month.11,12 If the brain is still in recovery from a first injury, it is vulnerable metabolically to lesser impacts. This vulnerability leads to a chain of chemical and other responses that can cause malignant cerebral edema without hematoma, herniation, and death.6,9,21

A second blow to the head after a prior concussion that has not subsided fully can lead to neurometabolic imbalances with severe long-term consequences.11 At times, these second injuries lead to diffuse cerebral swelling, severe functional impairment, and death. This reinjury is sometimes called second impact syndrome9; however, labeling a second concussion as a syndrome is controversial and lacks evidence. Still, physicians recognize the serious clinical condition of diffuse cerebral swelling as an important factor in treating concussions and clearing athletes to return to play.4 Some evidence has shown that having a mutation in the calcium channel, voltage dependent, P/Q type, alpha 1A subunit (CACNA1A) gene that is related to encoding of calcium channels could lead to delayed cerebral edema following minor head trauma.21 Researchers continue to discuss the importance of recognizing diffuse cerebral swelling and especially of developing markers to help physicians determine when cerebral recovery takes place following a first concussion to better prevent complications and long-term sequelae from a second blow to the head. Few human studies have been completed, and none have identified the precise time after which a second concussion does less damage.4

Repetitive Head Trauma

Research demonstrates increased risks for more severe neurological effects from repeated concussions and potentially catastrophic long-term consequences.11,19 Repeated mild blows to the head from sports such as soccer can trigger pathological white matter changes in the brain (see Figure 1). Some athletes appear to be more susceptible to long-term effects from repetitive blows than others, although the reasons are not entirely understood.11

With repeated head trauma, athletes face higher risk of developing mild cognitive impairment or dementia, depression, and suicidal thoughts or actions.19 Investigators have confirmed that sustained trauma from boxing can lead to progressive neurological deterioration, such as dementia.5
Neuroimaging of Sports Concussions

School students are involved in interscholastic athletics every year in the United States. Marar et al studied more than 14,000 sports injuries that were reported for high school athletes between 2008 and 2010. Of these injuries, 1289 were concussions occurring in sports competition, and 647 were concussions occurring during athletic practice.

Safe Kids Worldwide examined emergency department data from 2011 to 2012 for sports injuries in children aged 6 to 19 years. The group found that 12% of all sports injuries presenting for emergency care in the age group were concussions. Most sports concussions occur in high school athletes, but reports of concussions in younger athletes are increasing. In children younger than 10 years, mTBI accounts for 16% of medical visits, and as many as 25% to 50% of all concussions in children are from sports injuries.

Football

Football is associated with more traumatic brain injuries than any sport, because of the high contact involved and because more people participate in football than in other sports in the United States. Between 1965 and 1974, at least 167 people died from football-related brain injuries. Since that time, new rules, penalties, and helmet-safety standards have reduced the number of severe TBIs. The emphasis now has shifted to preventing milder TBIs such as concussions.

At least 10% of college football players and 20% of high school football players have brain injuries each season. The Marar et al study found that nearly half (47.1%) of the concussions reported in high school athletes for a 2-year period were from football injuries. Multiple concussions were noted in nearly 35% of athletes in an early study (1996 to 1997) of high school football players. Most of these injuries were from running plays that led to contact between players. At least 62% of concussions reported in the Marar et al study were a result of tackling. A study of NFL player concussions found that causes vary, but that helmet-to-body impacts led to slightly more concussions than helmet-to-helmet contacts.

Studies suggest a statistically significant increase in concussions when athletes play football at the collegiate level. This could be the result of better access to sports Epidemiology

As many as 20% of athletes participating in contact sports have a concussion each competitive season. Estimates of the millions of sports concussions per year vary because of a widespread lack of reporting. Multiple factors affect reporting, including failure of some coaches, athletic trainers, and other sports medicine professionals to follow concussion assessment and management guidelines. Intense pressure can be placed on athletes and team medical or coaching staffs to keep top performers in play or return them to play as soon as possible. Likewise, players worry about adverse consequences of reporting concussion, particularly at professional levels.

Although National Football League (NFL) injuries have received more of the spotlight, concussions occur in many sports and affect recreational and athletic participants at almost all ages. More than 7 million high school students are involved in interscholastic athletics every year in the United States.
medicine professionals and more consistent reporting of the injuries than at the high school level. Marar et al. found that 25% of concussions in high school baseball and softball players were the result of fielding a hit ball. According to Safe Kids Worldwide, of 61,510 baseball injuries in 2011 among children aged 12 to 17 years, 11% were concussions. Of nearly 39,100 softball injuries in the same group, 11% were concussions.

**Basketball**

Basketball is among the most popular high school and college sports for both sexes. The sport is associated with higher rates of concussion in female players than in male players. The Safe Kids Worldwide evaluation of sports injuries in athletes aged 6 to 19 years from 2011 to 2012 found that concussions accounted for 11.5% of basketball injuries in girls and 7.2% in boys. Women have more concussions in competitive play than do men, although concussion rates during practice are similar for men and women. Ball handling and chasing of loose balls tend to cause the most concussions in basketball. Marar et al. found that male high school players had more concussions while shooting or from player-to-player contact than did female athletes.

**Wrestling**

Fewer athletes participate in competitive wrestling, but the sport is associated with the highest number of injuries among winter high school and college sports. Takedown maneuvers are the most common cause of concussion in the sport, mostly from contact with an opponent, and about one-fourth of the time from head contact with the playing surface. Competitive matches were associated with 3 times as many concussions than practice sessions in Marar et al’s study on high school sports concussions. The authors also found that take-down maneuvers accounted for the most concussions among study participants during competitions, with a slightly higher rate of concussions occurring from player-to-surface contact.

**Other Sports**

Concussions occur in a variety of sports, with injury levels relating to participation, activities that increase risk of injury, and effectiveness of following rules and wearing protective gear to prevent concussion. According to Safe
Kids, ice hockey has fewer overall injuries (9540) than other sports, but 31% of those injuries are concussions. See Table 1 for summaries of concussions in other sports.23,24

