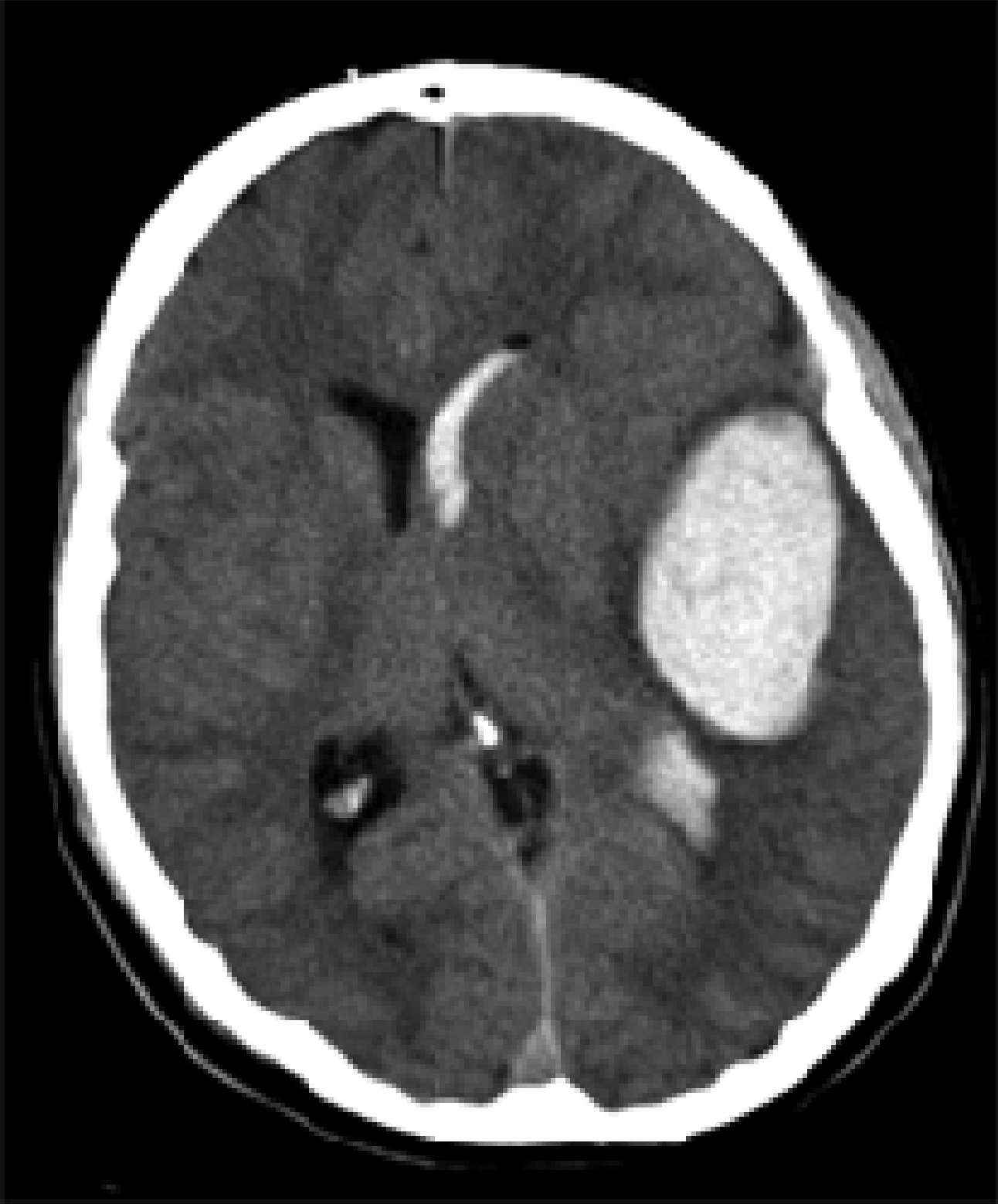

Introduction

Mild traumatic brain injury

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This issue of *Neurosurgical Focus* addresses the management of mild traumatic brain injury (TBI) in children and adults, including hospital, outpatient, and community settings. Much is yet to be elucidated about even basic physiology underlying secondary injury processes in this particular population, in part due to the relatively benign clinical picture with which many patients present in emergency hospital settings. Furthermore, many patients suffering mild TBI are never involved in organized health care delivery, making the identification of concussion and education regarding diagnosis and management important endeavors for those in neurosurgery.

This issue begins with a focus on biochemical and neurochemical sequelae of mild TBI. Dr. Signoretti and colleagues have provided an in-depth review of the literature and summary of the experimental body of work from a 12-year group study on mild TBI, along with the clinical implications of their research conclusions. The utility of protein S100B measurements in the treatment of children with mild TBI is subsequently reviewed by Filippidis et al., highlighting the importance of identifying biomarkers to aid in prognostication and management of TBI in this special population.

As our society is attempting to grapple with the cost- and comparative-effectiveness research results in an era of health care reform, assessments of the socioeconomic impact to patients and society are critical. To evaluate triage criteria and formulate bases for decisions regarding utilization of resources, Dr. Carlson and colleagues conducted a retrospective review to identify the rate of delayed deterioration requiring surgical treatment in cases of mild TBI in which patients were transferred to a tertiary care center.

Finally, given the frequent representation of mild TBI in sports, studies of brain-injured athletes are of particular interest. We are introducing a series of articles related to concussion in junior league hockey players in Canada. In a prospective observational study, Echlin and associates noted an increase in reported concussions and medical evaluations of athletes after placing trained observers in the stands and instituting an evaluation and return-to-play protocol. Additional work is presented that examines compliance with protocols by athletes, their support systems, and athletic organizations; duration between concussion and return to play as well as the influences on decision making; and obstacles to injury-prevention education.

After review of these manuscripts, the reader will have additional understanding of the pathophysiological underpinnings of neurological, cognitive, and behavioral deficits after mild TBI, as well as the complexities involved in the conduct of research in this area. Additionally, in Dr. Echlin's accompanying editorial, the reader will gain insight into some of the social factors that influence treatment seeking and medical management of concussion and mild TBI. *(DOI: 10.3171/2010.11.FOCUS.Intro)*

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Biochemical and neurochemical sequelae following mild traumatic brain injury: summary of experimental data and clinical implications

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Although numerous studies have been carried out to investigate the pathophysiology of mild traumatic brain injury (mTBI), there are still no standard criteria for the diagnosis and treatment of this peculiar condition. The dominant theory that diffuse axonal injury is the main neuropathological process behind mTBI is being revealed as weak at best or inconclusive, given the current literature and the fact that neuronal injury inherent to mTBI improves, with few lasting clinical sequelae in the vast majority of patients.

Clinical and experimental evidence suggests that such a course, rather than being due to cell death, is based on temporal neuronal dysfunction, the inevitable consequence of complex biochemical and neurochemical cascade mechanisms directly and immediately triggered by the traumatic insult.

This report is an attempt to summarize data from a long series of experiments conducted in the authors' laboratories and published during the past 12 years, together with an extensive analysis of the available literature, focused on understanding the biochemical damage produced by an mTBI.

The overall clinical implications, as well as the metabolic nature of the post-mTBI brain vulnerability, are discussed. Finally, the application of proton MR spectroscopy as a possible tool to monitor the full recovery of brain metabolic functions is emphasized. *(DOI: 10.3171/2010.9.FOCUS10183)*

Key Words • **mild traumatic brain injury** • **N-acetylaspartate** • **concussion** • **brain energy** • **metabolism** • **oxidative stress**

At present, TBI is a major public health concern and a leading cause of disability worldwide.[8] In European countries, the annual incidence of TBI is estimated at between 100[89] and 1967 per 100,000[90] persons, with mild and moderate TBI accounting for 80%–95% and severe TBI accounting for about 5%–20% of all cases. It has been calculated that the ratio of the occurrence of mTBI to that of sTBI is approximately 22:1.[74] In the US, 1.5–8 million people per year suffer from TBI ranging from mild to severe.[8] A proportion of these patients ranging from 75% to 90% is classified as mildly injured.

These wide ranges of annual incidence are probably due to the fact that an unknown proportion of mTBI victims do not seek any medical attention, but it might also be due to the fact that there is still confusion and inconsistency among researchers and organizations in defining and understanding this type of trauma.[15,23]

Mild TBI has, indeed, too many synonyms, including brain concussion, mild head injury, minor head injury, and minimal TBI.[41,49] Even the terms "head" and "brain" have been used interchangeably.

Historically, the most often used system for grading the severity of craniocerebral trauma is the Glasgow Coma Scale (GCS), which permits 120 possible mathematical combinations of eye, verbal, and motor scores, and contains rather crude scoring categories. We all know that different patients with the same GCS score of 15 may not function at the same level.

Given the limitations of the GCS, other parameters,

Abbreviations used in this paper: ADP = adenosine diphosphate; AMP = adenosine monophosphate; ATP = adenosine triphosphate; GCS = Glasgow Coma Scale; GDP = guanosine triphosphate; GMP = guanosine monophosphate; GTP = guanosine triphosphate; HPLC = high-performance liquid chromatography; mTBI = mild TBI; NAA = *N*-acetylaspartate; NAD^+ = nicotinamide adenine dinucleotide; NADH = reduced NAD^+; NADP = NAD^+ phosphate; NADPH = reduced $NADP^+$; RNS = reactive nitrogen species; ROS = reactive oxygen species; SIS = second impact syndrome; sTBI = severe TBI; TBI = traumatic brain injury.

like posttraumatic amnesia and loss of consciousness, have been increasingly scrutinized during the past 10 years. Loss of consciousness was no longer considered a necessary condition for the diagnosis of mTBI, and there was soon a general agreement among experts that the criterion of posttraumatic amnesia must be used with great care because it may be easily under- or overestimated. Therefore, there currently are no objective biological measures to determine the degree of severity of the neuropathology of this condition.

Conversely, the general view that mTBI is a very common entity but should not be considered a very serious injury, leading only to transient disturbances, is mainly supported by the absence of structural brain damage on traditional neuroimaging. If mTBI was as "mild" as we might think, it would be difficult to explain the actual complex management of these patients, which may involve various health care professionals, including family doctors, behavioral psychologists, clinical psychologists, neuropsychologists, neurologists, psychiatrists, neuroophthalmologists, neurosurgeons, physiatrists, nurses, occupational therapists, and physical therapists. Furthermore, long beyond the typical recovery interval of 1 week to 3 months, at least 15% of persons with a history of mTBI continue to see their family physician because of persistent problems.[2,7,31,34,37] Because of such enormous social impact, the number of literature reports addressing many different clinical aspects of mTBI has grown annually during the past 2 decades.

