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Retirement-from-sport considerations following pediatric sports-related concussion: case illustrations and institutional approach

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The decision to advise an athlete to retire from sports following sports-related concussion (SRC) remains a persistent challenge for physicians. In the absence of strong empirical evidence to support recommendations, clinical decision making must be individualized and should involve a multidisciplinary team of experts in concussion and traumatic brain injury. Although previous authors have advocated for a more conservative approach to these issues in child and adolescent athletes, there are few reports outlining considerations for this process among this unique population. Here, the authors use multiple case illustrations to discuss 3 subgroups of clinical considerations for sports retirement among pediatric SRC patients including the following: those with structural brain abnormalities identified on neuroimaging, those presenting with focal neurological deficits and abnormalities on physical examination, and those in whom the cumulative or prolonged effects of concussion are suspected or demonstrated. The authors' evolving multidisciplinary institutional approach to return-to-play and retirement decision making in pediatric SRC is also presented.

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KEY WORDS concussion; traumatic brain injury; neuropsychology; neuroimaging; return to play; retirement

Sports-related concussion is a form of traumatic brain injury (TBI) that affects millions of North Americans annually.[27,60,73] Historically, SRC has been viewed as a functional disturbance of cerebral metabolism and blood flow that results in temporary alterations in neurological functioning that resolve within 7–10 days.[68,69] More recently, however, increasing attention has focused on the more serious effects of concussion and subconcussive injuries including abnormalities documented on advanced structural neuroimaging studies and the long-term risk of developing cognitive impairment, mood disorders, and neurodegenerative diseases including chronic traumatic encephalopathy (CTE).[7,29,44,48,49,51,65,70,71,80,94,98,99]

To mitigate the risks of more serious brain injury following SRC, experts offer consensus statements containing supervised return-to-play (RTP) guidelines that promote the safe return of athletes to the field of play after concussion symptoms have fully resolved.[4,68,69] These guidelines may reduce the risk of second-impact syndrome, a very rare and poorly defined condition thought to arise from loss of cerebral autoregulation and resultant diffuse cerebral edema.[67] However, they do not provide direction as to whether athletes should be advised to avoid future contact and collision sports because of the risk of adverse short- and long-term outcomes associated with future concussion. Over the years, several authors have offered recommendations about when athletes should be advised to retire from contact or collision sports, but most have focused on collegiate and professional athletes.[16,18,20,21,23,43,66,76,91,93] Although some authors suggest a more conservative approach should be applied to child and adolescent athletes,[16,23] indications for retirement from sports remain controversial and there are limited reports that discuss these issues in application to pediatric SRC patients. Because decisions regarding athlete retirement are complex and must be tailored to the individuals in the absence

ABBREVIATIONS CTE = chronic traumatic encephalopathy; PCS = postconcussion syndrome; RTP = return to play; SCI = spinal cord injury; SCIWORA = SCI without radiographic abnormality; SRC = sports-related concussion; TBI = traumatic brain injury.

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of evidence-based guidelines, it is important for multidisciplinary concussion centers to share their experience with patients presenting with indications for sport retirement.

Here we discuss 3 important subgroups of clinical considerations pertaining to sport retirement for pediatric SRC patients. These are patients with structural brain abnormalities identified on neuroimaging, those presenting with focal neurological deficits and abnormalities on physical examination, and those in whom the cumulative or prolonged effects of concussion are suspected or demonstrated. Three cases are presented to help illustrate our evolving multidisciplinary institutional approach to these unique patients.

General Considerations

The decision to advise an athlete to retire from competitive sports is among the greatest challenges facing physicians who care for athletes with SRC. Retirement from sport decision making must be approached on an individualized basis, taking into consideration important factors such as age; sex; medical and concussion history; sport; position and level of play; severity, type, and duration of concussion symptoms; neuroimaging and neuropsychological testing results; and natural history and outcome data for coexisting neurological disorders. Ultimately, in making these decisions we must weigh the risk of future injury against the potential negative consequences of discontinuing sport. Although the clinical decision-making process regarding retirement/RTP for collegiate and professional athletes may need to consider other social and legal factors such as a loss of income or scholarship and suitability to perform other occupations,[43,93] the process when children are involved requires a more conservative approach that is based solely on the future health of the patient. As these decisions are often more complex than typical RTP decisions, ideally, they should involve a multidisciplinary team of experts with clinical training in pediatric TBI, a team in which each member offers complementary expertise from within his/her clinical training and practice. In our opinion, neurosurgeons play an important role in retirement decision making following SRC because they are the health care professionals with the highest level of clinical training in the diagnosis and management of structural nervous system injuries that can accompany head and spine trauma. Neuropsychologists also play an integral role in the management of this unique population because they are the only health care professionals trained to administer and interpret formal neuropsychological testing instruments that are often the only tools capable of detecting subtle evidence of persistent functional brain injury. In certain circumstances, input from other professionals with specialized training in neurological disorders, such as neurologists, neuro-ophthalmologists, and orthopedic spine surgeons, can also be valuable. Because RTP decisions are often made in the absence of firm empirical evidence, the experience of the multidisciplinary team plays a pivotal role in arriving at clinical recommendations. Importantly these cases can have medicolegal implications for the treating physician and team, so it is imperative that the clinical decision-making process places the highest value on preserving the long-term health and neurological functioning of the athlete. It must be acknowledged that the approach described here is not firm rules but represents a conceptual framework that can be modified based on individual patient factors and must incorporate new research findings as they become available.