**Table 1**

<table>
<thead>
<tr>
<th>Sports Concussion Facts and Statistics23,24</th>
<th>Sport</th>
<th>Incidence</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field hockey</td>
<td>High concussion rate for No. of participants, 1.4%</td>
<td>More concussions during competition than practice; 60% from equipment contact; 29% from player-to-player contact</td>
<td></td>
</tr>
<tr>
<td>Ice hockey</td>
<td>High concussion rate for No. of participants, 3.9%</td>
<td>Higher concussion rate during competition than practice; 45% from player-to-player contact, others from ice, wall (glass)</td>
<td></td>
</tr>
<tr>
<td>Cheerleading</td>
<td>&gt; 27 000 ED visits in 2007; 20% of all injuries are concussions</td>
<td>Rising participation rates; higher risk of injury from more difficult tumbling moves; most head injuries occur during practice</td>
<td></td>
</tr>
<tr>
<td>Gymnastics</td>
<td>1.7% in high school gymnasts</td>
<td>Concussions are 9 times more likely in competition than in practice; risk decreases slightly with age</td>
<td></td>
</tr>
<tr>
<td>Lacrosse</td>
<td>76% of male players from player-to-player contact; 9.8% of all female player injuries</td>
<td>Relatively low participation; higher concussion rate in competition than in practice for both sexes; rate decreased after helmets introduced</td>
<td></td>
</tr>
<tr>
<td>Volleyball</td>
<td>4.1% of all injuries during games</td>
<td>2 times more likely in games than in practices; most result from playing surface impact</td>
<td></td>
</tr>
<tr>
<td>Skiing/snowboarding</td>
<td>9.6% of all ski injuries; 14.7% of snowboarding injuries</td>
<td>More recreational athletes than organized competition; similar head injury rates between both snow sports but more severe head injuries in snowboarders</td>
<td></td>
</tr>
</tbody>
</table>

*Abbreviation: ED, emergency department.*

**Signs and Symptoms**

Concussion leads to neuropathological changes, but the symptoms reflect functional problems associated with these changes instead of an evident structural injury.4 Signs such as cognitive impairment, memory deficits, shortened reaction times, or concentration difficulties can signal suspicion of concussion.9 Specifically, symptoms can be categorized into 5 domains3,15,31:

- **Cognitive** – problems with memory and concentration, inattentiveness, confusion, slowed reaction time.
- **Somatic** – dizziness, headache, nausea, photophobia, phonophobia.
- **Mood** – anxiety or nervousness, sadness, irritability, mood swings.
- **Sleep** – insomnia, sleeping too much, problems falling asleep.
- **Physical signs** – loss of consciousness.

Many of these symptoms are apparent following all types of TBI, however. For example, headache, cognitive impairment, and sleep disturbance are among symptoms common across the TBI severity spectrum. Further, the complex nature of the brain and small degrees in variations in protective gear or of impact force, direction, and other biomechanical factors means that symptoms do not necessarily match the apparent severity of a given injury. Seemingly minor injuries can have lasting effects.5

Estimates show that as many as 47% of athletes report feeling no symptoms after a concussive blow to the head.32 Although concussion effects and symptoms vary from 1 individual to another, the symptoms tend to evolve and appear in phases, and other symptoms might not be apparent until minutes or hours following injury.19 Immediate symptoms appear on impact; acute symptoms are evident within hours or days of injury, and subacute symptoms appear up to 4 weeks following injury. Common symptoms of concussion can overlap phases depending on the individual but typically reflect functional disturbances.4 In addition, many symptoms...
resulting from impaired neurological function resolve spontaneously within the acute and subacute periods.\textsuperscript{3,5} Still, some athletes can experience symptoms such as depression or anxiety for months or years following a concussion.\textsuperscript{33}

It is possible for a person with a concussion to have complications in the acute symptom phase. Seizure or an undetected injury in the brain parenchyma are examples. Brain parenchyma injury can cause hemorrhage and hematoma, and an intracranial hematoma can further complicate seizure activity.\textsuperscript{4}

Although confusion is a hallmark sign of concussion,\textsuperscript{18} fewer than 10% of athletes with sports concussions experience loss of consciousness.\textsuperscript{24} More often, concussions cause less evident symptoms in the 5 domains.\textsuperscript{15} If an individual has a known impact or injury involving the head, any 1 or more symptoms in these domains suggests further assessment.\textsuperscript{31} Wasserman et al evaluated sports concussions in more than 1600 college athletes and found that headaches were the most common complaint in concussions from nearly all organized sports studied, followed by dizziness and difficulty concentrating.\textsuperscript{34} The most common reported symptoms in the Marar et al study of high school athletes were headache, followed by dizziness, difficulty concentrating, confusion, photosensitivity, and nausea.\textsuperscript{24} A high variability in concussion symptoms has led clinicians to abandon concussion symptom severity grading scales.\textsuperscript{31} Symptom recognition is critical to early assessment and diagnosis of concussion, yet athletes often dismiss their symptoms.\textsuperscript{35}

Postconcussion syndrome is the name applied to 20% to 30% of patients with apparently mild closed-head (ie, the skull and dura matter remain intact) injuries but continued symptoms.\textsuperscript{5,36} It is marked by severe concussion symptoms that appear in the acute or subacute symptom phases (from a few weeks to months following injury) and persistent symptoms for up to 3 months.\textsuperscript{9,34} Students (elementary through college) with sports concussions often experience recurring or worsening symptoms after they return to play or to the classroom.\textsuperscript{7}

Susceptibility to and recovery from concussions can be affected by pre-existing conditions such as genetic factors and a history of migraines, psychiatric disorders, or learning disabilities.\textsuperscript{37} In addition, children and adolescents have different brain water content, degree of myelination, and anatomy that could affect biomechanics of injury. As a result, children can take longer to recover from some concussion symptoms and potential long-term effects, especially from repeat concussions.\textsuperscript{38}

Some evidence suggests that women have a different symptom pattern from concussions than do men. These reports have included greater incidence of fatigue, light-headedness, difficulty concentrating, and initial vision deficits compared with men. Men reportedly experience greater depression following concussions and more vomiting in the acute phase, although women tend to have the vomiting symptom in the subacute phase (about 8 days following concussion).\textsuperscript{9}

**Long-term Sequelae**

Concern is growing regarding the possible long-term effects of sports concussions.\textsuperscript{22,39} A single concussion can lead to cognitive deficits in animal models 18 months following concussion.\textsuperscript{3} Chronic episodic memory deficits occur in a small subset of people with a history of concussion or more severe TBI.\textsuperscript{40} Another complicating factor in identifying postconcussion symptoms and helping assess injury accurately is that each individual’s perception of symptoms and subsequent reporting can vary. Psychological or social-psychological factors could lead to a person either magnifying symptoms or discounting them. A possible relationship might exist between mental health issues already present before concussion and problems with persistent anxiety following injury.\textsuperscript{33} Scientific evidence shows that concerns about long-term psychiatric complications in adults with concussion history are valid. Depression has been associated with retired athletes who had an average history of 3.97 concussions and who were an average age of about 59 years. There also is concern about chronic substance abuse and behavioral changes in retired athletes, especially increased aggressiveness, but insufficient evidence exists on a relationship to concussion history.\textsuperscript{6}