The problem is that to date, due to the formidable challenge of studying this type of cerebral damage in the laboratory, most of the reported experimental data have been obtained in more severe levels of injury, with very little information on the biochemical modifications occurring in mild injury as a function of time after impact. It appears clear that the biochemical and molecular processes triggered by mTBI, where hardly any discernible cell death occurs, are likely to be, at least in part, different from those present following severe injury.

This report is an attempt to recap the results of a series of previously published experiments produced during the past 12 years by a single group of investigators, all focused on understanding the pathophysiology of a "mild" injury to the brain, where apparently there is nothing "obviously" harmful. These findings have been further discussed in light of the most recent findings from other laboratories worldwide.

The "Perfect" Model and the Evidence of "Immediate" Biochemical Damage

For many years, research groups have attempted to provide a clinicopathological correlation to the existence of primary (mechanical) and secondary (delayed, nonmechanical) damage. Two main stages were identified in the development of posttraumatic sequelae: 1) primary damage, occurring at the time of injury, directly responsible for discrete, "focal" anatomical lesions, such as laceration, contusion, and intracranial hemorrhage, and for diffuse axonal injury; and 2) secondary damage, produced by complex processes, initiated at the moment of injury, but which do not present clinically for a period of hours to days. These mainly include damage due to ischemic phenomena, swelling, edema, and alteration of the brain's major endogenous neurochemical mechanisms.

Much of this core of knowledge was obtained by virtue of complicated animal models, such as fluid percussion,[18,51] cortical impact,[17] or the cryogenic focal brain injury model,[40] producing a focal brain contusion[14,47] very similar to those observed in clinical conditions. However, where the basis of these lesions could be determined with a good degree of certainty, it was more difficult to be confident about the nature of the diffuse damage in patients who can present with the widest range of neurological disturbances up to a coma but with minimal or no evidence of intracranial lesions.

A number of clinical and laboratory studies reported over the past 2 decades have now established that the principal mechanism of diffuse brain damage after trauma is due to acceleration/deceleration injury, resulting in unrestricted movements of the head and leading to shear, tensile, and compressive stress. Still, knowledge about changes in cell homeostasis after this type of injury was more difficult to obtain, mainly because of challenges related to modeling the exact circumstances in the laboratory.

In 1994 Marmarou and coworkers[26,48] set up a rodent "closed" head injury model characterized by pronounced diffuse brain damage, the severity of which was modulated by the impact force acting on the skull. Although brain injury was thoroughly characterized in many neuropathological aspects, at that time, there was virtually no information on the biochemical modifications, particularly in the mild injury model. Furthermore, it was not yet clear if trauma per se was responsible for such changes or if they were a consequence of the onset of ischemic-hypoxic phenomena successively occurring following head impact.

The initial efforts from these laboratories were focused on study of the time course of changes of several metabolites representative of the cell energy state (high-energy phosphates, nucleosides, oxypurines, nicotinic coenzymes) and of the occurrence of oxidative stress, a phenomenon defined as an overproduction of ROS from different intra- and extracellular sources[36,71] and leading to a decrease of antioxidant cell defenses with consequent irreversible modification of biologically important macromolecules.[53,91] Reactive oxygen species–mediated damage is mainly characterized by the onset of lipid peroxidation and revealed by measuring tissue malondialdehyde (MDA). For a better understanding of the phenomenon we evaluated the aforementioned parameters from 1 minute to 120 hours after the induction of mTBI both in spontaneously breathing and in mechanically assisted rats.[83]

It was surprising that, starting from 1 minute after trauma, the MDA level progressively increased up to the second hour, when its maximum concentration was recorded. Relatively high levels of this compound, originating from decomposition of peroxidized membrane phospholipids, still persisted at 24 and 48 hours after trauma. It is worth emphasizing that, as previously reported,[45,87] MDA is undetectable under normal conditions. Interestingly, oxidation of ascorbate (the main water-soluble brain antioxidant) paralleled MDA production, although

the minimum ascorbate value was observed 6 hours after trauma, showing a 60% decrease with respect to controls. Comparison of MDA and ascorbate concentrations of spontaneously breathing rats with those of mechanically ventilated rats did not show any statistically significant difference.

Similarly, with respect to values in controls, the levels of ATP and GTP were significantly reduced at 2 hours after cerebral injury, showing their lowest concentrations at 6 hours postinjury. Consequently, their dephosphorylation products showed an opposite trend, with the highest values of ADP, AMP, GDP, and GMP determined after 6 hours. Due to the imbalance between ATP production and ATP consumption, also inosine monophosphate (IMP), oxypurines (hypoxanthine, xanthine, and uric acid), and nucleosides (inosine and adenosine) were subjected to changes as a function of time. Particularly interesting were the 5- and 7-fold increases of xanthine and uric acid, respectively, thus suggesting the activation of xanthine oxidase, which is generally considered one of the major sources of superoxide anion production. Finally, nicotinic coenzymes (NAD^+ + NADH and $NADP^+$ + NADPH) were found to be profoundly affected in the time interval between the 2nd and 24th hours after trauma—that is, for a much longer time than that observed for other energy-linked metabolites. Comparison of all parameters related to energy metabolism of spontaneously breathing and mechanically ventilated animals did not show any statistically significant difference. Therefore, it could be affirmed that no ischemic or hypoxic episodes of any relevance occurred within the monitoring time in our mildly injured rats and that the force acting at the time of impact was directly responsible for triggering energy metabolism imbalance, ROS production, and, consequently, lipid peroxidation.

In this regard, Smith et al.[70] have reported that, in the model of unilateral cortical impact head injury, maximal amounts of hydroxyl radicals (which are the most oxidizing and reactive ROS) are produced within 5 minutes after induction of cerebral damage. They also reported a significant increase of phosphatidylcholine hydroperoxide at the same time point. Once the lipid peroxidation reaction chain is initiated, it propagates spontaneously, as indicated by the maximum level of MDA recorded 2 hours after impact, when no more radicals should be produced. The concomitant significant ascorbate depletion supported the existence of a remarkable oxidative stress following mTBI, which can be explained either with the direct oxidizing action of ROS on ascorbate, or with its utilization in the redox cycling of α-tocopherol (vitamin E), which represents the only membrane-bound lipid-soluble compound capable of breaking the lipid peroxidation reaction chain.[62]

The temporal difference between the onset of oxidative stress and the depression of energy metabolism, both occurring without cerebral conditions of ischemia or hypoxia, was indeed intriguing. In fact, it is highly probable that ROS-mediated lipid peroxidation involves not only the plasma membrane but also the mitochondrial membrane, thereby producing a dysfunction with inhibition of reactions linked to energy production. The slow recovery of the cellular energy metabolism could also be attributed to the drastic decrement of the nicotinic coenzyme pool that would certainly have jeopardized all the oxidoreductive reactions, including those related to the cell energy supply. Several other models of increased oxidative stress have demonstrated that the nicotinic coenzyme pool undergoes a significant depletion, although no valid explanation of this phenomenon had been given.[33,35,56,81] It was demonstrated that NADH and NADPH can be subject to direct ROS attack, which is responsible for the partial irreversible degradation of the coenzymes into ADP-ribose and ADP-ribosephosphate, respectively.[76,77] It could be hypothesized that such ROS-mediated nicotinic coenzyme degradation might be operative immediately after trauma. In rats subjected to this type of mTBI, however, most biochemical parameters returned to almost physiological levels within 1–5 days, thus confirming the "mild" severity level of this experimental model.

The overall evidence from these studies suggested that the traumatic insult, albeit mild, is directly responsible for sudden biochemical changes, triggered immediately, and for the subsequent depression of brain energy metabolism.

This hypothesis was more recently examined by Wu and colleagues[93] in a study concerning synaptic plasticity and cognitive function in the hippocampus following mTBI. The results showed that oxidative stress was clearly implicated in the dysfunction of energy metabolism, and the post-mTBI "energy crisis" compromised synaptic plasticity and cognitive function with subsequent synaptic and cognitive deficits.

N-Acetylaspartate: A Surrogate Marker of Neuronal "Health"

Two fundamental findings brought *N*-acetylaspartate (NAA) to the attention of neuroscientists in general, dramatically accelerating the pace of research into the neurochemistry and neurobiology of this unique molecule.[55] The first of these findings was that NAA is the most prominent compound detectable with proton MR spectroscopy in the human brain, making it one of the most reliable molecular markers for proton MR spectroscopy studies of the brain. The second was the connection to the rare but fatal hereditary genetic disorder known as Canavan disease.

Although the exact role of NAA remained to be established, brain NAA was found to be present in concentrations a hundred-fold higher than NAA in nonnervous system tissue, and it was therefore considered a brain-specific metabolite[54,82] and an in vivo marker of neuron density. Unfortunately, spectroscopic studies have dramatically outnumbered studies into the basic biochemistry of NAA, and this disparity has complicated the interpretation of proton MR spectroscopy results in various diseases due to a lack of basic knowledge of NAA function and metabolism. A decrease in NAA levels has been observed in many neurological diseases that cause neuronal and axonal degeneration such as tumors, epilepsy, dementia, stroke, hypoxia, multiple sclerosis, and many leukoencephalopathies. More generally, any major CNS disease involving either direct neuronal and axonal damage or secondary hypoxic-ischemic or toxic insult will result in abnormalities in the proton spectrum.

The objective of our further research was then to investigate the time course of NAA changes, always starting 1 minute postinjury and continuing for up to 5 days in varying grades of diffuse TBI to verify the hypothesis that reduction of NAA levels was proportional to injury severity, as had been proposed by Garnett et al.[29] in 2000.