Structural Brain Abnormalities

Illustrative Case 1

A 13-year-old boy with a history of insomnia and no previous head injuries sustained a head injury that was associated with a loss of consciousness while playing dodgeball during gym class. Immediately after the patient's head hit the gym floor, he displayed convulsions involving the right upper and lower extremities, and following the convulsions he experienced a 5-minute period of right-sided weakness. The patient was evaluated at an outside emergency department where he underwent brain CT that demonstrated a 3.4-mm focal hyperdensity in the left frontoparietal white matter suspicious for a small intraparenchymal hemorrhage. Brain MRI performed 5 months later demonstrated a left frontoparietal focus of gliosis with associated hemosiderin deposition, confirming the presence of an intraparenchymal hemorrhage (Fig. 1A and B). The patient was referred to the pediatric concussion program 8 months postinjury. At that time, he complained of chronic low-grade headaches that had been present since the head injury; were not associated with any aura, photophobia, or nausea; and were not exacerbated by physical or cognitive activity. The patient had continued to play hockey despite ongoing headaches. There were no further seizures reported and findings on physical examination were normal. The clinical picture was in keeping with an initial SRC and posttraumatic seizure, as well as ongoing posttraumatic headaches. Based on the presence of a structural abnormality detected on neuroimaging, we advised the patient to avoid future contact sports and referred the patient to a pediatric neurologist for management of posttraumatic headaches and further workup of his posttraumatic seizure.

Discussion

Historically, SRC has been considered a metabolic or functional brain injury that occurs in the absence of structural damage to the brain. In rare cases, however, traumatic forces applied to the head and spine during sporting activities can result in more serious central and peripheral nervous system injuries that can be detected on clinical neuroimaging. In other cases, neuroimaging studies can reveal structural brain abnormalities that can have an important impact on RTP and retirement decision making.

Some authors have suggested that any athlete with a traumatic abnormality detected on neuroimaging be considered for sport retirement.[16,17,93] Traumatic injuries documented on neuroimages of athletes with sports-related head injuries range in severity from nondisplaced basal and calvarial skull fractures, to cerebral contusions, to life-threatening subdural hematomas and diffuse cerebral edema.[115] In the pediatric population, evidence-based clinical decision rules have been devised to help guide the

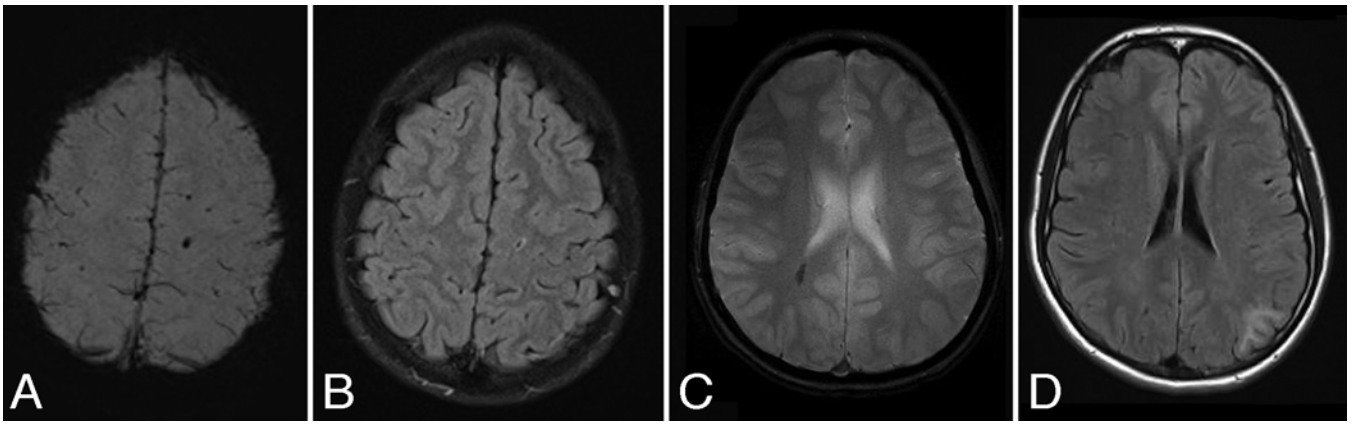

FIG. 1. Traumatic structural brain abnormalities identified on neuroimaging in patients with SRC. Axial susceptibility-weighted (**A**) and FLAIR (**B**) MR images obtained in a 13-year-old boy presenting with posttraumatic seizure and right-sided Todd's paralysis after he sustained a concussion playing dodgeball, demonstrating focal left frontal intraparenchymal hemorrhage. Axial gradient recalled echo MR image (**C**) acquired in an 11-year-old boy presenting with persistent headaches following hockey-related concussion, demonstrating intraparenchymal hemorrhage within the occipital white matter. Axial FLAIR MR image (**D**) obtained in a 14-year-old girl presenting with formal neuropsychological deficits following Ringette-related concussion. Features are consistent with nonhemorrhagic intraparenchymal contusion. All patients were advised to retire from contact and collision sports based on imaging findings. Panels C and D are reproduced from Ellis et al.: *J Neurosurg Pediatr 16:*241–247, 2015. Published with permission.

judicious use of CT scanning in the emergency room setting.[58,82] In contrast, evidence-based guidelines for the use of MRI, which avoids being exposed to ionizing radiation, in the evaluation and management of pediatric SRC patients are lacking. At present, expert consensus guidelines suggest that clinical MRI studies add little value to the evaluation of concussion patients but should be considered in patients with persistently altered level of consciousness (which is rare in sports injury) and those with focal neurological deficits and persistent symptoms, the duration of which is not well defined and can vary across age groups.[69] More recently, advancements in MRI techniques such as gradient recalled echo and susceptibility-weighted imaging that are more sensitive to iron-containing blood products have facilitated enhanced detection of microhemorrhages in children with moderate and severe TBI, but there are few studies that have examined the added clinical value of these sequences in pediatric SRC.[5,9,103] In a small retrospective study at our institution, we detected traumatic abnormalities in 11% of pediatric SRC patients who underwent clinical neuroimaging, including 2 patients with a nondisplaced calvarial skull fracture and orbital fracture demonstrated on CT and 2 patients with an intraparenchymal hemorrhage and nonhemorrhagic contusion demonstrated on MRI (Fig. 1C and D).[38]

Because clinical neuroimaging studies show normal findings in the vast majority of SRC patients, recent studies have applied numerous advanced neuroimaging techniques to this population including diffusion tensor imaging, task-based and resting-state functional MRI, resting cerebral blood flow imaging, and cerebrovascular reactivity mapping.[36,79,114] Although they have increased our insight into this condition, at present, none of the aforementioned techniques has advanced beyond research use to impact the routine clinical management of individual concussion patients.