Long-term effects and symptoms vary based on a second injury or a history of multiple concussions. Returning to physical or cognitive activity before full brain recovery can prolong symptoms and make a
person more susceptible to lasting neurological dysfunction.\(^2\) Sports are particularly risky for long-term consequences of concussion from repeated head injury. It is estimated that professional football players receive between 900 and 1500 blows to the head each season.\(^{31}\) Even repeated subconcussive blows lead to damage.\(^4\) Further, symptoms such as slowed reaction time or impaired cognitive ability could put an athlete at higher risk for concussions and neurologic injury, depending on the sport and circumstances of play. Players who have had multiple concussions can exhibit mild cognitive impairment, diffuse swelling, motor dysfunction, and mood disturbances years after concussive injuries.\(^{3,32}\)

**Chronic Traumatic Encephalopathy**

In 2005, neuropathologist Bennet Omalu gave a name to the long-term neurological signs and symptoms caused by multiple concussive head injuries. Omalu performed autopsies on 3 former NFL players who had died at relatively young ages and found a pattern in their brains. Each former player had a high concentration of the protein tau. Tau is the protein also associated with Alzheimer disease. Omalu published his findings, calling the degenerative disease associated with tau and head injuries *chronic traumatic encephalopathy (CTE).*\(^1\)

Observations of degenerative disease associated with a history of concussions have been made for many years, but Omalu defined the neuropathological process.\(^3,^4\) By doing so, Omalu opened the door to additional research to explain late or long-term cognitive and psychiatric effects of multiple concussions.\(^5\) Among observed effects are memory and executive functioning problems, aggressive behavior, poor impulse control, mood disorders ranging from apathy to anxiety, and suicidal thoughts or self-harm behaviors (see Figure 2).\(^4\)

In 2016, researchers at the University of California, San Francisco noted a loss of brain volume associated with tau in midbrain regions associated with CTE. The researchers compared MR scans acquired 4 years apart on a 51-year-old man who had played football for 3 years in high school and in college summer camps for an estimated 900 blows to the head.\(^31\) Postmortem studies show tau-associated neurofibrillary tangles, along with glial tangles and neuropil threads.\(^6\)

---

**Figure 2.** The interrelationships between concussion, postconcussion syndrome (PCS), chronic traumatic encephalopathy (CTE), and all the neurodegenerative diseases. A. There is considerable symptom overlap between concussion, PCS, CTE, and the neurodegenerative diseases. B. Pathologically, the relationship between concussion, PCS, CTE, and all the neurodegenerative diseases is unclear. In CTE there is substantial evidence for overlapping pathology of tau, TDP-43, amyloid, and alpha-synuclein with neurodegenerative diseases. In neurodegenerative diseases such as Alzheimer disease (AD), Parkinson disease (PD), and Lewy body disease (LBD), there is also overlapping pathology. The pathology of concussion and PCS and their relationship to CTE remains to be explored. Abbreviations: ALS-PDC, amyotrophic lateral sclerosis-parkinson dementia complex (Guam); CBD, corticobasal degeneration; CBS, corticobasal syndrome; FTD, frontotemporal dementia; MND, motor neuron disease; PSP, progressive supranuclear palsy. “?” indicates uncertainty about overlap. Reprinted with permission under the terms of the Creative Commons Attribution license. Tartaglia MC, Hazrati LN, Davis KD, et al. Chronic traumatic encephalopathy and other degenerative proteinopathies. Front Hum Neurosci. 2014;8:30.
The abnormal cortical tau deposition represents pathology similar to Alzheimer disease, but the association of tau and CTE to cognitive effects still is under study, particularly in relation to aging. \(^6,43\) Overlap exists between normal age-related cognitive decline and the pathophysiology of late effects of sports concussion, and it has been proposed that latent microstructural results of concussion in brain tissue make the brain more vulnerable to aging-related decline. \(^43\)

In the most recent Zurich consensus statement from the International Consensus Conference on Concussion in Sport, attendees concluded that CTE is a distinct tauopathy, and that incidence in athletes still is unknown. The statement also said that much needs to be ascertained about the cause-and-effect relationship of sports concussions to CTE. \(^31\)

Strain et al showed an association between history of concussion with loss of consciousness in retired athletes who had reduced hippocampal volumes and poor verbal memory. The study’s retired athletes who had mild cognitive impairment tended to be older (about 63 years) and have a history of loss of consciousness with concussion. \(^40\) Studies also are being conducted to identify biomarkers associated with concussion in the acute phase and with CTE and diffuse white matter anomalies. \(^41\)

**Assessment and Diagnosis**

The key to assessing concussions is initial observation of subjective and nonspecific symptoms. \(^21,44\) Some common symptoms of concussion are similar to those of other conditions, and variability among individual athletes’ symptoms is wide. In fact, the symptoms associated with concussion are so common that many people who do not have a concussion report that they are experiencing 1 or more concussion-associated symptoms during assessments. This includes 60% of male athletes and 48% of female athletes, according to 1 researcher. \(^21\) The lack of an objective measure complicates early assessment. \(^20\)

In the past, sports concussion evaluation relied on observable symptoms and a neurological examination that included checking cognitive function and balance. \(^19\) Although more thorough assessment tools are available for evaluating head injuries, the tools rely primarily on self-reporting and other subjective findings. \(^18\)

To date, the only definitive diagnosis for CTE is made after death, with postmortem tissue samples showing the disease’s unique pattern of tau deposition. \(^45\)

**Sideline Assessment**

On-field, or sideline, assessment is a method of determining whether an athlete should return to play after a potentially concussive impact or injury. Determining a high probability for concussion as soon as injury occurs is critical in sports concussions because of the effects related to a second concussion before the brain has recovered from the first. \(^19,44\) There often is tremendous pressure on athletes and those evaluating their injuries to return the player to competition. Athletes can be unaware of and show no signs of a concussion and can minimize or mask symptoms to hasten their return to play. \(^4\)

A number of tools have been developed to improve this initial assessment. Most notably, the Sports Concussion Assessment Tool (SCAT) provides a sideline assessment approach to measuring acute symptoms or for evaluating injured athletes immediately after injury. \(^44\) The SCAT combines clinical assessment into a brief assessment of concussion during sports practices or competition, and it has been through several revisions since its introduction in 2005. \(^18\) The most recent Zurich consensus statement recommends use of SCAT3 for evaluating adults and Child SCAT3 for evaluating pediatric athletes for concussion. \(^31\)

Concussion assessment tools included in SCAT are:

- Maddocks Sideline Questions—This series of measures addresses the fact that many sports concussions do not cause loss of consciousness, which was a measure used in early assessment systems. Maddocks proposed using questions pertinent to the activity in which the athlete was participating instead of traditional questions to determine orientation (eg, What day is it? Who is the president?). Instead, sideline assessment can ask questions such as, “What quarter are we in?” or “Who did we play against last week?” \(^20,31\)
- Graded Symptom Checklist—This assessment looks at subjective measures of preinjury and postinjury symptoms. \(^44\)
- Standardized Assessment of Concussion—This tool was 1 of the first systems for sideline...
assessments of sports concussions. The rapid assessment includes evaluating orientation, immediate memory, concentration, and delayed recall. This assessment has been shown to be sensitive at assessing sports concussions within the first 48 hours following injury.