By measuring whole-brain NAA via HPLC[79] in 3 different levels of trauma, we demonstrated for the first time that, at 48 hours postinjury, NAA reduction was graded according to the severity of insult, showing spontaneous recovery with lower levels of trauma and irreversible decrease in the others.[69] These data were strongly consistent with previous histological characterization of this type of TBI model.[26] The findings were also consistent with long-term behavioral observation in animals injured using the same model, showing only slight differences from sham-injured animals, with the main differences being present at 1 day postinjury and consistent improvement occurring over time.[6] All these bench observations strongly supported the clinical observations with proton MR spectroscopy with respect to a potential role of NAA in quantifying neuronal damage[12] and predicting neuropsychological outcome after TBI.[27,28]

In the reported study, however, we measured whole-brain NAA using HPLC; thus, especially at the latest time points, it was difficult to delineate whether an absolute percentage reduction represented a uniform reduction within dysfunctional cells or a reduction caused by neuron depletion with normal residual cells. Our finding of recovery in the mildly injured animals implied that at least one process leading to NAA reduction was reversible and not simply due to cell death. Once again, the striking finding was the rapidity of the onset of significant NAA reduction, already detectable after only 1 minute in severe injury, and the spontaneous recovery in mild injury, with a maximum drop observed at 15 hours postinjury, when NAA levels reached 46% of the control value.

The analysis of the temporal course of NAA levels also showed clear differences between the various degrees of TBI, demonstrating that different levels of "physical" injury correlated with different levels and kinetics of "biochemical" damage, reversible in mTBI and irreversible in sTBI. Notwithstanding such robust data and the experimental evidence of a biochemical marker of neuronal distress, a plausible explanation for this clear phenomenon remained controversial.

Energy Metabolism and NAA Synthesis

At that time, the most important link in NAA research worldwide as well as our research project was the initial work by Patel and Clark published in 1979,[63] showing a relationship between NAA synthesis and energy metabolism. The authors found that brain-derived mitochondrial preparations were clearly distinct from those derived from other tissues in their ability to synthesize large amounts of NAA, a phenomenon not detectable with nonneuronal mitochondria. In the same context, Patel and Clark also demonstrated the synthesis and efflux of NAA from mitochondria incubated in the presence of glutamate, malate, and pyruvate. An important finding of this study was that without pyruvate as a source of acetyl-CoA, no NAA efflux was detected.

These data, along with the initial intuition by Tallan in 1957,[75] that in mammals the distribution pattern of NAA closely paralleled the distribution of "respiratory activity," was confirmed by other investigators, but it took many years until a close linear relationship between ATP synthesis and the ability to synthesize NAA was described for the first time.[5] This study showed a biochemical "coupling" between NAA synthesis and energy production in brain mitochondria, a notion soon substantiated by additional reports describing decreases in NAA in a number of conditions of impaired brain energy metabolism in the brain. (For an overview of the data supporting a bioenergetic role for NAA in neurons see Moffet et al. 2007.[55])

In the same set of experiments,[69] together with the measurement of whole-brain NAA concentration, we then assessed ATP concentration and studied its trend course. It was quite surprising to observe that ATP changes literally mirrored the NAA changes. In mTBI, a gradual reduction of ATP levels started within minutes, reaching statistical significance at 2 hours, at which point a net reduction of almost 40% was recorded (relative to the values in controls). The lowest ATP value was found at 6 hours, showing a decrease of 57%. From that time point, there was a spontaneous gradual restoration, completed within 5 days postinjury, after which there was no statistically significant difference between ATP levels in the injured animals and those in control animals.

In contrast to NAA, which was found to decrease comparably in all 3 grades of injury severity during the early phase after trauma and to only show significant intergroup differences beginning at 48 hours after injury, ATP levels showed significant differences at earlier time points, suggesting that the underlying energetic derangement was something like a "preliminary step" necessary for observing NAA decrement.

Although ATP measurement assessed by ^{31}P-MR spectroscopy did not detect posttraumatic fall, several reports documented ATP reduction following TBI always related to mitochondrial dysfunction. Sullivan et al.[72] reported a significant time-dependent alteration in synaptosomal mitochondria, describing an immediate ATP reduction within 10 minutes following cortical contusion injury. Ahmed at al.[1] reported altered mitochondrial membrane potential and a 22%–28% cellular ATP reduction in mixed neuronal and glial cultures that had undergone stretch-induced injury, starting 15 minutes after trauma.

However, although the overall weight of evidence would favor a link between NAA synthesis in neuronal mitochondria and energy metabolism, studies have so far failed to make a direct connection between the synthesis of NAA and that of ATP. Certainly, the relationship between these 2 molecules is more indirect, since NAA synthesis is an energy-requiring process dependent on the availability and the energy of hydrolysis of acetyl-CoA. When acetyl-CoA is used for NAA synthesis instead of entering the citric acid cycle, there is a high energy cost to the cell because that molecule is no longer available to produce reducing equivalents (3 NADH and 1 $FADH_2$) as the fuel for the electron transport chain and subsequent

synthesis of 11 ATP molecules. Only when the ATP deficiency is fully restored does acetyl-CoA become available again to be shifted to the NAA synthesis pathway. Thus, a low NAA concentration can be seen as an indirect marker of metabolic energetic impairment.

A criticism of this interpretation could arise from the observation that ATP reduction might represent a simple metabolic mismatch between energy demand and supply. It is very important then to consider that these metabolic alterations occurred in a trauma model characterized by the constant presence of adequate cerebral blood flow. The marked posttraumatic increase in lactate/glucose ratio and reduced oxygen consumption (VO_2) recently described at 4–6 hours postinjury, with preserved cerebral blood flow,[46] rules out the ischemic etiology and suggests an increase in anaerobic glycolysis for the need to restore ATP, confirming that the mitochondria are dysfunctional.

To better address this issue we performed a supplemental study in which we compared the effects produced by 10 minutes of hypoxia and hypotension, both alone and coupled with traumatic insult.[78] A simultaneous ion-pairing HPLC analysis of MDA, ascorbate, oxypurines (hypoxanthine, xanthine, and uric acid), nucleosides (inosine and adenosine), nicotinic coenzymes, and high-energy phosphates (ATP, ADP, AMP)—these last compounds useful to calculate the energy charge potential (ECP) (ECP = ATP + [1/2 ADP]/[ATP + ADP + AMP])[44]—was performed, showing again a proportional decline with the severity of brain insult. More interestingly, rats subjected to hypoxia and hypotension had minimal ECP values 15 hours after trauma, showing a progressive recovery thereafter; at 120 hours after injury, values were not significantly different from those in sham-injured animals. These findings were of particular interest because the time course resembled that of mTBI. Indeed the entire biochemical derangement of animals subjected to hypoxia and hypotension was similar to that seen in mTBI, simply indicating a reversible type of damage that spontaneously recovers with almost the same kinetics. In contrast, when hypoxia and hypotension were used together with an mTBI model, the metabolic consequences appeared irreversibly catastrophic.

Another important consideration was the net diminution of the nicotinic coenzyme pool (NAD^+ + NADH and $NADP^+$ + NADPH), which clearly plays a pivotal role in the final result of general depression of cell energy metabolism. This depletion jeopardizes either the reducing equivalent supply to mitochondrial oxidative metabolism, or the catalytic activity of dehydrogenase-mediated oxidoreductive reactions. To date, possible mechanisms for this phenomenon are the hydroxyl radical–induced hydrolysis of the N-glycosidic bond of the reduced forms of NAD and NADP and the activation of the enzyme NAD-glycohydrolase.[43] Both mechanisms cause the hydrolysis of nicotinic coenzymes and give rise to the same end products—ADP-ribose(P) and nicotinamide. Independent of the predominant mechanism, the final result is certainly deleterious for the correct functioning of cell metabolism. Finally, the augmentation of poly-ADP ribosylation reactions through the activation of the enzyme poly-ADP ribose polymerase[22,58,61] has been demonstrated to trigger the mechanisms of apoptotic induction.[95]

The fact that NAA, ATP, MDA, ascorbate, oxipurines, nucleosides, and nicotinic coenzymes spontaneously recovered in mTBI and after hypoxia and hypotension alone seemed to suggest that there is a threshold for mitochondrial dysfunction beyond which restoration of neurochemical physiology is prevented.

Mild TBI and the Hypothesis of Postconcussive Brain Vulnerability

With the exception of the reversibility of the modifications induced by mTBI, it was not clear to us what was "mild" about a traumatic event that can have such consequences to the fundamental metabolic and energy states of neuronal cells.

The legitimate and natural objection to this "gloomy" view is that, in spite of everything, animals and patients with mTBI show no or minimal focal neurological problems and all show a radiologically normal brain. In other words, all these biochemical modifications are rather interesting but clinically of negligible utility just because they are all spontaneously and fully reversible.

There was, however, an initial reasonable body of evidence suggesting that the "concussed" brain cells undergo a peculiar state of "vulnerability" for an undefined period of time, during which if they sustain a second, typically nonlethal insult, they suffer irreversible damage and die.[32]

Fascinated by this original hypothesis from Hovda and colleagues at the University of California, Los Angeles, we undertook, as a next step in our research, an analysis of the neurochemical and metabolic effects produced by 2 consecutive concussive mTBIs, the second injury occurring at different intervals from the first, to investigate how the temporal gap between traumatic events could influence the overall severity of injury. We used the same impact acceleration model and applied a new and easily reproducible protocol to simulate a "second impact" condition in rats.[85] Neuronal injury was quantified by HLPC measure of whole-brain NAA concentration with the synchronous assay of whole-brain ATP and ADP concentrations and consequent ATP-to-ADP ratio (an indirect indication of mitochondrial phosphorylating capacity). Animals were randomly assigned to one of the following experimental groups: sham-injured; single mTBI; single sTBI; 3-day interval "double mTBI"; 5-day interval "double mTBI."

We were astonished by the observation of an identical 10% mortality rate in animals subjected to sTBI and animals doubly injured by mTBI with a 3-day trauma interval, whereas no animals died when subjected to a single mTBI or double-impact mTBI with a 5-day interval.

After the second mTBI, delivered 5 days after the first, NAA decreased by 17%, a reduction not significantly different from that observed following a single mTBI. When the second trauma occurred after 3 days, however, the NAA revealed a further 43% reduction when compared with the 5-day interval, a value not statistically different from the dramatic reduction observed in severe injury, in which NAA decreased by 47% versus controls and by a further 37% versus rats subjected to a single mTBI. These findings were interesting because, at least according to

the experimental model adopted, 2 consecutive mTBIs occurring within the shortest interval of time considered for the study (3 days) produced the same biochemical damage observed after sTBI. In particular, neuronal distress, indicated by reduction of NAA levels, doubled when compared with that observed after a single mTBI.