Patients who have undergone craniotomy represent an important patient population who must be carefully considered for retirement from sports. Some authors suggest that any athlete who has undergone a craniotomy for evacuation of any intracranial hemorrhage should be considered for retirement,[93] while others suggest that athletes with subdural and epidural hematomas may be considered for RTP if the patient has normal findings on neurological examination, brain reexpansion, and radiographic evidence of bone flap healing.[28,76] One survey-based study of the American Association of Neurological Surgeons included 32 patients who underwent craniotomy, the vast majority (approximately 80%) of whom returned to sports between 3 months and 1 year postinjury.[91]

In addition to traumatic abnormalities, some authors have suggested that patients found to have other congenital and acquired structural abnormalities of the brain, including arachnoid cysts, hydrocephalus, cavum septum pellucidum, and Chiari malformations, should also be considered for sport retirement.[16,23,76,93] Arachnoid cysts arise from CSF accumulation within layers of the arachnoid and are a common incidental finding on neuroimaging.[1] In some cases, children with arachnoid cysts have been found to present with intraarachnoid cyst hemorrhage, subdural hematoma, or hygroma following sports-related head injury.[31,52,87,110] Bleeding associated with arachnoid cysts is thought to arise from fragile vessels within the cyst wall or bridging veins.[76] One recent retrospective study suggested that arachnoid cyst diameter of 5 cm or more was associated with a higher risk of hemorrhage/rupture in children.[26] Hydrocephalus accounts for an estimated 69,000 hospital discharges per year in the United States[11] and is most commonly treated with ventriculoperitoneal shunting or endoscopic third ventriculostomy.[55] In one survey of members of the Joint Section on Pediatric Neurosurgery of the American Association of

Neurological Surgeons and the Congress of Neurological Surgeons, the rate of shunt-related complications among pediatric hydrocephalus patients participating in sports was exceedingly low (< 1%) but may include shunt malfunction, damage to shunt hardware, and subdural fluid collections and hematomas.[10] Of pediatric neurosurgeons surveyed in this study, one-third advised against participation in all contacts sports, one-third advised against participation in selected sports, and one-third did not impose restrictions on sports participation. Cavum septum pellucidum is a normal congenital variant that is a common incidental finding on neuroimaging in children and can persist in up to 20% of adults.[111] Some authors have suggested that a cavum septum pellucidum is an absolute contraindication to return to sports[16] because of its previously observed association with other neuropathological and neuroimaging findings in patients with repeated head injury, while others have suggested that isolated cavum septum pellucidum should not preclude contact sports participation.[76] Finally, several authors have suggested that patients with symptomatic or pain-causing lesions at the level of the foramen magnum, including Chiari malformations, be considered for retirement from contact and collision sports.[20,76,93] These recommendations largely stem from rare reports of sudden death among patients with Chiari malformations exposed to minor head trauma, and from speculation that medullary compression could have accounted for these outcomes.[76] A recent retrospective cohort study, however, demonstrated an exceedingly low risk of future catastrophic injury during sports participation in children with Chiari I malformation, even after foramen magnum decompression.[72] Taken together, arachnoid cysts, cavum septum pellucidum, and Chiari malformations are all relatively common incidental findings on neuroimaging, and, as such, it is likely that a large number of children playing contact sports have these lesions but do not know it.

In our institutional opinion, all patients with evidence of a structural abnormality on neuroimaging should undergo consultation with a neurosurgeon to discuss decision-making options for RTP and retirement. As little is known about the clinical and genetic factors that place athletes at risk for the potential long-term consequences of SRC, we view traumatic brain abnormalities detected on clinical neuroimaging (CT, conventional MRI including recalled echo and susceptibility-weighted imaging) as an absolute contraindication to allowing the patients to return to contact and collision sports, especially when the patients have clinical or neuropsychological evidence of abnormal brain function or if they have required neurosurgical intervention. We acknowledge that there is no empirical evidence to support this recommendation and that others have documented successful RTP for professional athletes who have sustained an intracranial hemorrhage.[76] However, we believe pediatric patients warrant a more conservative approach and that there is little acceptable rationale to permitting a child or adolescent athlete with structural brain damage to return to an environment where the potential risk of additional injury exists. In our opinion, pediatric patients with basal and nondepressed calvarial skull fractures should be managed on an individualized basis and can often be returned to full sports participation after there is clinical and radiological evidence of fracture healing. Patients who have undergone previous craniotomy for nontraumatic lesions as well as those treated with endoscopic, endovascular, and transsphenoidal approaches are managed on an individualized basis and can often be returned to play without restriction. Because clinicopathological spectrum structural abnormalities such as Chiari malformation, arachnoid cyst, hydrocephalus, and septum pellucidum can present, we recommend patients with these conditions be managed by neurosurgeons on an individualized basis tailored to clinical and radiographic findings as well as available natural history data (Fig. 2). In our opinion, there is no empirical evidence to declare these conditions as absolute contraindications to safe contact sports participation in children and adolescents, but patients and their parents must be informed of rare reports of fatal and disabling outcomes related to RTP with these conditions (Table 1).