- Balance Error Scoring System—Maintaining balance requires multiple sensory inputs and outputs to the muscles. Measuring postural stability is proposed as a method of sideline assessment of head injury. The assessment might not be as effective as others because balance recovers more quickly than other functions and because of wide variability in how observers rate balance.

- Reaction time—Reaction time often is slower to improve following concussion and could prove helpful as a measure of neurological deficit. Computerized testing can be used clinically or on the sidelines; a clinical reaction time test can be performed without a computer.

Sideline assessment can require evaluating an athlete in a locker room or other adequate facility. The assessment and final decision about potential concussion and clearance for activity should be based on clinical judgment and made by a physician or other licensed health care provider.

Clinical Diagnosis

Because many concussion measures are subjective, preparticipation or preseason examinations can provide baselines against which medical and sports personnel can compare postinjury assessment. A preparticipation examination should include questions about previous concussions and evaluation of medical history, in particular, history of headaches, depression, or sleep problems. For example, knowing that an athlete has attention deficit hyperactivity disorder (ADHD) can inform later evaluation of symptoms. Although the reasons are unclear, injured athletes who have ADHD experience significantly higher rates of concussion diagnoses than do children who do not have ADHD. It is possible that typical neuropsychological measures of concussion (eg, speed of information processing, word fluency, and memory) can be affected by existing ADHD or learning disabilities. Preseason examinations include similar medical history evaluation and preinjury, or baseline, testing. Recommendations include a clinical examination and documentation of postural stability and neurocognitive measures. In addition, evaluating an athlete for common concussion symptoms before play provides a baseline performance against which to compare postinjury evaluation.

Athletes with head injuries also can be assessed in an emergency department or physician office. Nearly 80% of patients seen in the emergency department for head injury are treated and released, but about 20% have more severe injuries. Mild TBIs account for nearly 95% of head injuries. Therefore, although early assessment is critical to prevent further injury to the brain, many of the imaging examinations conducted to assess concussion are unnecessary.

The Glasgow Coma Scale is used widely in emergency departments to assign a score to head injuries. The assessment includes adding points for eyes that do not open, open in response to painful stimuli, or open to verbal commands. The assessment also measures ability to speak clearly and whether the patient can move, such as extending limbs or moving away when exposed to painful stimuli. The assessment results in a numerical score; a low score (3-8) indicates severe injury, and a higher score (>13) indicates mTBI. Glasgow Coma Scale findings are then classified into mild, moderate, or severe categories based on the score.

In emergency departments, use of imaging varies considerably, ranging up to nearly 42% for ordering head CT examinations to assess TBI. A 2014 study showed that trauma centers were more likely to order imaging examinations than were nontrauma centers. Utilization of CT to evaluate pediatric head trauma increased from 12.8% in 1995 to more than 28% in 2000, even though hospitalization rates for head trauma remained stable. Pediatric organizations, such as the Pediatric Emergency Care Applied Research Network, have developed clinical recommendations to assist physicians in identifying pediatric patients at risk for negative outcomes from TBI as well as low risk for moderate to severe TBI. The recommendations also help assist clinicians in diagnosis and imaging decisions. Signs and symptoms evaluated include level of altered consciousness, presence or absence of clinical signs of...
basilar skull fracture, headache severity, mechanism of injury severity, vomiting, and loss of consciousness.  

Role of Medical Imaging

The objectives of medical imaging following a head injury are to help determine whether patients need emergency care or intensive surveillance, or to determine prognosis in more severe head trauma. The metabolic chain of events from concussion is functional rather than structural, so neuroimaging typically is negative in patients following a sports concussion. Because of this and concerns about cost and risk vs benefit, the American College of Radiology and other societies have developed recommendations and guidelines for use of neuroimaging in the diagnosis and management of concussion. Still, neuroimaging has a place in sports concussion evaluation, especially in research and clinical imaging of CTE and other chronic effects of concussion.

Clinical

According to the American College of Radiology, minor or mild acute head trauma (>13 on the Glasgow Coma Scale) imaging usually is not appropriate as an initial study in diagnosing concussion. When imaging is indicated in head injury, the first examination chosen is CT without contrast. An MR examination without contrast might be indicated when a patient has new, persistent, or worsening symptoms. Pediatric neurologists generally recommend use of CT and MR only for suspicion of moderate or severe TBI, intracranial hemorrhage, evidence of skull fracture, or multiple or severe trauma.

Conventional neuroimaging can falsely reassure physicians and patients by returning findings that do not indicate underlying functional problems. Since 2009, several entities have brought together experts in TBI to develop and refine a standard set of terminology and definitions to better characterize intracranial injuries. In early 2017, the Head Injury Institute worked on developing a Traumatic Brain Imaging Reporting and Data System to standardize reporting and data collection from imaging of TBI. The intent is to apply evidence-based protocols to provide appropriate imaging rationales across disciplines and standardize reporting on findings, similar to the use of the Breast Imaging Reporting and Data System.

In general, clinical diagnosis and grading of TBI involves:

- Comprehensive injury and medical history.
- Physical examination and comparison of clinical status immediately after injury (ie, whether symptoms have worsened).
- Neurological examination assessing mental status, cognitive function, gait, and balance.
- Neurocognitive (and sometimes neuropsychological) testing.
- Determining whether imaging is needed to exclude severe TBI and structural abnormality.

Use of neuroimaging in evaluating mTBI might be more useful with advanced imaging methods and with a large database of images and findings on people who do not have TBI to which concussion and mTBI could be compared.

Conventional Imaging

Conventional neuroimaging (CT and MR) is expected to be normal if used to evaluate patients who have a sports concussion. Pediatric neurologists, radiologists, and sports concussion recommendations do not support the use of neuroimaging to diagnose an acute concussion without strong suspicion of intracranial injury. Morgan et al studied imaging results of 52 pediatric neurology clinic patients with postconcussion syndrome, 40 of whom had received a sports concussion. Only 5% of MR examinations and 13% of CT examinations yielded significant findings. Of 7 total findings on imaging, only 2 were related to the concussion.

Despite the level of evidence studies and recommendations stating little value to imaging athletes with sports concussions using conventional structural imaging, a 2014 study showed lack of knowledge and consistency regarding imaging. White et al surveyed coaches and sports trainers involved in Australian football and rugby and found that a high proportion believed that postconcussion imaging could show concussion injury damage to the brain. The authors’ findings were consistent with a similar survey of Canadian hockey coaches.