Energetic metabolites showed a very similar trend. In single mTBI, the levels of ATP and ADP and the ATP-to-ADP ratio varied by a value not significantly different from animals in which the second trauma was delivered 5 days after the initial one. In contrast, animals with a second mild injury 3 days after the first exhibited severe energetic imbalance, showing a 50% drop in ATP levels and very low (–70%) ATP-to-ADP ratio, reductions almost identical to those seen after sTBI.

These data provided the experimental demonstration of the exquisitely metabolic nature of the "brain vulnerability" after mTBI, and offered a contribution to the understanding of the complex biochemical damage underlying the clinical scenario of a repeated concussive trauma, sometimes leading to catastrophic brain injury. Most importantly, it was evident that when the second injury took place after a longer interval, recovery of the energetic imbalance was completed and the 2 traumatic insults acted as independent events, the additional injury simply representing a new "mild" event.

Similar data were reported just a few months before these findings by Laurer et al.[42] in a study describing important cumulative effects of 2 episodes of mTBI (24 hours apart) in mice, which led to pronounced histopathological damage compared with animals sustaining only a single trauma. The authors' conclusion was that although the brain was not morphologically damaged after a single concussive insult, its vulnerability to a second concussive impact was dangerously increased.

According to Hovda and colleagues, metabolic alterations can persist for days after concussion, creating no morphological damage, but representing the pathological basis of the brain's vulnerability.[19,30,94] In our study, after a single mTBI, we found a 22% reduction in ATP levels; although neither histological nor behavioral abnormalities have been described with this model, these data confirm that energy recovery was incomplete. The ADP levels did not increase because, despite significant ATP depletion, mitochondria were not yet irreversibly damaged, possessing a sufficient phosphorylating capacity to allow spontaneous full restoration of ATP levels, which was complete after approximately 5 days. A profoundly different situation was observed in sTBI, with a 50% decrease in ATP levels and 35% increase in ADP levels, indicating altered capacity of mitochondria to support the cell energy requirements in terms of ATP synthesis.

When the second mTBI was delivered during the aforementioned restoration period, it caused further mitochondrial malfunctioning leading to the same energetic failure observed in severe injury. It could be concluded that 2 mTBIs that occur too close in temporal proximity simulate the effects of a severe injury, and that one of the biochemical bases of the vulnerable brain is the incomplete overcoming of the initial reversible energetic crisis, triggered by the first insult.

The first striking clinical implication of these experimental data was that the metabolic effects of 2 consecutive concussions occurring within a period of days can be dangerously additive. This information might not be surprising, but similar human data regarding brain metabolites were not available.

The further clinical implications of these findings are also remarkable: because it is very difficult to establish how long the above-described period of brain vulnerability will last, one cannot predict the time point at which a second trauma would be uneventful.

Brain Vulnerability

The high correlation demonstrated between energy metabolism and the ability to synthesize NAA seemed to suggest that the decrease of NAA after mTBI might be considered a reflection of dysfunction in cells that had impaired energy metabolism but were not yet irreversibly damaged. However, a more definite picture of the effect of the time interval between 2 mTBIs, as well as more robust evidence of whether the mitochondrial dysfunction observed was partially or totally reversible, was still lacking. Likewise, the kinetics of the aforementioned period of brain vulnerability were still unclear.

Our next study entailed an extensive screen of markers of mitochondrial-related functions obtained in animals subjected to 2 mTBIs at intervals of 1, 2, 3, 4, or 5 days.[88] Besides measuring NAA values, the levels of adenine nucleotides, oxypurines, nucleosides, free-CoA-SH, acetyl-CoA, malonyl-CoA, propionyl-CoA, and oxidized and reduced nicotinic coenzymes were also determined. Ultimately, the concentrations of the NAA-related compounds, like N-acetylglutamate (NAG) and N-acetylaspartatylglutamate (NAAG), the most concentrated neuropeptide in the human brain, as well as the expression of N-acetylaspartoacylase (ASPA), the enzyme responsible for NAA hydrolysis into aspartate and acetate mainly within oligodendrocytes, were determined.

Overall, the results indicated that a broad interrelated series of metabolites were deeply affected by a second mTBI if it occurred within the brain vulnerability window. The majority of these compounds have the common feature of being related to the mitochondrial activity devoted to the cell energy supply. Levels of NAA, adenine nucleotides, acetyl-CoA, and oxidized nicotinic coenzymes all showed the same pattern of variation with time between impacts, and all showed values similar to controls when the second concussion was delivered 5 days after the first. Of particular note were the variations of acetyl-CoA levels in view of its dual role as a fundamental compound for the reducing equivalent supply in the Krebs cycle activity and as the acetyl group donor in the NAA biosynthetic reaction. This was the first report showing that cerebral acetyl-CoA concentration was remarkably decreased after repeat mTBI. The diminished availability of this compound has a negative consequence on the continuous flow of NADH necessary for the electron transport chain, thus playing an important role in the deeply decreased mitochondrial phosphorylating capacity (decrease of the ATP/ADP ratio) and leading to a profound drop in ATP con-

centration as observed in rats reinjured after 3 days. The almost 50% decrease in NADH recorded in these animals is consistent with this hypothesis and corroborates the concept of extensive involvement of the tricarboxylic acid cycle in the energy state impairment.

A slight but statistically significant decrease in the NAD^+/NADH ratio was observed only when the second mTBI was delivered after 3 days (–20% with respect to controls). Such a phenomenon appears to be mainly attributable to the dramatic decrease in NAD^+ levels. Because brain metabolism is primarily based on glucose utilization, the main site of acetyl-CoA cerebral generation is at the pyruvate dehydrogenase level. According to previous results, pyruvate dehydrogenase activity is markedly inhibited by increased oxidative stress, a pathological condition common in TBI. On the other hand, in the reaction catalyzed by aspartate N-acetyltransferase, the enzyme responsible for NAA biosynthesis, low acetyl-CoA levels should certainly reduce the velocity of NAA production and contribute to the NAA depletion observed after repeat mTBI when the second concussion was delivered 3 days after the first. Therefore, acetyl-CoA availability might represent the phenomenon effectively linking the parallel NAA and ATP changes.

Results of the analysis of mRNA transcript of the *ASPA* gene revealed that there was an effect of the time interval between concussions on *ASPA* gene expression. A progressive increase in the mRNA transcript of the *ASPA* gene was observed, with a maximum 4-fold increase of ASPA expression in animals injured again after 3 days. Animals reinjured past 5 days had values of mRNA for ASPA comparable to those recorded in controls.

From these data it appears that TBI-induced NAA variations may not be simply attributable to a decreased rate of biosynthesis.

In accordance with the knowledge of different compartmentation for NAA biosynthesis (neuronal mitochondria) and degradation (oligodendrocytes), it could be hypothesized that TBI-induced NAA decrease occurs in 2 distinct phases and with 2 different mechanisms. Initially, independently from the severity of injury, a change in mitochondrial permeability[25] causes an increased velocity of NAA outflow from neurons to the extracellular space. Simultaneously, mitochondrial impairment leads the cell to use energy for more "urgent" requirements and, therefore, leads to diminished NAA synthesis. In the case of reversible brain damage such as single mTBIs or repeat mTBIs in which the second impact occurs outside the brain vulnerability "window," recovery of mitochondrial functions takes place with normalization of the rate of NAA efflux and biosynthesis (NAA levels close to controls and no increase in ASPA expression).

In single sTBIs or in repeat mTBIs in which the second impact occurs within the brain vulnerability window, higher amounts of NAA than normal continuously reach oligodendrocytes, which, as an adaptive mechanism, increase the expression of ASPA. This phenomenon, combined with the decreased rate of NAA biosynthesis caused by persistent mitochondrial impairment, is ultimately responsible for the dramatic NAA depletion. Beyond the specific interest in TBI studies, this finding gives an insight into the possible mechanisms of NAA homeostasis, strongly suggesting that NAA concentration within oligodendrocytes regulates the gene expression of ASPA and, in turn, the velocity of its own degradation.

These results were immediately followed by another collaboration study on transcriptomics in which the simultaneous expression of about 30,000 rat genes, whose products are involved in a variety of cellular processes, were studied.[16] Using complementary DNA microarray technology, we reported that following stretch injury to hippocampal slice cultures (as a suitable cell model to induce graded TBI), the expression of 999 genes was altered in mTBI, compared with controls.

The altered genes in mTBI-stretched cells clustered in the "Biological Process" group, which had been shown to be involved in the structural damage of cellular architecture. Most of these genes are involved in signal transducer activity, regulation of transcription, and cell communication. This indicated that even after a mild stretch injury (comparable to a closed-head diffuse mTBI), intense activity involving transcription and signaling exchange is initiated. Additionally, we have found that certain genes involved in the apoptotic process, such as *Vdac1 (voltage-dependent anion-selective channel protein 1), Sh3glb1 (SH3-domain GRB2-like endophilin B1), Phlda1 (leckstrin homology-like domain, family A, member 1), Rock1 (Rho-associated coiled-coil containing protein kinase 1),* and *Eif4g2-predicted (eukaryotic translation initiation factor 4 gamma, 2)* were downregulated. Further, an upregulation was seen in genes involved in the antiapoptotic process, such as *Ccl2 (chemokine [C-C motif] ligand 2), Vegfa (vascular endothelial growth factor A), BIRC3 (baculoviral IAP repeat-containing 3), Tsc22d3 (TSC22 domain family, member 3), Bnip3 (BCL2/adenovirus E1B 19-kD interacting protein 3),* and *Nr4a1 (nuclear receptor subfamily 4, group A, member 1).* The majority of these expression changes were only found following mild stretch injury, indicating that these hippocampal cell cultures have activated protective and repair mechanisms.

The most interesting finding was that more genes were differentially expressed following mild brain injury than following severe injury, further supporting the notion that even following mTBI, in which an absence of radiological and clinical abnormalities is the norm, an invisible complex cellular response is initiated and distinct neuronal dysfunction occurs. This corroborates previous findings that these are "primary" cellular effects not determined by local blood or oxygen delivery or by systemic factors.