Abnormalities on Physical Examination

Illustrative Case 2

A 16-year-old boy with a history of 3 previous concussions sustained a head injury when he was thrown from his bike during a competitive motocross event. This injury was associated with a 4-minute loss of consciousness and posttraumatic amnesia lasting into the following day. The patient was transferred to a pediatric trauma center where he underwent CT brain and cervical spine imaging that demonstrated no abnormalities. Following the resolution of posttraumatic confusion, the patient began to complain of headache as well as diplopia that was worse when he looked downward. At the time of consultation 2 days postinjury, he continued to complain of diplopia when looking downward but endorsed no other concussion symptoms. Physical examination revealed a left trochlear nerve palsy but no other abnormalities. Neuro-ophthalmology consultation confirmed a left traumatic trochlear nerve palsy that was treated with prism glasses. Brain MRI demonstrated no evidence of structural brain injury. Graded aerobic treadmill testing elicited no symptom-limiting threshold at a maximal blood pressure of 214/86 mm Hg and maximal heart rate of 191 bpm suggestive of physiological recovery. However, formal neuropsychological testing revealed deficits in complex auditory attention, phonemic fluency, retrieval of auditory information, in the presence of intact processing speed, visual reproduction, and visual memory. His neurocognitive profile was suggestive of a subcortical pattern of cognitive deficits secondary to TBI. At 3 months postinjury the patient's diplopia had resolved and neuro-ophthalmological follow-up confirmed clinical resolution of the trochlear nerve palsy. Although the patient expressed interest in returning to competitive motocross sports, the multidisciplinary team advised him to retire from contact, collision, and motocross sports primarily due to the potential risk of repeat and permanent cranial nerve injury associated with repeat head trauma. Repeat neuropsychological testing to monitor neurocognitive recovery following SRC was declined by the patient and his parent.

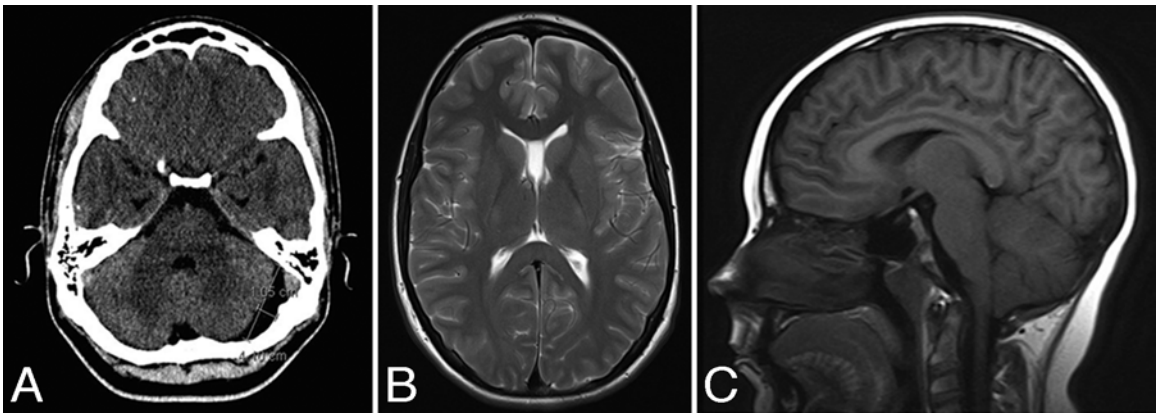

FIG. 2. Incidental structural brain abnormalities identified on neuroimaging in pediatric patients with sports-related concussion. **A:** Posterior fossa arachnoid cyst measuring 1.05 × 4.10 cm. **B:** Cavum septum pellucidum. **C:** Chiari I malformation with 7-mm tonsillar herniation below the level of the foramen magnum. All patients were returned to full sporting activities without restriction.

Discussion

Another important group of patients who should be considered for retirement from contact and collision sports are those who present with focal neurological deficits and abnormalities on physical examination.[16] Unlike the majority of generalized concussion symptoms that reflect global alterations in cerebral metabolism and blood flow,[45] focal neurological deficits often point to isolated damage or dysfunction within specific areas of the central or peripheral nervous system. Focal neurological deficits following SRC can often be localized by salient features of the clinical history and physical examination performed by a physician with clinical training in traumatic brain and spine injury. In this population, neuroimaging plays an important role not only in defining the extent of structural injury but also in the evaluation of other neurological disorders that can coexist with SRC and present with focal neurological deficits.[38,113] Understanding the pathophysiology of focal neurological deficits following SRC not only is important to allow physicians to initiate prompt, evidence-based management of underlying neurological conditions but also can be helpful in minimizing the risk of future or recurrent brain and spine injuries. In our experience, focal neurological deficits following pediatric SRC most commonly present as coexisting cranial nerve, cervical spine, or peripheral nerve injuries.

Visual disturbance is common following TBI and SRC and can arise from structural or functional injury to the oculomotor, vestibular, and visual processing systems of the brain. Subjective and objective evidence of vestibuloocular dysfunction can manifest in the form of convergence insufficiency, and abnormalities of smooth pursuits,

TABLE 1. Summary of our current institutional approach to RTP and retirement considerations in children and adolescents with structural brain abnormalities

Clinical Indication	Institutional Approach/RTP Consideration
Traumatic structural brain injury	Retirement from future contact & collision sports participation
Skull fractures & prior craniotomy for nontraumatic brain lesions	Individualized approach. RTP considered following radiographic evidence of bone healing
Craniotomy for traumatic lesions (e.g., subdural hematoma, intraparenchymal hemorrhage, second-impact syndrome)	Retirement from future contact & collision sports participation
Transsphenoidal, endovascular, endoscopic approaches to intracranial lesions	Individualized approach
Cavum septum pellucidum	No contraindication to safe RTP
Arachnoid cyst	Individualized approach. Patient must be informed of risk of intracystic hemorrhage, subdural hematoma/hygroma. RTP considered in patients w/ small, asymptomatic, or incidental arachnoid cysts (<5 cm) w/ no or minimal mass effect
Hydrocephalus	Individualized approach. Patient must be informed of risk of shunt malfunction, hardware damage, subdural hematoma/hygroma. RTP considered in patients treated w/ endoscopic third ventriculostomy
Chiari Type I malformation	Individualized approach. RTP considered for patients w/ asymptomatic or minimal tonsillar herniation w/ no syrinx. RTP considered in patients w/ foramen magnum decompression w/o associated spinal malformation & instability