RADIOLOGIC TECHNOLOGY, July/August 2017, Volume 88, Number 6

631CT
Neuroimaging of Sports Concussions

Computed Tomography

CT without contrast can serve as the initial triage imaging examination for moderate to severe TBI but seldom is appropriate for mild TBI or a sports concussion.\textsuperscript{35,48} Shorter examination time requirements, tolerance of life support equipment during scanning, and ability to show signs of neurosurgical emergencies make CT the head trauma scan of choice.\textsuperscript{12} CT without contrast can demonstrate signs of severe injury such as intracranial hemorrhage, collection of fluid in the extraxial space, skull fractures, cerebral edema, swelling, and herniation.\textsuperscript{35}

Efforts to encourage judicious use of CT for concussion have intensified since 2001, particularly in evaluating children.\textsuperscript{15,35} Utilization of CT to evaluate minor head injuries increased in the late 1990s and early 2000s following release of studies reporting the rate of TBI in mild injuries to be as high as 13%, leading to more aggressive use of scanning.\textsuperscript{15} CT radiation dose to pediatric patients is of concern because children's brains are more sensitive to ionizing radiation than adults' brains and because head CT effects can increase the risk of cataracts later in life. Decisions regarding referral to CT for children who have a concussion generally follow the Pediatric Emergency Care Applied Research Network rules. Several prediction rules also exist to help identify whether a possible intracranial injury requires CT evaluation and to help adults with low risk for detectable brain injury avoid noncontrast CT examinations.\textsuperscript{35}

An analysis of the prediction rules evaluated CT use and results in children who were observed clinically for TBI before referring to CT and those sent directly to CT. Utilization was slightly lower in the observed group, but results of clinically significant injury were similar for both groups. Another study showed that delaying CT in favor of clinical observation in the emergency department (with the exception of significant injuries; these children received immediate CT examination) reduced the rate of CT utilization and subsequent dose with no delays in diagnosis.\textsuperscript{35} Zonfrillo et al reported that emergency department visits and use of head CT for concussion increased in a nationwide sample of emergency departments between 2006 and 2011. The authors attributed increased visits to public awareness of concussions and reported that despite increased visits and CT examinations, injury severity was low.\textsuperscript{58}

Magnetic Resonance Imaging

MR imaging is more sensitive than CT at detecting small lesions in TBI.\textsuperscript{35} However, use of MR as a primary imaging modality for concussion is not recommended, partly because of availability and the inability to assess head injury patients rapidly under the constraints of MR accessibility.\textsuperscript{35} Most guidelines for concussion management reserve MR examinations for patients who have persistent and consistent symptoms or signs of focal neurological deficits.\textsuperscript{36} Still, the practice of acquiring MR scans for patients who have normal noncontrast CT results and persistent but unexplained neurological symptoms is common, despite a lack of evidence for clinical utility.\textsuperscript{35}

Rose et al studied predictors for CT and MR use in a group of pediatric patients referred to a sport concussion clinic.\textsuperscript{50} Although use of CT generally followed standard clinical predictors for pediatric patients, acute signs and symptoms did not predict use of MR examinations. In most cases, ordering MR imaging in these patients was related to persistent postconcussion symptoms.\textsuperscript{50}

Typical pulse sequences for MR imaging of TBI include T1 weighting, T2 weighting, fluid attenuation inversion recovery, T2* gradient echo imaging, and diffusion-weighted imaging.\textsuperscript{35} MR with T2 weighting or T2W and fluid attenuation inversion recovery sequences have been shown to be more sensitive than CT without contrast in demonstrating epidural and subdural hematomas, small cortical contusions that are not hemorrhaging, brain stem injuries, and hemorrhaging such as in axonal injury.\textsuperscript{21,35} Ellis et al reviewed records and CT and MR imaging reports of patients referred to a Canadian concussion program between September 2013 and July 2014. MR scans demonstrated hemorrhagic and nonhemorrhagic injuries that affected decisions about letting athletes return to play.\textsuperscript{56}

MR spectroscopy, a form of multimodal MR imaging, has shown neurometabolic changes up to 1 month following sports concussion, even though the patients' symptoms had resolved 2 weeks prior.\textsuperscript{28,53} The amino
imaging with 3-D magnetization prepared gradient echo sequences followed by blood oxygenation level dependent (BOLD) images acquired with T2* weighted gradient echo-planar images. The authors found similar functional changes in brain activity of children who had concussion to adults who had concussion during working memory tasks. They found some differences, however, including reduced working memory accuracy compared with healthy controls.

Neurovascular coupling suggests that increased neuronal activity leads to a rise in cerebral perfusion in the area. Increased blood flow alters the ratio of hemoglobin with and without oxygen and influences the BOLD signal. Properties of hemoglobin alter local magnetic susceptibility. Use of BOLD techniques provides a means to noninvasively evaluate brain activity (see Figure 3).

Cerebrovascular reactivity refers to the change in cerebral blood flow in response to a stimulus. For example, decreases in cerebral blood flow of up to 50% have been demonstrated in patients with severe TBI, and it is theorized that insufficient delivery of blood coupled with other parts of the cascade of concussion effects account for the severe lack of neurometabolic energy following concussion. Neuroimaging studies have shown alterations in cerebrovascular reactivity in patients with moderate and severe TBI. In particular, functional MR methods have shown excellent potential in evaluating brain changes associated with behavioral and cognitive deficits. These studies support the possibility of examining cerebral blood flow with MR scans to evaluate concussion but lack sufficient evidence of routine clinical utility for functional MR imaging with BOLD in diagnosis and prognosis of concussion patients.

Functional Magnetic Resonance

Researchers continue to explore ways to use conventional or widely available MR techniques in clinical assessment of TBI. Czerniak et al studied college athletes who had concussions within the previous 6 months along with a group of college athletes who had no history of concussion, using clinical interviews, neurocognitive assessments, T1-weighted MR techniques, and functional MR. The authors found that athletes who had a recent concussion performed similarly to those who had no concussion history on executive function tests, but on neuroimaging, their resting brain networks had significantly increased connectivity compared with the athletes who had not had a concussion in the previous 6 months.

Keightley et al used functional MR examinations to evaluate working memory performance and related brain activity in youths who had concussions and a control group of healthy children. Participants had high-resolution T1-weighted, 3-D anatomical imaging with 3-D magnetization prepared gradient echo sequences followed by blood oxygenation level dependent (BOLD) images acquired with T2* weighted gradient echo-planar images. The authors found similar functional changes in brain activity of children who had concussion to adults who had concussion during working memory tasks. They found some differences, however, including reduced working memory accuracy compared with healthy controls.