Two Often-Neglected Phenomena: Oxidative and Nitrosative Stresses

In the reported works, data showed for the first time that NAAG was also markedly affected by repeat mTBIs. In contrast to the situation with NAA, several biological activities were clearly demonstrated for NAAG either under physiological[92] or pathological conditions.[4,59] With regard to head injury, the beneficial effects connected to the inhibition of glutamate carboxypeptidase II, also known as N-acetylated α-linked acidic dipeptidase, are

of particular interest in models of neuropathies, stroke, and focal TBI.[57,96] Glutamate carboxypeptidase II, which catalyzes the hydrolysis of NAAG to glutamate and NAA, is activated under these pathological conditions, leading to an increase in glutamate release. The NAAG decrease observed in our experiments might contribute to perpetuating glutamate generation. High levels of glutamate are believed to be one of the major contributors to the excessive amounts of intracellular calcium, which is another fundamental mechanism of mitochondrial functional and morphological alteration. An essential point of posttraumatic calcium overloading is the mitochondrial damage due to induced changes of the organelle's membrane permeability, the uncoupling of oxidative phosphorylation, and organelle swelling.[66,97]

As suggested by experiments in which the mitochondrial capacity to catalyze the tetravalent reduction of molecular oxygen through the electron transport chain appears compromised, dysfunctional mitochondria seem to be the main intracellular source of ROS production.[58,60,61,73]

However, in conjunction with oxidative stress, we also studied the importance of another event occurring as a consequence of TBI, a phenomenon known as nitrosative stress. Only more recently the object of substantial investigations, nitrosative stress is defined as an overproduction of reactive nitrogen species (RNS) through the Ca^{2+}-dependent activation of neuronal nitric oxide (NO) synthase and of the increased synthesis of the inducible form of NO synthase, generally taking place in concomitance with oxidative stress.[13] Nitric oxide generation, resulting from elevated neuronal NO synthase and the inducible form of NO synthase activities, can either induce an increase of nitrosylation reaction of various hydroxyl- or sulfhydryl-containing biomolecules (tyrosine, serine, or cysteine residues of proteins, glutathione, and so forth) or react with ROS, giving rise to secondary, highly reactive radicals such as peroxynitrite.[20,21,68]

At this point of the project, it seemed relevant to us to further investigate whether, during the aforementioned window of brain vulnerability, oxidative and nitrosative stresses contributed to the metabolic damage in cerebral tissue following concussion. By assessing different biomarkers reflecting ROS-mediated oxidative stress (MDA, GSH, oxidized glutathione [GSSG], ascorbic acid) as well as indices representative of NO-mediated nitrosative stress (nitrite and nitrate), we studied the effects of repeat mTBI delivered with increasing time intervals.[80]

Consistently, we found that MDA and ascorbic acid in animals in which repeated mTBIs were spaced by 3 and 5 days had values similar to those observed after single sTBI and after single mTBI, respectively. Intermediate time intervals between concussions produced intermediate intensities of oxidative stress. However, much more important was the reported parallelism between oxidative and nitrosative stresses observed in our experiment, strongly reinforcing the concept that the time interval between 2 concussions is a critical factor for transforming the biochemical effects of an mTBI, which are fully reversible, into a metabolic picture of sTBI.

Our data indicated that compounds reflecting NO generation by activated neuronal NO synthase and an inducible form of NO synthase (nitrite and nitrate) had maximal concentrations when mTBIs were delivered 3 days apart and minimal concentrations when mTBIs were spaced by 5 days. Animals subjected to mTBIs with the latter interval had approximately normal levels of both compounds, thus confirming that, in this case, mTBIs can be considered as independent events with no cumulative effects. It should be remembered that the concomitant presence of oxidative and nitrosative stresses is highly hazardous because of the risk of generating highly reactive RNS such as peroxynitrite and nitroxyl.

Both these RNSs have damaging effects on biomolecules and greatly contribute to deplete tissue antioxidant defenses.[65] In particular, GSH is a selected target of either peroxynitrite, which transforms GSH into nitrosoglutathione,[38,67] or nitroxyl, which reacts with GSH to give rise to the amidated GSH derivative sulfonamide.[20,21] Therefore, it can reasonably be inferred that in our experiment, the production of RNS through the simultaneous occurrence of oxidative and nitrosative stresses played a significant role in causing the dramatic GSH depletion recorded after repeat mTBIs spaced by 1, 2, 3, or 4 days. Furthermore, our results suggested that, because peroxynitrite is actively scavenged by ascorbic acid,[3,39] this RNS may also have an active role in the depletion of ascorbic acid observed.

The data from this study, as well as those from our previous work on repeat mTBIs, offered again a clear picture of the existence of a temporal window of brain vulnerability, demonstrating that a number of linked molecular events concur to provoke severe biochemical brain damage if a second concussion falls within such a temporal window.

Clinical Implications

Managing mTBI: Does Proton MR Spectroscopy Have a Role?

Since in Western countries a head trauma occurs approximately every 15 seconds, it appears improbable that an emergency physician will not encounter a patient with an mTBI during an emergency department shift.

The fundamental issue of whether to observe, discharge, or obtain imaging studies in each one of these patients is addressed continuously and it is focused essentially on identifying those patients at risk for hemorrhagic complications that would threaten their lives. In fact, dramatic tales regarding patients who "talk and deteriorate," die, or end up with severe permanent disability after a "simple blow to the head" abound; yet such events are very uncommon and frequently are based on no more solid literature than case reports. As a matter of fact, a patient presenting with a GCS score of 15 with no associated risk factor has a chance of intracranial hemorrhage that will require neurosurgical intervention of less than 0.1%.[24]

The real dilemma about mTBI has a completely different perspective. How many individuals sustaining mTBI remain medically unattended and how many of those who present to emergency departments will receive specific advice regarding the possible sequelae of what has just happened to them? How much is the whole picture confounded by conditions related to age, gender, race, ethnicity, and so-

cioeconomic status? What is the proportion of concussions that are already repeat injuries, so that what the emergency physician is managing is actually a "double mTBI"? How many times are patients asked if they have sustained a prior head injury a few days before? Would the discharge instructions be different in such cases, or should the patient be discharged at all? How much is the risk for subsequent TBIs increased during the week after a TBI? How many times are patients discharged with the strong recommendation to absolutely avoid, for a yet-to-be-defined period, any situation that would raise the chance of suffering another concussion (driving scooters, engaging in sports)? What about infants, toddlers, and other children?

Basic science data collected from the reported bench studies has clarified some aspects of this particular clinical entity, suggesting that, after all, mTBIs are not always as "mild" as the name would suggest, and short-term as well as long-term consequences may very well be overcome simply by understanding the metabolic conditions of the injured brain cells. Data reported in this summary strongly suggest that measuring NAA after an initial concussion and monitoring it until normalization might represent a significant step in quantifying the objective nature of the postconcussive metabolic disturbances. Due to its high concentration within neurons (~ 10 mmol/L brain water), NAA levels are easily demonstrated by proton MR spectroscopy. This technique is based on the ability to localize the MR signal into a specific volume of tissue, thus providing a real-time "image" of the brain neurochemistry.

As recently emphasized,[9] it is profoundly necessary to "biologically" grade the "severity" of mTBI, since absence of clinical signs and symptoms often does not coincide with full cerebral metabolic recovery. In selected cases, monitoring NAA via proton MR spectroscopy until complete normalization might represent a strategy to confirm the total metabolic recovery commonly observed after concussion and to avoid a second mTBI soon afterward that could lead to a more severe injury.

Sports-Related Concussion

The outlined experimental results have implications not only for the clinical sequelae associated with postconcussive syndromes, but also support the current concerns regarding athletes in terms of when they should return to play after sustaining a concussion on the field. As we know, athletes often sustain repetitive head impacts, frequently during a short time course consistent with the timing used in the reported studies.

Clearly, any translation of rodent experimental time frames into human experience is a very complicated matter. But it can be reasonably assumed that the timing of events in rat models would be a lot shorter than similar periods in humans, and it would be realistic to speculate that the periods of postinjury pathophysiological changes last longer in humans. This issue is crucial, because a second concussive injury occurring within a short period (hours, days, or weeks) can be catastrophic,[10,11,50,52,64,] a phenomenon also known as "the second impact syndrome" (SIS).

Unfortunately, many team physicians' decisions are based on limited observations and sideline evaluations and may frequently be made under intense pressure from coaches, fans, sponsors, and other players, who are all eager to see the injured athlete return to play as quickly as possible.

The imprudence of such a strategy was recently demonstrated by a pilot study involving concussed athletes from different sport disciplines. The results clearly showed that after a concussion, despite normal radiological appearance and complete resolution of clinical symptoms, substantial neurochemical abnormalities were present in the injured brain and readily detectable by measurement of NAA using proton MR spectroscopy.[86] As repeatedly observed in the laboratory, NAA decrease in concussed athletes was seen to be a dynamic process, still detectable 15 days after a concussion; its restoration over time appeared to be nonlinear (slow recovery in the first 2-week period, followed by fast recovery until normalization in the next week), and it was profoundly influenced when a second concussive insult occurred during the recovery process, lengthening the NAA normalization curve and causing a significant delay in symptom resolution. Although none of the players who experienced a second concussion in this study suffered from SIS or showed signs of sTBI, all demonstrated a more severe clinical picture, somehow not proportional to the concussive insult.

Most likely, the second concussion occurred when the brain cells were completing the recovery process and, thus, it only produced a limited cumulative effect with a moderate worsening of the expected clinical and biochemical consequences. The severe brain swelling observed in SIS is attributable to the fact that the second insult must take place when the cells are experiencing their maximum distress (oxidative, neurotoxic, mitochondrial, genetic), are still intensely engaged in restoration of their energetic integrity, and therefore are unable to withstand further energetic expenses, thus experiencing uncontrolled swelling.

The use of proton MR spectroscopy to measure NAA levels offers the unique opportunity to detect the actual state of brain metabolism, to have a snapshot of the degree of energetic impairment, and to monitor the eventual recovery curve, in consideration of the much higher risk of recurrent concussions in sports-related activities.

The results of a multicenter clinical trial involving 40 concussed athletes and 30 healthy volunteers have been recently published, revealing that, despite different combinations of field strengths (1.5 or 3.0 T) and modes of spectrum acquisition (single- or multivoxel) among the scanners currently in use in most neuroradiology centers, NAA determination by proton MR spectroscopy represents a quick (15-minute), easy-to-perform, noninvasive tool to accurately measure changes in cerebral biochemical damage occurring in mTBI, the normalization of which should markedly enhance the ability of physicians and trainers to determine when concussed players should be allowed to return to play.[84]

Conclusions

Mild TBI is a relatively "neglected world" from a research point of view, especially because it is very difficult to accurately reproduce it in laboratories. Trauma is

directly responsible for sudden biochemical changes occurring at the time of impact, and the severity of brain insult can be graded by measuring these biochemical modifications—specifically, ROS-mediated damage, energy metabolism depression, alteration of gene expression and ultimately variation of NAA concentration, a surrogate marker of neuron dysfunction.