saccades, and the vestibuloocular reflex that have been reported in 29%–63% of pediatric SRC patients.[35] These deficits are proposed to be mediated by isolated functional impairment of the vestibular and oculomotor subsystems that often resolve spontaneously and can be addressed with targeted vestibular rehabilitation.[3,37,92] On the other hand, visual disturbance associated with traumatic cranial nerve injury following pediatric TBI occurs less commonly and can have a variable prognosis. Trauma is the most common cause of acquired oculomotor, trochlear, and abducens nerve palsies in children, who often present with blurred vision and diplopia.[56] Traumatic optic neuropathy occurs in 0.5%–12% of TBI patients[24,97] with approximately 20% of pediatric cases due to sports-related injuries.[42,46] The clinical presentation of traumatic optic neuropathy can vary from subtle monocular blurred vision or visual field deficits to complete blindness. All patients with suspected cranial nerve injuries affecting vision should be promptly referred to a neuro-ophthalmologist for comprehensive assessment.[40] Although neuroimaging is commonly normal even in cases of severe cranial nerve deficits, these studies can also be helpful to rule out other conditions responsible for these deficits (neoplasm, inflammatory conditions, etc.).[38] The prognosis of traumatic cranial nerve palsies is largely dependent on the severity of injury at initial presentation. Most patients with traumatic optic, oculomotor, trochlear, and abducens neuropathies that present with mild deficits improve with conservative management, while those with complete injuries rarely experience a complete recovery.[42,46,63,88] Despite a relatively good prognosis, there are no evidence-based guidelines to help direct RTP and retirement decision making in these populations. Nevertheless, because of the potential risk of recurrent injury and the significant disability associated with permanent injury, it has been our institutional approach to recommend retirement from contact and collision sports in all pediatric SRC patients presenting with traumatic cranial nerve palsies even after clinical recovery has been achieved.[40]

Children and adolescents with SRC can also present with focal neurological deficits due to coexisting acute spinal cord injury (SCI), central cord neurapraxia, SCI without radiographic abnormality (SCIWORA), and nerve root/brachial plexus traction injuries. Distinguishing between these conditions requires a careful history, complete neurological and spine physical examination, and the appropriate use of neuroimaging that may include plain and dynamic radiography, CT, and MRI. Clinical presentation of pediatric SCIs can range from subtle unilateral motor or sensory deficits to complete quadriplegia. In some cases, children and adolescents can sustain injury to spinal column that presents with localized pain and decreased range of motion but without neurological deficit. Similar to RTP and retirement recommendations regarding SRC, guidelines for cervical spine injuries are also controversial and derived from retrospective studies of collegiate and professional adult athletes. Patients who sustain an acute SCI with evidence of a spinal cord structural injury are typically advised to retire from contact and collision sports.[6] Adult patients with stable fractures without neurovascular injury can often be returned to full athletic competition after radiographic confirmation of bone healing, return of full and painless range of motion, and a normal neurological examination.[85] In certain cases, retirement from contact sports should be considered; this would include retirement for individuals with atlantoaxial instability or fusion, and dynamic subaxial instability indicated by greater than 3.5 mm translation or greater than 11° of angulation on radiographic imaging.[2,6,85,112] Some authors have suggested that adult patients treated with 1-level anterior or posterior instrumented fusions can be cleared for RTP, with patients who have undergone multilevel instrumented fusions considered for sports retirement.[19,85,108] Others have reported safe return to contact sports of patients with multilevel fusions and evidence of spinal cord signal change on MRI.[101] Because these types of injuries are rare in children and adolescents and because RTP and retirement guidelines do not exist for these populations, we recommend that patients with confirmed structural cervical spine and spinal cord injuries be managed on an individualized basis by neurosurgeons and orthopedic surgeons with experience in pediatric spine injuries. In our opinion, children and adolescents who have sustained a structural SCI and those who have undergone spinal fusion with instrumentation should be considered for retirement from contact and collision sports.

In our experience, more common than patients presenting with fixed neurological deficits and structural SCI at the time of SRC are those who experience transient neurological deficits with variable clinical examination findings and normal imaging features. Again, distinguishing between underlying conditions in this setting depends on a careful assessment of the presenting symptoms; the location, nature, and duration of associated sensorimotor deficits; a history of previous neurological events, trauma, or spinal disorders; and complete neurological and spine examinations. Central cord neurapraxia, cervical SCIWORA, and nerve root/brachial plexus injuries are conditions that can present with transient focal neurological deficits and can coexist in patients with SRC. The clinical presentation of central cord neurapraxia and cervical SCIWORA can range from subtle neurological symptoms such as burning or tingling in one or both upper extremities to complete quadriplegia. Spinal canal stenosis, defined as a canal-body ratio of 0.8 or less, has been observed in up to 95% of reported cases of central cord neurapraxia.[106] Owing to unique anatomical and biomechanical features of the developing spine, SCIWORA occurs predominantly in children and adolescents, accounting for 67% of traumatic spine injuries, with 43% of cases occurring during sporting activities.[12] In contrast, patients with "burners" or "stingers" typically present with unilateral burning pain that radiates from the neck down the arm in a dermatomal distribution, and these injuries can be associated with motor weakness of muscles innervated by the affected nerve root(s). Central cord neurapraxia is typically defined as the presence of myelopathic symptoms that resolve within 10 minutes to 48 hours of the injury, while symptoms of SCIWORA can persist for hours to weeks after injury. All patients with suspected central cord neurapraxia or SCIWORA should undergo structural imaging including MRI and plain and flexion-extension radiography, while

the diagnosis of burners and stingers can usually be made clinically. Unlike central cord neurapraxia where symptoms resolve within 48 hours, the prognosis of SCIWORA is more variable and dependent on the severity of the initial neurological deficits[81,84] and the presence of structural changes on MRI.[83]