Diffusion Tensor Imaging

Diffusion tensor imaging (DTI) is a well-established technique in concussion evaluation, however, its
Figure 3. Blood-oxygen level dependent images. Second-level analysis maps and postconcussion symptom scale scores for healthy control subject (A) and adolescent postconcussion syndrome patient (B). Second-level individual comparisons examined at the \( P = .005 \) level demonstrate no evidence of abnormal voxels in the healthy control subject compared with the atlas of normal controls. Quantitative patient-specific alterations in cerebrovascular responsiveness are demonstrated in the adolescent postconcussion syndrome patient. Reprinted with permission under the terms of the Creative Commons Attribution license. Ellis MJ, Ryner LN, Sobczyk O, et al. Neuroimaging assessment of cerebrovascular reactivity in concussion: current concepts, methodological considerations, and review of the literature. Front Neurol. 2016;7:61.

Axonal pathology is characteristic of long-term concussion history. The technique uses 6 diffusion gradient directions to compute the diffusion tensor. In chronic mTBI, a decrease in fractional anisotropy in the corticospinal tracts, sagittal stratum, and superior longitudinal fasciculus has been shown. These changes correlate with deficits in cognitive function. The axonal damage is measured using fractional anisotropy and mean diffusivity. DTI involves several metrics, and specialized data processing and analysis can translate the data to depict white and gray matter tract abnormalities. Fractional anisotropy measures diffusion along the longitudinal access of the axon, and mean diffusivity measures amplitude of overall diffusion regardless of direction. Methods of axial and radial diffusivity most likely illustrate axonal and myelin loss (see Figure 4).

Using DTI, Tremblay et al demonstrated the effect of concussion history in retired athletes. Their study revealed that aging brains of patients who have a history of concussion show a diffuse pattern of white matter anomalies. The data reflecting acute and chronic changes to the brain from TBI vary, however, and fractional anisotropy can indicate other disorders affecting white matter. Although more research is needed, group analyses have shown that DTI can detect alterations in the brain in mild to severe TBI.

With diffusion spectroscopy, more accurate mapping of axonal trajectories can be produced. The technique requires comprehensive sampling, which can show heterogeneity inside voxels and crossing of fiber tracts.
Future Advanced Neuroimaging Methods

Conventional neuroimaging and neuropsychological tests can fail to detect concussion injury, especially diffuse axonal injury.\(^3\) As research into advanced neuroimaging techniques continues, it is possible that new ways to assess concussion and recovery will emerge.\(^5\) To date, however, little evidence exists to support the use of advanced imaging techniques in clinical diagnosis or prognosis for patients who have TBI.\(^55\) Some studies have demonstrated utility of advanced neuroimaging for showing microstructural and functional brain abnormalities in patients who have concussion, but little consistency exists across reported studies.\(^21\) Advanced neuroimaging can add to the body of research on the pathophysiology of sports concussion.\(^3\)

Quantitatively demonstrating amyloid plaque deposition could help evaluate CTE on neuroimaging. This has been accomplished with use of a compound such as Pittsburgh compound B (PiB) or Florbetapir F 18, both of which assist in evaluation of Alzheimer disease plaques and can detect neurodegeneration.\(^3\) At the 2016 Traumatic Brain Injury Conference, Samuel Gandy reported on use of positron emission tomography (PET) in displaying characteristic CTE tau in the brain of a former NFL player who had a history of at least 22 concussions in his 11-year career. The former player’s MR scans displayed no scar tissue or atrophy.\(^56\) PET scans could prove effective at measuring use of medications to treat neurodegeneration from concussion.\(^5\) Other PET agents under study can accumulate in areas of neuroinflammation or apoptosis/caspase activity.\(^47\)

Studies on use of single photon emission CT and PET for TBI typically evaluate cerebral blood flow...
and metabolism. Amen et al demonstrated use of functional single photon emission CT perfusion imaging to show that specific brain regions among NFL players had abnormally low perfusion compared with control subjects (see Figure 5). Few studies have tried techniques beyond blood flow and metabolic mapping, however. Once these modalities include mapping of specific ligands related to TBI, the next step could be evaluation of molecular biomarkers. The recent finding regarding PET’s potential role in evaluating CTE-associated amyloid tau could provide a definitive diagnosis in living patients who have a history of multiple concussions and symptoms suggesting CTE.

The use of biomarkers as indicators of sports concussion or CTE has been studied since 2000. Biomarkers can correlate to both brain function and structure. A literature review by Papa et al evaluated the use of biomarkers in imaging of TBI and concussions. Identified studies involved athletes aged 11 to 52 years who participated in 7 sports. The biomarkers included tau, glial fibrillary acidic protein, neuron-specific enolase, and others. The authors reported that several biomarkers have potential for determining concussion severity or correlation to repeat injury, mechanism of injury, and postconcussive symptoms, but the markers have not as yet been validated by further study or cannot be compared easily because of variability in research methods. The authors concluded that once validated, biomarkers could help provide diagnostic and prognostic information and be combined with neuroimaging to assess how concussion effects evolve or how the brain recovers.

Diffuse axonal injury imaging has been shown to detect microhemorrhages and demonstrate diffuse axonal injury. MR imaging with susceptibility weighting or gradient echo sequences can show microbleeds in the brain. The microbleeds appear as signal dropout on T2* gradient echo images, but resolution is better with susceptibility weighting. Measuring the number and volume of diffuse axonal lesions could help correlate with chronic depression and intellectual function problems.

In addition to the techniques discussed above, possible advanced neuroimaging methods for evaluating concussion and TBI include:

- Quantitative volumetric imaging such as MR with 3-D isotropic short-echo time spoiled gradient echo sequences to evaluate atrophy associated with TBI.
- Perfusion imaging, which uses PET, stable xenon-enhanced CT, single photon emission CT, or perfusion CT and MR techniques to show scattered perfusion deficits that can be correlated to neuropsychological and neurocognitive deficits or amnesia. Stable-xenon CT requires special, expensive equipment and is impractical for emergency settings. Perfusion CT is the most readily available perfusion method.
- Magnetoencephalography, which uses neuromagnetometers around the head to collect data through hundreds of sensors in waveforms showing magnetic fluctuations. The technique has low spatial resolution but high temporal resolution.

The use of advanced neuroimaging protocols in research is common, but protocols and database reporting are not standardized. A 2014 workshop brought together physicians and researchers to reach consensus on how to proceed with recommendations on research standardization for several conventional and advanced neuroimaging sequences. Future clinical use of advanced imaging for concussion diagnosis and management depends on systematic review of these evidence-based studies.