Within days after injury, this complex biochemical derangement can result in a dangerous state for the brain, generating a situation of metabolic vulnerability, to the point that if another, equally "mild" injury were to occur, the 2 mTBIs would show the biochemical equivalence of an sTBI. The immediate clinical implication derived from the growing body of experimental evidence is that trials are warranted to investigate the application of proton MR spectroscopy for measurement of NAA and for monitoring the full recovery of brain metabolic functions.

Disclosure

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Role of the S100B serum biomarker in the treatment of children suffering from mild traumatic brain injury

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Object. The aim of this study was to provide a systematic update of the current literature regarding the clinical role of the S100B serum biomarker in the initial evaluation of children who have sustained a mild traumatic brain injury (TBI).

Methods. Searches in MEDLINE were defined with the keywords "mild TBI children S100," "mild TBI pediatric S100," and "children S100 brain injury." From the pool of obtained studies, those that had the inclusion criteria of mild TBI only or mixed types of TBI but including detailed information about groups of children with mild TBI were used.

Results. Few studies were identified and fewer included more than 100 cases. The prospective studies showed that the S100B biomarker levels could be influenced by patient age and the time frame between head injury and blood sampling. Moreover, extracranial sources of S100B or additional injuries could influence the measured levels of this biomarker. A normal value of S100B in children with mild TBI could rule out injury-associated abnormalities on CT scans in the majority of reported cases.

Conclusions. The vulnerability of S100B serum levels to the influences of patient age, blood sampling time, and extracranial S100B release limits the biomarker's role in the initial evaluation of children with mild TBI. The application of S100B in pediatric mild TBI cases has an elusive role, although it could help in selected cases to avoid unnecessary head CT scans. *(DOI: 10.3171/2010.8.FOCUS10185)*

Key Words • biomarker • children • mild traumatic brain injury • S100B biomarker

Traumatic brain injury is one of the leading causes of death and morbidity in children.[1,4,8,20] Patients with mild TBI demonstrate heterogeneity in clinical presentation with or without loss of consciousness or posttraumatic amnesia and with GCS scores ranging from 13 to 15.[23] The different age groups and communication difficulties in pediatric patients may sometimes present further obstacles in obtaining a detailed injury history and identifying TBI symptoms in an accurate and timely manner. The neurological examination in pediatric patients, especially in the very young ones, may be quite challenging, and the patient's initial clinical picture and injury history may frequently be unreliable. Their evaluation requires time and patience, which unfortunately can be difficult to find in a chaotic and busy emergency room. In addition, pediatric cases of mild TBI can impose a diagnostic dilemma on the managing physician, since the decision for a hospital admission to obtain imaging studies is not easy and significantly raises the cost of treatment. The physician's experience is the key factor dictating the management plan given that there are currently no guidelines for the treatment of mild TBI in children.[1,4,8,20]

The above considerations in pediatric cases of mild TBI create a need to design a diagnostic tool that would combine diagnostic performance, ease of use, minimal invasiveness, cost effectiveness, and outcome prediction in a timely and efficient manner.[6,20] For years, imaging studies have been used as supplemental tools in diagnosing and managing pediatric TBI cases. However, these studies are not always feasible because of their prohibitive use due to high costs, time requirements, and difficult application. The necessity of finding an optimal biomarker from the blood or CSF that could establish a TBI diagnosis, accurately measure its severity, and predict its outcome is more than apparent.[6,20] Protein S100B, neuron-specific enolase, and glial fibrillary acidic protein

Abbreviations used in this paper: GCS = Glasgow Coma Scale; TBI = traumatic brain injury.

are the most commonly studied biomarkers, while protein S100B has been studied the most in the field of pediatric TBI.[1,3–7,14,18,20]

The aim of our study was to assess the role of S100B as a clinical biomarker in pediatric cases of mild TBI and to systematically review the pertinent literature.

Methods

We accessed the MEDLINE database to gather the required data and information for this review article. Our search strategy involved 3 different search sessions using the keywords "mild TBI children S100," "mild TBI pediatric S100," and "children S100 brain injury." We included only those articles published in the English language. After obtaining the first pool of studies, a second filter procedure followed. The inclusion criteria isolated studies with pediatric cases of mild TBI only. Whenever studies with mixed types of TBI or mixed populations (adult and pediatric) were encountered, we tried to extract information specific to pediatric cases of mild TBI.

Results

Profile of S100B

The S100 calcium binding protein B, or S100B, belongs to the S-100 protein family and is characterized by 2 calcium-binding sites of the helix-loop-helix conformation. The S100 proteins are located in the cytoplasm and nucleus of a wide range of cells and are involved in the regulation of a number of cellular processes, such as cell cycle progression and differentiation. Specifically, S100B regulates cellular homeostasis and enzyme activity and inhibits protein kinase C phosphorylation of growth-associated protein 43, which is involved in axonal growth and synaptogenesis during development, synaptic remodeling, and long-term potentiation.[13] It also plays a significant role in the stabilization of tau and microtubule-associated protein 2 (MAP-2).[26] The *S100* genes include at least 13 members, which are located as a cluster on chromosome 1q21. There are at least 21 different types of S100 proteins.[25] The name of this protein group derives from its solubility in ammonium sulfate, which is 100% at a neutral pH.

The S100B protein was first identified in 1965 by Moore.[15] It is a low-molecular-weight protein (10–12 kD) composed of 2 subunits, alpha and beta, with the αα subtype found mostly in striated muscles, heart, and kidneys; the αβ subtype, in glial cells; and the ββ subtype, in high concentrations in astroglia.[9] The S100 proteins and especially S100B can act as a cancer biomarker in malignant melanoma. It has a serum half-life of 60–120 minutes and is eliminated by renal clearance.[11,12] Although S100B is glial-specific and expressed primarily by astrocytes and Schwann cells, it is also found in several non–nervous system cells, such as adipocytes (white and brown fat), chondrocytes, skin, and glioblastoma and melanoma cells.[27] However, it is not expressed by all astrocytes. It has been shown that S100B is only expressed by a subtype of mature astrocytes, which are in proximity to blood vessels, and also by NG2-expressing cells.[25] It can be found in very low levels in human CSF and serum, and normal levels of this protein have been strongly correlated with the absence of any intracranial injuries.[21] Low basal levels of S100B in human serum suggest that sharp increases in the concentrations of this protein are sensitive indicators of brain injury. Cerebral lesions cause immediate leaking of S100B from damaged glial cells into the blood or CSF.[19] The precise mechanism of the increased serum concentration of S100B in cases of TBI remains uncertain. The S100B could be directly released by damaged cells, but it is also secreted into the extracellular space by activated glial cells. It may enter the serum through a transient disruption of the blood-brain barrier or via the CSF circulation.[20] It has been shown that serum S100B levels correlate well with a patient's clinical condition and imaging findings as well as their outcome scores in cases of TBI. It has been postulated that S100B protein is the most promising marker for evaluating the severity of TBI in patients suffering from mild injuries.[10] It has also been shown that in patients with severe TBI, serum S100B concentrations higher than 1.13 ng/ml are associated with increased death and morbidity.[24] Thus, this protein has been proposed as a potential biomarker indicating the severity of neuronal injury and the disruption of the blood-brain barrier and predicting a patient's outcome.[22] On the other hand, it has been demonstrated that there is a poor correlation between CSF and serum S100B levels; this is because the intact blood-brain barrier is not permeable to S100B. It has been postulated that an increase in serum concentration may be indicative of blood-brain barrier disruption rather than irreversible neuronal damage.[6] Furthermore, increased S100B serum levels have been described in cases of melanoma and hepatic, renal, and/or intestinal ischemia, probably due to the presence of S100B in other nonglial cells.[17] In addition, the use of S100B as a neuronal injury biomarker has been questioned because its concentration was increased in trauma patients with no head injuries.[2]

Clinical Studies of S100B in Children With Mild TBI

Most of the clinical studies concerning mild TBI and S100B serum levels in children included a limited number of patients, and thus no statistically powerful conclusions can be extracted. Interestingly, very few studies included more than 100 patients. Geyer et al.[8] conducted a prospective clinical study involving 148 children with mild TBI. The biomarkers S100B and neuron-specific enolase were measured within 6 hours of injury. Two diagnostic groups were studied. The first one, called the "mild TBI group" included children with GCS scores of 13–15 and signs of concussion. The second one, called the "head contusion group," included children with a GCS score of 15 and no signs or symptoms of concussion. The authors found that patient age and the time frame between injury and blood withdrawal significantly influence the serum S100B concentrations. The levels of S100B in the mild TBI and head contusion groups did not significantly differ. Moreover, there was no significant difference between the levels of S100B in patients with GCS Scores 15 or 14. These authors concluded that S100B demonstrates low sensitivity in mild TBI cases in children (Table 1).

TABLE 1: Literature review of studies on pediatric patients with mild TBI*

Parameter	Geyer et al., 2009	Castellani et al., 2009	Morochovic et al., 2009	Akhtar et al., 2003	Berger et al., 2005
sample size	148	109	102	17	12†
type of population	pediatric	pediatric	pediatric & adult‡	pediatric	pediatric
% males	57.4	67	ND	ND	ND
age range	6 mos–15 yrs	5 mos–17.5 yrs	12–84 yrs	6–15 yrs	ND
GCS score	>12	>12	>12	§	15
time point of S100B sampling (hrs)	≤6	≤6	≤6	≤6, ≤12¶	≤12
imaging modality	none	CT	CT	CT & MRI	CT

* No outcome measurements (Glasgow Outcome Scale or neuropsychological tests) were used in any of the studies. Abbreviation: ND = no data.
† Extracted data of 12 patients with mild TBI (from a total of 168).
‡ Extracted pediatric data used in the paper.
§ Traumatic brain injury patients with negative CT.
¶ First sample, second sample.