Return-to-play recommendations for these 3 conditions also vary across sources. Some authors have suggested that athletes with a single episode of central neurapraxia can be safely returned to play as long there are no neurological deficits and no radiological evidence of SCI or spinal stenosis;[104,109] however, those with a second episode should be advised to retire.[85,89,104] In one study, recurrent episodes of central cord neurapraxia in athletes returned to sporting activities occurred in 56% of cases, but no athlete suffered permanent neurological injury.[105] Patients with central cord neurapraxia and MRI evidence of structural SCI are often advised to retire.[6,104] Patients with asymptomatic or incidentally discovered cervical stenosis are often managed on an individualized basis and informed of the potential risk of SCI associated with a return to contact sports.[19] RTP management in patients with SCIWORA remains controversial. Some authors have suggested that SCIWORA is associated with occult spinal instability that precludes a return to contact or collision sports,[84,86] while others have suggested that there is insufficient evidence to support persistent spinal instability in this population.[12] In patients presenting with nerve root/brachial plexus injuries,[53] some authors have suggested that those with 1 or 2 episodes can be returned to play following complete resolution of symptoms and a normal neurological examination,[107] whereas those with 3 or more episodes should be withheld from sports pending the results of cervical spine neuroimaging to rule out predisposing conditions (e.g., foraminal stenosis or disc herniation) and electrodiagnostic studies to confirm neurophysiological recovery.[85]

Because there is a lack of empirical evidence to guide clinical decision making, we view pediatric patients with transient or focal neurological deficits localized to the cervical spine and occurring in the absence of abnormalities on comprehensive imaging to represent a unique population whose care must also be individualized. In our experience, children and adolescents with coexisting SCIWORA who present with transient or subtle neurological deficits in the setting of a normal imaging workup can be returned to contact sports without increased risk of future injury.[39] However, individuals with more severe and prolonged deficits and whose imaging workup demonstrates evidence of cervical spine stenosis (anteroposterior cervical canal diameter < 14 mm, Torg ratio < 0.8) or other congenital spine malformations that may confer a risk of instability (e.g., Type I Klippel-Feil syndrome, os odontoideum, atlantooccipital fusion, etc.)[104] should be considered for retirement from contact and collision sports (Fig. 3). Patients with coexisting nerve root/brachial plexus injuries must also be managed on an individualized basis following appropriate clinical and imaging evaluation to rule out structural cervical spine injuries. In all of these circumstances, patients and their parents must be informed of the elevated risk of recurrent injury with return to contact and collision sports (Table 2).

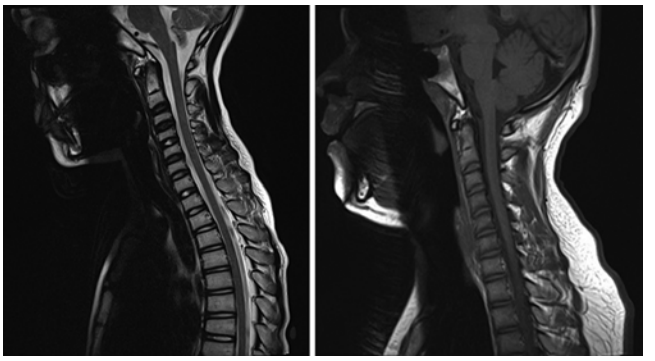

FIG. 3. SRC patients with coexisting SCIWORA and central cord neurapraxia. **Left:** Sagittal T2-weighted MR image obtained in a 13-year-old presenting with hockey-related concussion and 6-week period of bilateral hand numbness and sensory deficit. The image demonstrates no evidence of SCI, ligamentous injury, or spinal stenosis. This patient was successfully returned to contact sport (hockey) following symptom resolution, normal neurological examination, full and painless range of motion, and evidence of normal findings on flexion-extension radiographs without further injury. **Right:** Sagittal T2-weighted MR image acquired in a 17-year-old child with SRC and transient upper- and lower-extremity numbness and weakness following a tackle in football. The image demonstrates congenital cervical spinal stenosis (cross-sectional anteroposterior canal diameter at C-3 measuring 12 mm) and loss of cervical lordosis. This patient with coexisting central cord neurapraxia and spinal stenosis was advised to retire from contact and collision sports due to elevated risk of future SCI.

Cumulative or Prolonged Effects of Concussion

Illustrative Case 3

A 15-year-old boy with a history of migraine headaches and 2 prior SRCs sustained an injury from a head-to-head tackle during a football game; he did not lose consciousness or suffer posttraumatic amnesia. He underwent consultation at the pediatric concussion program 1 month postinjury, at which time he complained of headaches, dizziness, and difficulties with focusing, concentrating, and memory. His initial Post-Concussion Symptom Scale score[57] was 70. Initial physical examination revealed a near point of convergence of 10 cm, symptomatic horizontal saccade testing, and impaired balance testing. The patient underwent aerobic treadmill testing, the results of which were consistent with a diagnosis of physiological postconcussion disorder, and brain MRI, for research purposes, revealed no structural injury. The patient's vestibulooocular dysfunction resolved spontaneously, and submaximal exercise was prescribed. Three months later the patient's symptoms had improved significantly (Post-Concussion Symptom Scale score of 15) and he underwent formal neuropsychological testing. Testing revealed deficits in complex attention span, divided attention, and encoding of unstructured auditory information in the setting of otherwise normal cognitive processing. The results were suggestive of cognitive changes secondary to concussion. The patient continued to be managed with submaximal aerobic exercise prescription and 5 months later underwent repeat treadmill and neuropsychological testing. At that time, 9 months postinjury the patient was capable of exercising to

TABLE 2. Summary of our current institutional approach to RTP and retirement considerations for children and adolescents presenting with focal neurological deficits and physical examination abnormalities