**Management**

The number of athletes, especially youth athletes, seeking medical attention for concussions has increased since 2004 and likely will continue as awareness of sports concussion expands. Consensus statements regarding concussion management and safe return to play or other activities have been in development since 2005 and can assist primary care providers and subspecialists in managing concussions and minimizing long-term effects. These statements include the Concussion in Sport Group best practice recommendations, developed by an international panel of experts. However, Stoller et al reported in 2014 that implementation of consensus statement recommendations has been inconsistent across specialties.
The first step taken when concussion is suspected is removing the athlete from risk of subsequent concussion until assessed on the sidelines and evaluated further if indicated. The next step is 24 to 48 hours of physical and cognitive rest, which is recommended by the main consensus statements for children and adults.20,22 During the first few days following concussion, cognitive activities, such as reading and computer work, can worsen symptoms or delay recovery, and student athletes should not attend school.23 The patient should begin activity gradually, based on symptom persistence or recovery.20 Although there is consensus on the physical and cognitive rest approach for concussion management, research on effectiveness of the strategy is sparse.24 Athletes’ mood and cognitive symptoms can worsen with prolonged rest, so monitoring of symptoms and low-level physical activity can improve recovery without increasing risk.20

Clinical and neuropsychological assessment of symptoms should guide evaluation and management. A treating physician should perform neuropsychological assessment that includes cognitive function, typically using computerized tools. Few athletes need formal testing from a neuropsychologist.20

No specific medications are recommended for concussion treatment, but medical therapy is relevant to treating symptoms.20,21 Over-the-counter pain relievers, such as nonsteroidal anti-inflammatory drugs, can help relieve headache in most patients with concussion. If headaches have migraine-like features, such as auras, physicians might prescribe triptans for acute relief, or prophylaxis for persistent migrainous headaches with the anticonvulsant topiramate, tricyclic antidepressants such as amitriptyline, beta blockers, or magnesium supplements until symptoms improve.20 Topiramate should be used carefully because of the drug’s effect on cognition, and continued use of analgesics and triptans can cause headaches. Opioids are not recommended for routine postconcussion headaches.21

Concussion patients who have sleep disturbances can benefit from education on removing distracting stimuli, avoiding caffeine, and other strategies. Those who have erratic sleep patterns might receive a light sleep aid such as melatonin, but prescription medications such as sedatives are not recommended because the drugs can affect arousal and cognition negatively.20 Dizziness in the acute phase of concussion that persists might require evaluation and management based on whether the cause is benign paroxysmal position vertigo, migraine, or central vestibular system damage.25

Some studies have reported on use of catecholaminergic and cholinergic agents to improve cognition following TBI, citing faster information processing with the drugs’ use. No significant evidence supports that use of the agents is superior to cognitive rest for patients with concussion. In fact, cognitive rehabilitation for patients who have more severe TBI usually involves practice and training on how to compensate for cognitive impairment.26 Research continues on the specific nature and duration of cognitive rest following concussion.22

Upon discharge from emergency or primary care, providers should give athletes, or their parents, clear instructions for second injury prevention, symptom monitoring, and follow-up care. Patients seen in an emergency department should follow up with their primary care provider.15

**Return to Play**

It is important to educate those in physical contact sports and sports involving collisions so that the athletes can understand how to prevent exacerbating second or multiple injuries.26,27 The most recent International Conference on Concussion in Sport consensus statement (November 2012) recommends a gradual return to school and social activities before return to contact sports and no return to play the same day a concussion occurs (see Table 2). Studies have shown that some college and high school students who are allowed to play the same day as injury have delayed onset of neuropsychological deficits following concussion that might not be evident in a sideline assessment.21

In addition, studies are demonstrating longer recovery times than universally recognized, especially in youth and adolescent populations, where recovery times have been found to extend to up to 4 weeks in children and teens vs established theories of a typical 1 to 2 weeks.53,64 Although children should receive cognitive rest, pediatric neurologists do not support extended school absences.21
Role of Imaging in Management

Currently, there is no established role for imaging in monitoring symptoms and managing return to play or prognostic decision-making in sports concussions. Although DTI shows increasing promise as a management tool, results of studies have been inconsistent about use of DTI in concussions vs more severe TBIs. The distribution of diffuse axonal injury also varies significantly from 1 patient to another. One method for standardizing findings is to conduct preinjury or preseason DTIs on athletes and compare the baseline findings to examinations taken after injury.4

Prevention

The only modifiable risk factor for the neurocognitive and behavioral symptoms related to concussion is further concussions; preventing a second injury is critical for athletes.2,15,22 Still, athletic trainers and team medical staffs are pressured to return athletes to sports participation prematurely. Kroshus et al surveyed athletic trainers and team physicians from 530 institutions that belong to the National College Athletic Association. More than half of the participants reported receiving pressure from coaches and athletes to return players to competition prematurely following concussion.66 An inherent conflict of interest exists for training and medical personnel who work for college or professional athletic departments, especially when
the staff reports to a coach or athletic manager instead of a physician. Addressing sports culture and sports-ing rules is a primary step in concussion prevention. Preparticipation examinations should be required before athletes participate in sports that add to risk of concussion.

Although use of helmets in contact sports and sports such as cycling has prevented head lacerations, skull fractures, and intracranial bleeds, use of protective headgear has done more to minimize severity of TBI than to prevent concussions. No significant evidence suggests as of the 2012 Zurich conference that protective equipment available for sports prevents concussion. It is possible that protective equipment use encourages false confidence and higher risk behavior, especially in young athletes. Still, there is consensus that protective head gear or helmets should be worn for several sports to minimize TBI effects; this includes evidence supporting use of helmets for skiing, snowboarding, football, cycling, equestrian sports, and others.

Prevention Efforts

Although it is not possible to eliminate concussions from most sports, steps can be taken to reduce the frequency and severity of the injuries. Rule changes and enforcement in sports likely prevent some concussions, although more study is needed on their effects. Limiting the amount of contact in practices can lower the number of concussions. In addition, studies have shown that athletes, parents, and coaches need more education to make informed decisions about concussion identification and prevention. Athletes in particular need to learn techniques that help minimize concussion and TBI from collisions or falls, although doing so can be difficult because of various biomechanics involved in concussion-related impacts.

The intense focus on sports concussion and CTE has led to additional organized efforts to address the concerns. Best practice recommendations have been developed, along with student and coach fact sheets on concussions. Heads Up Football is a program piloted in 2012 that exists in more than 7000 youth and high school football programs as of 2017. The program includes coach certification, training of player safety coaches, and concussion recognition and response education. The Chuck Noll Foundation for Brain Injury Research was established in the name of a former NFL coach to fund research for understanding, preventing, and treating sports concussion. As of 2015, all 50 states have passed laws requiring that a medical professional clear youth for return to sports.