In a prospective study, Castellani et al.[4] tried to reveal whether S100B levels in 109 children with mild TBI (GCS Scores 13–15 at admission and clinical symptomatology present) were related to their CT findings. The inclusion criteria were as follows: 1) children who required a CT scan during hospitalization and 2) whose S100B levels had been determined within 6 hours of the traumatic event. Blood sampling had also occurred within 6 hours after the injury event. An interesting finding was the increased serum S100B levels in patients with an abnormal CT scan as compared with levels in children with nondiagnostic findings on CT, and this difference was statistically significant. However, no statistically significant difference in the serum S100B concentrations was found between the different GCS subgroups (patients with GCS scores of 13 vs 14 vs 15), after the adjustment of p values for pairwise analysis. When CT findings were used as a factor to assess serum S100B marker performance, sensitivity was 1.00, specificity 0.42, positive predictive value 0.46, and negative predictive value 1.00 with an area under the curve of 0.68. All children with normal serum S100B values had no injury-related abnormalities on head CT scans. This finding can be used in routine clinical practice to avoid unnecessary CT scans in children with normal S100B values. It should be noted that children with head and other systemic injuries had higher mean S100B levels than those with isolated head injuries. This difference reached the levels of statistical significance in their study (Table 1).[4]

Akhtar et al.[1] tried to assess the significance of serum S100B levels in 17 children who had sustained a TBI and had been screened with brain MR imaging. All children in their study had a negative CT scan. Unfortunately, there were no details regarding the admitting GCS scores. The S100B biomarker did not efficiently identify TBI patients with positive or negative MR imaging studies. Moreover, additional systemic injuries affected the serum levels of S100B, so that children with concomitant injuries had consistently higher S100B serum concentrations than the children with head injury only (Table 1).[1]

Berger et al.[3] reported their experience with 12 children who had sustained TBIs, with admitting GCS scores of 15, normal head CT scans, and no clinical evidence of concussion. In that cohort, 67% of the children demonstrated increased serum levels of S100B. The authors concluded that S100B could be a more sensitive biomarker than CT or MR imaging in cases of pediatric TBI.[3] The high levels of S100B could potentially reflect CNS damage that was undetected with imaging modalities (Table 1).[3]

Discussion

The application of serum S100B protein as a clinical biomarker and outcome-predicting factor in pediatric cases of mild TBI meets several obstacles given that numerous factors can influence baseline serum S100B concentrations and many pathological conditions other than TBI can cause elevated S100B levels. Patient age is one of the most influential factors in determining normal baseline serum levels of S100B. The effect is significant in the pediatric population, which expresses highly varying growth factors at different developmental stages and produces a variety of proteins to meet everyday growth demands. This observation has been confirmed by Geyer et al.[8] in their pediatric study of mild TBI as well as in other clinical studies.[5,7,20] Gazzolo et al.[7] evaluated the normal levels of S100B in serum in 1004 children to create a reference curve and found that there are 2 peaks, 1 in children younger than 1 year of age and another occurring in adolescents. The changes in S100B reference levels in children of different ages were also confirmed in the study by Castellani et al.[5] All of these studies show that S100B is definitely an age-dependent protein, and any future S100B TBI studies should use reference levels for specific age groups.

Another source of variability in the S100B levels in cases of TBI is the presence of additional injuries.[1,2,8,20] Although S100B can be found at high levels in astroglia and neurons, the lack of specificity of this biomarker for the CNS may create a distorted image in cases of mild TBI associated with multiple injuries. Concomitant systemic injuries, such as long bone fractures and extensive skin injuries, adipose tissue injuries, and muscle or joint injuries, can become a source of additional S100B release in the serum and thus perplex its diagnostic accuracy in TBI cases.[27]

The sampling time of S100B in relation to the time of head injury is also an important factor that may influence its serum concentrations and thus make the interpretation of any S100B increases inconclusive in TBI cases.[8,16] Delayed serum measurements of S100B following a head injury may lead to erroneous conclusions regarding the severity and extent of neuronal damage, because of the relatively short half-life of the S100B protein. Geyer et al.[8] emphasized the importance of the time span between injury and S100B blood sampling in the accurate measurement of S100B serum levels. It cannot be overemphasized that exact knowledge of blood sampling is mandatory for interpreting serum S100B levels and evaluating their association with the severity and prognosis of the underlying head injury.

The role of S100B as a biomarker in children suffering from mild TBI meets strong criticism in the literature. Studies by Geyer et al.,[8] Berger et al.,[3] and Akhtar et al.[1] demonstrated a low sensitivity for S100B in pediatric cases of mild TBI. In all of these series, serum levels of S100B failed to efficiently identify children with intracranial pathology on imaging studies.[1,3,8] These findings agree with those in the mild TBI study by Morochovic et al.,[16] which showed that S100B is an unreliable screening tool for detecting intracranial pathology in adults and children. On the other hand, the study by Castellani et al.[4] identified a role for S100B in the initial evaluation of children with mild TBI. These authors found that S100B had 100% sensitivity in identifying children with no intracranial pathology on obtained head CT scans. The authors clearly stated that selection biases could probably affect their study, since the decision to perform a CT scan was not blinded and only children with a progressively worsening clinical picture underwent CT scanning.[4] Nonetheless, their findings were promising, and the potential role of S100B in the triage of children with mild TBI should be explored in a large-scale, prospective clinical trial.

Conclusions

In summary, the role of the S100B biomarker in the initial evaluation of children with mild TBI is still controversial and remains to be defined. Many factors—including a patient's age, the serum sampling time, and the presence of multiple extracranial injuries—can influence the levels of S100B, yielding inadequate or even confusing results. The identification of a more specific biomarker for CNS injuries, the use of paired biomarkers in pediatric studies of mild TBI , and the design and performance of large-scale, prospective clinical studies could provide more data and shed more light on the ambiguous role of biomarkers in the evaluation of children with mild closed-head injuries.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author contributions to the study and manuscript preparation include the following. Conception and design: Filippidis. Acquisition of data: Filippidis. Analysis and interpretation of data: Filippidis, Kapsalaki. Drafting the article: all authors. Critically revising the article: all authors. Reviewed final version of the manuscript and approved it for submission: Fountas.

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Low rate of delayed deterioration requiring surgical treatment in patients transferred to a tertiary care center for mild traumatic brain injury

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Object. Patients with mild traumatic brain injury (mTBI) only rarely need neurosurgical intervention; however, there is a subset of patients whose condition will deteriorate. Given the high resource utilization required for interhospital transfer and the relative infrequency of the need for intervention, this study was undertaken to determine how often patients who were transferred required intervention and if there were factors that could predict that need.

Methods. The authors performed a retrospective review of cases involving patients who were transferred to the University of New Mexico Level 1 trauma center for evaluation of mTBI between January 2005 and December 2009. Information including demographic data, lesion type, need for neurosurgical intervention, and short-term outcome was recorded.

Results. During the 4-year study period, 292 patients (age range newborn to 92 years) were transferred for evaluation of mTBI. Of these 292 patients, 182 (62.3%) had an acute traumatic finding of some kind; 110 (60.4%) of these had a follow-up CT to evaluate progression, whereas 60 (33.0%) did not require a follow-up CT. In 15 cases (5.1% overall), the patients were taken immediately to the operating room (either before or after the first CT). Only 4 patients (1.5% overall) had either clinical or radiographic deterioration requiring delayed surgical intervention after the second CT scan. Epidural hematoma (EDH) and subdural hematoma (SDH) were both found to be significantly associated with the need for surgery (OR 29.5 for EDH, 95% CI 6.6–131.8; OR 9.7 for SDH, 95% CI 2.4–39.1). There were no in-hospital deaths in the series, and 97% of patients were discharged with a Glasgow Coma Scale score of 15.

Conclusions. Most patients who are transferred with mTBI who need neurosurgical intervention have a surgical lesion initially. Only a very small percentage will have a delayed deterioration requiring surgery, with EDH and SDH being more concerning lesions. In most cases of mTBI, triage can be performed by a neurosurgeon and the patient can be observed without interhospital transfer. *(DOI: 10.3171/2010.8.FOCUS10182)*

Key Words • **mild traumatic brain injury** • **cortical contusion** • **skull fracture** • **traumatic subarachnoid hemorrhage** • **subdural hematoma** • **brain concussion**

Mild traumatic brain injury is common due to various causes including sports-related accidents, assault, and motor vehicle collisions. Optimal treatment of these patients likely involves some degree of imaging and observation in a medical environment due to the potential fear of delayed deterioration.[15,22] The need for and timing of repeat imaging as well as the length of the observation period remains controversial, although basic treatment paradigms have been developed.[8,28] Furthermore, many community hospitals do not have the neurosurgical coverage that might be needed if deterioration were to occur. It has been shown that patients with mild-to-moderate TBI, with a lesion on the initial head CT scan that does not require immediate intervention, can safely be observed at a peripheral hospital without neurosurgical coverage. If surgery is required, as determined by a neurosurgeon via a teleradiology system, the decision can be made to transfer the patient to a tertiary care facility.[4] Because of inexperience in the treatment of patients with TBI, as well as concerns about potential litigation, patients are frequently transferred. These transfers are often at a high cost, use limited recourses in tertiary referral centers, and may result in further unnecessary expenditure (for example, due to a lack of transportation back to the referring facility when observation period is complete). We sought to evaluate the need for neurosurgical intervention in a cohort of patients transferred from other hospitals to UNM for evaluation and treatment of mTBI.

Abbreviations used in this paper: EDH = epidural hematoma; GCS = Glasgow Coma Scale; LOS = length of stay; mTBI = mild traumatic brain injury; SDH = subdural hematoma; TBI = traumatic brain injury; UNM = University of New Mexico.

Methods

A retrospective review from the UNM databases for the period January 2005 to December 2009 was performed with local institutional review board approval. Patients who were transferred to UNM for evaluation of mTBI (GCS Scores 13–15 at admission to UNM) were included and all patients with GCS scores < 13 were excluded. The GCS score at admission to UNM was used because such GCS scores are not routinely available from the other facilities involved. In pediatric patients, the pediatric modification of the GCS was used. The UNM trauma center is the only Level 1 trauma center in New Mexico and serves a catchment area that includes New Mexico and the surrounding regions of border states, with a total population of around 2.2 million. There is limited emergency neurosurgical coverage throughout the remainder of the state of New Mexico.

Baseline demographic data were extracted from the databases along with information regarding CT examinations (whether the patient had CT scanning of the head performed at UNM, the timing and findings of the first and second CT scans, and rate of worsening). In addition, data regarding need and timing of surgical intervention were recorded, as were disposition, LOS, and discharge GCS score. The group of cases involving patients who were surgically treated was examined for risk factors for surgery based on initial imaging.