Indication	Institutional Approach/RTP Considerations
Traumatic cranial neuropathy	Retirement from future contact & collision sports participation
Structural acute SCI	Retirement from future contact & collision sports participation
Spinal column fractures w/o neurological deficit & spinal instrumentation	Individualized approach. RTP considered for patients w/ radiographic evidence of fracture healing & spinal column stability, full & painless range of cervical spine motion
Spinal column fractures w/ spinal instrumentation	Retirement from future contact & collision sports
Central cord neurapraxia/SCIWORA	Individualized approach. First event: RTP considered for children w/ mild & short-duration symptoms & normal neurological exam, full & painless range of cervical spine motion, & no evidence of spinal stenosis or instability. Patients must be informed of increased risk of recurrent & potentially disabling injury. For patients w/ imaging evidence of spinal stenosis/spinal instability: Retirement from future contact & collision sports. Second event: Retirement from future contact & collision sports
Asymptomatic or incidental cervical stenosis	Individualized approach. Patients must be informed of increased risk of temporary neurological deficits & potentially disabling SCI
Nerve root/brachial plexus injuries	Individualized approach. First event: RTP considered in asymptomatic children w/ normal neurological exam. Patients must be informed of increased risk of recurrence in presence of foraminal stenosis. Second event: Retirement from future contact & collision sports participation

exhaustion during treadmill testing and neuropsychological testing results had returned to normal. Because of the patient's concussion history and prolonged clinical course with associated objective cognitive deficits, the decision was made to proceed with retirement from competitive football.

Discussion

The most challenging group of patients to manage, from a retirement-from-sport perspective, are those who had prolonged symptoms and in whom the cumulative effects of multiple concussions are suspected or demonstrated. Over the past decade, mounting evidence suggests that concussions and subconcussive head injuries can have a cumulative effect on short- and long-term neurological health and functioning. In the short term, clinical research suggests that athletes with a history of concussions are significantly more likely to sustain future concussions[50] and present with more severe symptoms.[22] In the long term, some evidence suggests that retired professional football players with a history of repetitive head trauma are at an elevated risk of depression, mild cognitive impairment, and earlier onset of Alzheimer's disease.[48,49,54] One study demonstrated an elevated risk of death due to Alzheimer's disease and amyotrophic lateral sclerosis among professional football players compared with a healthy population.[62] Importantly, other authors have failed to identify alterations in cognitive functioning in collegiate athletes with multiple concussions.[14] In addition to multiple concussions, research has begun to suggest that cumulative exposure to subconcussions, defined as "a cranial impact that does not result in known or diagnosed concussion," can lead to neurocognitive deficits and structural and functional brain abnormalities detected on advanced neuroimaging studies.[7] Chronic traumatic encephalopathy (CTE) is a neurodegenerative condition characterized neuropathologically by gross features such as enlarged lateral ventricles; a fenestrated cavum septum pellucidum; scarring of the cerebellar folia; atrophy most often affecting the frontal and medial temporal lobes, thalamus, hypothalamus, and mammillary bodies; and degeneration of the substantia nigra and locus coeruleus. Histological features include glial and neuronal deposition of hyperphosphorylated tau with a perivascular distribution or localization at the depths of cortical sulci.[70,97] The clinical manifestations of chronic traumatic encephalopathy often present as 2 variants.[96] Athletes with the cognitive variant present primarily with memory and executive function impairments, while those with the mood/behavioral variant often present with symptoms of depression and anxiety as well as aggressive, violent, or disinhibited behavior. To date, the majority of published cases of CTE have occurred in collegiate and professional athletes who have retired from careers in boxing, American football, and hockey;[44,65] however, a limited number of cases of CTE have been also reported among adolescents with a history of repetitive head trauma.[71] While some authors continue to point out the lack of empirical evidence supporting a causal relationship between TBI and CTE,[29,44,94] there does appear to be empirical justification to actively limit individuals' exposure to concussions and subconcussive head injuries during a period of active brain development in children and adolescents.

Despite these concerns, there are no evidence-based guidelines that address how many total concussions are too many, how many concussions incurred in 1 season are too many, and what impact abnormalities on objective measures such as formal neuropsychological testing should have on retirement decision making. Historically, it was suggested that athletes who sustained 3 concussions associated with a loss of consciousness should take a season off before returning to sports.[102] These recommendations were later incorporated into the Colorado Medical Society/American Academy of Neurology and Cantu

grading systems to guide RTP decision making.[4,15,17,66] More recently, some authors have suggested that athletes be considered for retirement in the following scenarios: those who have sustained 3 or more concussions in 1 season, those who have sustained 2 major concussions in a season, those who have sustained 3 or more major concussions, those with evidence of a lowered threshold for concussions, those who developed objective evidence of impaired neuropsychological functioning, and those who exhibit symptoms of CTE.[16,20,23,93] Although symptoms of CTE are rare among the pediatric SRC population, children and adolescents can develop postinjury psychiatric outcomes that are often multifactorial in etiology and can take the form of novel psychiatric disorders, isolated suicidal ideation, or worsening symptoms of a preinjury psychiatric disorder.[41] To date, the majority of published case reports on the retirement decision-making process in the setting of multiple concussions and prolonged recovery are limited to discussions regarding collegiate and professional athletes.[16,43]

The RTP and retirement decision-making process regarding pediatric SRC patients with prolonged recovery is challenging due to our incomplete understanding of what constitutes a normal recovery in children and adolescents. Although most collegiate and professional athletes will achieve neurological and neurocognitive recovery within 1–2 weeks, the natural history of pediatric SRC remains poorly understood. Among studies of pediatric concussion patients, the median duration of symptoms varies from 25 to 75 days,[13,25,35] with 21%–73% of patients reporting symptoms persisting greater than 1 month[25,34,47,75] in duration and 2.3% reporting symptoms at 1 year postinjury.[8] Because of the wide variability in mean recovery time following pediatric SRC in the literature, the distinction between a major and a minor concussion is not particularly relevant to this patient population. Clinical variables that may impact the likelihood of prolonged symptoms in concussion patients include younger age, female sex, loss of consciousness or posttraumatic amnesia at the time of injury, a history of concussion, attention-deficit hyperactivity disorder, learning disorder, mood disorders, delayed symptom onset, postinjury headache or dizziness, as well as symptom burden and subjective and objective evidence of vestibuloocular dysfunction at initial consultation.[25,35,59,61,64,74,75,77]