Conclusion

Several investigations are underway to evaluate use of technology such as eye tracking, quantitative electroencephalography, and functional or advanced neuroimaging methods to diagnose concussion and assess recovery. Robotic prototypes made of foam are being tested to assist in football practices with less head impact. In neuroimaging, experts are developing protocols for using advanced neuroimaging for TBI and attempting to establish databases with evidence-based normative data for comparison. Future technologies such as advanced neuroimaging and biological markers could lead to improved evaluation and management of sports concussion.

Teresa Odle, BA, ELS, is a health care writer and editor living in New Mexico. She has written numerous Directed Readings and health materials for consumers. Reprint requests may be mailed to the American Society of Radiologic Technologists, Publications Department, 15000 Central Ave NE, Albuquerque, NM 87123-3909, or emailed to publications@asrt.org.

© 2017 American Society of Radiologic Technologists

References

4. Dimou S, Lagopoulos J. Toward objective markers of concussion in sport: a review of white matter and neurormeta-
Neuroimaging of Sports Concussions


Neuroimaging of Sports Concussions

1. Much of the public attention on sports concussion is focused on:
   a. acute effects.
   b. potential for severe traumatic brain injury (TBI).
   c. long-term sequelae and repeat concussions.
   d. faultiness of protective equipment.

2. Contrecoup head injuries result from ______ forces.
   a. low-energy
   b. shear
   c. direct-blow
   d. rotational

3. ______ is associated with more TBIs than any other sport.
   a. Soccer
   b. Skiing
   c. Boxing
   d. Football

4. Estimates show that as many as ______% of athletes report feeling no symptoms after a concussive blow to the head.
   a. 27
   b. 47
   c. 67
   d. 87

5. In 2005, a neuropathologist named the long-term effects of multiple concussive head injuries as:
   a. chronic traumatic encephalopathy.
   b. second impact syndrome.
   c. postconcussion syndrome.
   d. acute subconcussion syndrome.

6. Tools used to assess concussion rely primarily on:
   a. objective measurement of neurological function.
   b. the Glasgow Coma Scale.
   c. subjective and self-reported findings.
   d. neuroimaging.
7. Sideline assessment of sports concussion includes evaluation of:
   1. orientation by using questions about game activity.
   2. symptoms using a checklist.
   3. balance.
   a. 1 and 2
   b. 1 and 3
   c. 2 and 3
   d. 1, 2, and 3

8. When imaging is indicated for head injury evaluation, the first examination chosen is:
   a. computed tomography (CT) with contrast.
   b. CT without contrast.
   c. magnetic resonance imaging.
   d. diffusion tensor imaging.

9. The greatest concerns regarding use of CT examinations in imaging concussions in pediatric patients are:
   1. dose to the developing brain.
   2. increased risk of cataracts.
   3. missed structural pathology.
   a. 1 and 2
   b. 1 and 3
   c. 2 and 3
   d. 1, 2, and 3

10. MR with T2 weighting or T2W and fluid attenuation inversion recovery sequences have been shown to be more sensitive than CT without contrast in demonstrating:
    1. epidural and subdural hematomas.
    2. small cortical contusions that are not hemorrhaging.
    3. brain stem injuries.
    a. 1 and 2
    b. 1 and 3
    c. 2 and 3
    d. 1, 2, and 3

11. Measures of reduced ______ have been correlated with long-term neuropsychological deficits in children.
    a. tau
    b. N-acetylaspartate
    c. glial activity
    d. white matter

12. Fractional anisotropy measures:
    a. diffusion along the longitudinal access of the axon.
    b. amplitude of diffusion with no regard to direction.
    c. axonal loss.
    d. myelin loss.

13. ______ imaging has been shown to detect microhemorrhages in the brain.
    a. Magnetic spectroscopy
    b. Quantitative volumetric
    c. Diffuse axonal injury
    d. Magnetoencephalography
14. The first step taken when concussion is suspected is:
   a. 24 to 48 hours of rest.
   b. removing the athlete from risk of a subsequent concussion.
   c. gradual return to activity.
   d. CT scan without contrast.

15. Concussion patients who have sleep disturbances benefit most from:
   1. education about removing distracting stimuli.
   2. prescription sedatives.
   3. light sleep aids such as melatonin.
   a. 1 and 2
   b. 1 and 3
   c. 2 and 3
   d. 1, 2, and 3

16. Efforts to prevent concussions from most sports include:
   1. limiting the amount of contact during practices.
   2. providing concussion education to athletes, parents, and coaches.
   3. changing and enforcing rules in sports.
   a. 1 and 2
   b. 1 and 3
   c. 2 and 3
   d. 1, 2, and 3
Neuroimaging of Sports Concussions

Expiration Date: August 31, 2020
Approved for 2.0 Category A credits

-- A passing score is 75% or better.
-- Take the quiz online at asrt.org/drquiz for immediate results and your CE certificate.
-- Or, mail the original answer sheet to Processing Center 2908 Stewart Creek Blvd., Charlotte, NC 28216.
-- ASRT must receive this answer sheet before the quiz expires and before the end of the CE biennium for which you want credit.
-- To see a list of the Directed Readings available to you, visit asrt.org/drquiz.
-- To evaluate this Directed Reading, visit asrt.org/dreval.

Identification Section
We need your ASRT Member ID and your two-digit Birth Month to track your CE credits. Be sure to use your ASRT Member ID and not your ARRT Registry Number.

ASRT Member ID

Birth Month

Member Information Section
To ensure proper credit, please print the following information.

Name __________________________
City __________________________
State __________________________
Email __________________________

4 3 5 1 6 8

CE Answers Section
USE A BLACK INK PEN. Completely fill in the circles.

Get immediate Directed Reading quiz results and CE credit when you take your test online at asrt.org/drquiz.

Note: For true/false questions, A=true, B=false.

1 [ ] [ ] [ ] [ ] [ ]
2 [ ] [ ] [ ] [ ] [ ]
3 [ ] [ ] [ ] [ ] [ ]
4 [ ] [ ] [ ] [ ] [ ]
5 [ ] [ ] [ ] [ ] [ ]
6 [ ] [ ] [ ] [ ] [ ]
7 [ ] [ ] [ ] [ ] [ ]
8 [ ] [ ] [ ] [ ] [ ]

9 [ ] [ ] [ ] [ ] [ ]
10 [ ] [ ] [ ] [ ] [ ]
11 [ ] [ ] [ ] [ ] [ ]
12 [ ] [ ] [ ] [ ] [ ]
13 [ ] [ ] [ ] [ ] [ ]
14 [ ] [ ] [ ] [ ] [ ]
15 [ ] [ ] [ ] [ ] [ ]
16 [ ] [ ] [ ] [ ] [ ]

*Some quizzes are renewed and the expiration date extended. Check online at asrt.org/drquiz or call Member Services at 800-444-2778.