Overall, RTP and retirement decision making regarding pediatric patients with prolonged postconcussion syndrome (PCS; > 3–6 months) and multiple concussions must also be individualized. It is in this population that a multidisciplinary approach is most important and should always involve a clinical neuropsychologist who is the only health care professional with certified training in the administration, interpretation, and psychometrics of comprehensive neuropsychological testing.[32,33,78,90] Even with a certified neuropsychologist, however, there is a paucity of evidence regarding how computerized neurocognitive and formal neuropsychological testing should be used in the pediatric SRC population.[30] Neuroimaging can also be helpful to evaluate whether there are any structural findings that may contribute to a prolonged recovery or neuropsychological deficits.[38] At present, there is insufficient empirical data to mandate sports retirement in pediatric patients based on the duration of PCS symptoms, total number of lifetime concussions, or number of concussions sustained over any given time period. There is also no empirical evidence to establish thresholds of concussions or subconcussive injuries that places children and adolescents at an elevated risk of developing mental health disorders, persistent neuropsychological deficits, or neurodegenerative conditions such as CTE. Given these knowledge gaps, the retirement discussion with pediatric SRC patients and their parents must acknowledge the lack of evidence upon which to base firm recommendations. Nonetheless, because there is some evidence that points to increased vulnerability to future and more severe concussions among athletes with previous concussions, we advise all pediatric SRC patients and their parents that sustaining a single SRC may place the child at an elevated risk of future concussions that can occur with less force and may lead to more prolonged symptoms.[100] In our patients, those who sustain 2 or more concussions in a season and those who develop prolonged PCS (> 3–6 months) are often strongly advised to take the rest of the season off of contact sports. In pediatric patients who have sustained 4 or more lifetime, physician-diagnosed concussions, we generally strongly consider contact sport retirement, with those patients with 3 concussions managed on an individualized basis. Patients who exhibit persistent neurocognitive deficits on objective neuropsychological testing are not cleared for return to sport until a return to full-time academic studies is achieved and a return to baseline cognitive functioning is identified. Those who develop postinjury psychiatric outcomes represent a unique population whose management must also be individualized. At present, it remains unclear whether the pathophysiological mechanisms mediating these outcomes represent an unrecovered TBI and place patients at an elevated risk of concussion if returned to play even if controlled on psychiatric medications. As such, we consider multiple factors including preinjury psychiatric history, severity of symptoms, and neuropsychological testing and neuroimaging results when making recommendations to these patients. Finally, because of the lack of evidence-based guidelines regarding sport retirement decision making and lack of a gold standard objective test to determine physiological concussion recovery, it is our clinical practice to perform graded aerobic treadmill testing and formal neuropsychological testing prior to returning the following to contact and collision sports: all pediatric patients with prolonged PCS (> 3 months), those who have sustained 2 or more concussions in a single season, those who have sustained 3 or more total concussions, and those who develop postinjury psychiatric disorders. Although we acknowledge that viewpoints may differ among concussion health care professionals and from center to center, we believe these recommendations represent a more conservative approach to treating child and adolescent patients and reflect the limitations of current empirical evidence (Table 3).

Conclusions

Decision making regarding RTP and retirement from sport remains a persistent challenge for physicians and

TABLE 3. Summary of our current institutional approach to RTP and retirement considerations for children and adolescents with evidence of cumulative or prolonged effects of concussion

Clinical Indication	Institutional Approach/RTP Considerations
Two concussions in 1 season	Strongly considered indication for season-ending retirement. Consider RTP during the following season following symptomatic recovery, graded aerobic treadmill, & formal neuropsychological testing
Three lifetime concussions	Individualized approach. Consider RTP during the following season after symptomatic recovery, graded aerobic treadmill, & formal neuropsychological testing
Four or more concussions	Individualized approach. Strongly considered an indication for retirement from future contact & collision sports
Prolonged PCS (>3–6 mos)	Strongly considered an indication for season-ending retirement. Consider RTP during the following season after symptomatic recovery, graded aerobic treadmill, & formal neuropsychological testing
Persistent cognitive deficits on formal neuropsychological testing	Individualized approach. Follow-up formal neuropsychological assessment to monitor recovery. Consider RTP following symptomatic recovery, full return to school participation, & graded aerobic treadmill & formal neuropsychological testing
Postinjury psychiatric outcomes	Individualized approach. Must consider preinjury psychiatric history, severity of symptoms, & neuropsychological, aerobic treadmill testing, & neuroimaging results

health care professionals who manage pediatric SRC patients. At present, there are no evidence-based guidelines directing the care of pediatric SRC patients with structural brain abnormalities, focal neurological deficits, and abnormalities on physical examination, and those in whom the cumulative or prolonged effects of repetitive brain injury are suspected or demonstrated. Given these limitations, patients in this population are ideally approached by a multidisciplinary team of experts with clinical training and experience in pediatric TBI. In the future, this decision-making process would benefit from the development of novel neuroimaging tools capable of identifying the pathophysiological effects of concussion in individual patients and from research aimed at identifying risk factors associated with the development of adverse short-term outcomes such as PCS, postinjury psychiatric outcomes, and prolonged neurocognitive impairment following pediatric SRC. In addition, prospective and population-based studies are needed to reliably estimate the risk of serious long-term outcomes such as the development of neurodegenerative disease and CTE among child, adolescent, and adult athletes exposed to multiple concussions and repetitive head injury. Until such data are available, RTP and sport retirement decision making regarding children and adolescents must err on the side of caution and we must make every effort to preserve the long-term health of the patient.

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Disclosures

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Author Contributions

Conception and design: Ellis, McDonald, Ritchie. Acquisition of data: all authors. Analysis and interpretation of data: all authors. Drafting the article: Ellis, McDonald, Ritchie. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Ellis.

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