Statistical analysis was performed by a professional statistician using SAS 9.2 software. Logistic regression was performed using stepwise variable selection to determine factors associated with the need for surgery based on initial CT findings.

Results

A summary of when CTs were performed and when patients went to the operating room is presented in Fig. 1. Of 292 patients, 15 (5.1%) were taken to the operating room either on arrival or after the first CT at UNM. In some cases, CT scans performed at other facilities were available to the treating team (indicated by the fact that 3 patients were taken to the operating room on arrival without an initial CT at UNM). The presence of these CTs and the images themselves were not available for analysis for this retrospective review. In a significant number of cases, either the patients never needed a CT or the imaging performed at the facility from which they were transferred was thought to be adequate, as evidenced by the 22 patients (7.5%) who never had a CT performed at UNM. Furthermore, in 85 cases (25.1%) the initial CT showed no acute findings (negative CT group). Overall, the initial CT was performed relatively early (an average of 3 hours, 22 minutes after the patient's arrival). The group characteristics are summarized in Table 1. All patients had GCS scores in the 13–15 range.

In 182 cases (62.3%) some type of traumatic lesion was evident on the initial CT scan. Table 1 compares the characteristics of the patients with a lesion on initial CT imaging to those with a nondiagnostic CT scan and the whole group. Of the 182 patients with a lesion seen on the initial CT, 12 patients (6.6%) were taken immediately to the operating room for neurosurgical procedures. In 60 cases (33%), it was not deemed necessary to obtain a follow-up CT scan, and the remaining 110 cases (60.4%) were managed with clinical observation and follow-up imaging. (Of note, 5 patients with negative findings on initial CTs also had follow-up CT imaging; in all 5 cases

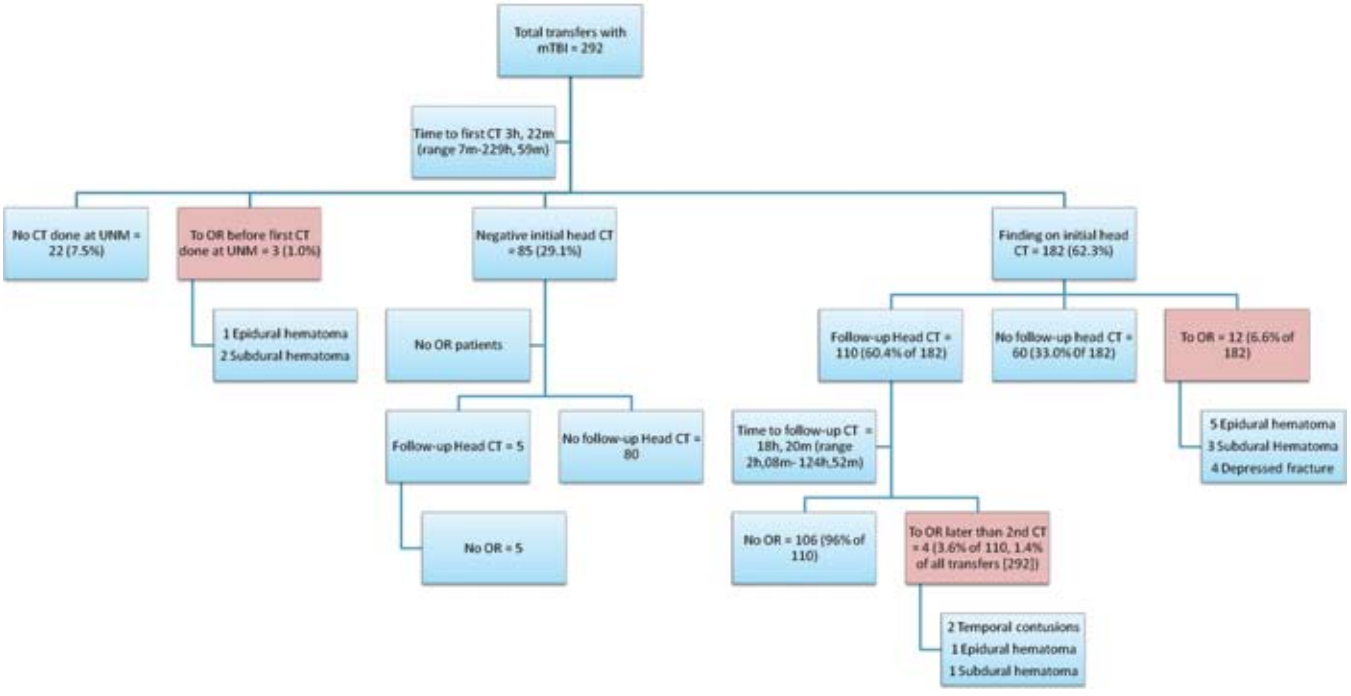

Fig. 1. Flowchart illustrating the management of 292 cases from patient arrival at UNM to final outcome. *Pink boxes* show the patients undergoing surgery and the timing of surgery. Abbreviations: h = hours; m = minutes; OR = operating room.

TABLE 1: Patient characteristics overall and stratified by findings on first CT*

Variable	All Patients	Patients w/ Positive 1st CT	Patients w/ Negative 1st CT
no. of patients	292	182	85
mean age (yrs)	33.7 ± 21.9	35.4 ± 23.0	32.6 ± 17.3
age range (yrs)	1–92	1–92	2–76
male	202 (69.2)	130 (71.4)	57 (67.1)
female	90 (30.8)	52 (28.6)	28 (32.9)
mean LOS (days)	6.3 ± 7.6	6.8 ± 6.4	5.5 ± 7.4
discharge from ED	62 (21.2)	14 (7.7)	42 (49.4)
discharge w/in 1 day	49 (16.8)	9 (4.9)	32 (37.6)
GCS score at discharge			
15	283 (96.9)	175 (96.2)	83 (97.6)
14	8 (2.7)	6 (3.3)	2 (2.4)
13	1 (0.3)	1 (0.5)	0 (0.0)

* Patients in the study group were admitted between January 15, 2005, and December 8, 2009. Values represent numbers of patients (%) unless otherwise indicated. Abbreviation: ED = emergency department.

the findings on follow-up CT were also negative.) Follow-up CT scans were performed an average of 18 hours, 41 minutes after the initial scan.

Of the 110 patients who underwent follow-up imaging to assess for progression, 13 demonstrated radiographic worsening on the second CT study, but only 4 patients were taken unexpectedly to the operating room (that is, despite plans for conservative treatment) some time after the second CT for neurosurgical procedure (see Table 2). In 3 of these cases, the second CT showed radiographic progression and in the third case, the patient showed clinical signs of deteriorating neurological condition. These 4 patients represent 1.4% of the overall group of transferred patients, 2.2% of patients with a traumatic finding on the initial CT, and 3.6% of patients observed with a follow-up CT. Table 2 summarizes the findings on the initial head CT in the overall group, the surgically treated patients, and the patients with radiographic worsening on the follow-up CT.

TABLE 2: Initial CT findings in the entire group, in the surgical group, and in patients with worsening on second CT*

Finding on 1st CT	Total (292 patients)	Surgically Treated (19 patients)	Worsening on 2nd CT (13 patients)
tSAH	68 (23.3)	4 (21.1)	2 (15.4)
EDH	19 (6.5)	6 (31.6)	1 (7.7)
SDH	53 (18.2)	7 (36.8)	4 (30.8)
pneumocephalus	23 (7.9)	0 (0)	3 (23.1)
fracture	77 (26.4)	8 (42.1)	7 (53.8)
contusion	72 (24.7)	6 (31.6)	10 (76.9)
negative	85 (29.1)	0 (0)	0 (0)
postop	3 (1.0)	3 (15.8)	NA
no CT performed	22 (7.5)	0 (0)	NA

* Values represent numbers of patients (%). Abbreviations: NA = not available; tSAH = traumatic subarachnoid hemorrhage.

Of the 4 patients who were treated surgically after initial plans for observation, 2 had fairly large temporal contusions that progressed on follow-up imaging. In addition, both of these patients had clinical worsening prior to intervention (Fig. 2A and B). One patient had an EDH associated with a fracture extending down into the floor of the middle fossa. Though the patient was neurologically intact and showed no signs of neurological deterioration, the hematoma was thought to be slightly increased in size on the follow-up images (Fig. 2C), and surgical evacuation was recommended to the patient. The fourth patient had suffered a concussion while playing football a week prior to admission, and was found to have an early subacute SDH after he presented with a seizure. He was neurologically intact at admission, but had a second seizure, and did not recover to baseline. Though the lesion remained stable, the decision was made to evacuate the hematoma because of neurological decline, and the patient subsequently recovered. All these patients recovered to a discharge GCS score of 14 or 15. Table 3 summarizes the characteristics of all patients who were treated surgically.

Logistic regression was performed using stepwise variable selection to determine if any of the factors (EDH, SDH, traumatic subarachnoid hemorrhage, contusion, pneumocephalus, or fracture) was independently associated with the need for surgery. Two-way interactions were included in the model, but none were significant. Both EDH and SDH were significantly associated with the patient having surgery, with a stronger association for EDH ($p < 0.0001$) than for SDH ($p = 0.0013$). There were no patients with both EDH and SDH. The odds ratio for a patient with EDH requiring surgery compared with all other patients was 29.5 (95% CI 6.6–131.8), and for SDH it was 9.7 (95% CI 2.4–39.1). A logistic regression model was also used to determine significant factors for worsening on second CT, and none of the findings were significant.

Overall, patients did well, with the discharge GCS score being 15 in 97% of patients and no deaths or patients discharged with a GCS score < 13. Overall, 49 patients (16.8%) were discharged home within 1 day, 62 (21.2%) were discharged from the emergency department, and the average LOS was 6.3 days. The average LOS was slightly longer in the group with positive findings on the initial CT examination (6.8 days) compared with 5.5 days in the group with negative findings (Table 1).

Discussion

This series demonstrates the potential for deterioration and need for surgical intervention in mTBI. We observed a rate of deterioration—either clinical or radiographic—to the point of needing surgery in 1.4% of all patients transferred with mTBI and in 3.6% of patients who had a positive finding on initial CT and underwent follow-up imaging. Available data suggests that although between 5% and 13% of patients with a GCS score of 15 evaluated in the emergency department will have a trau-

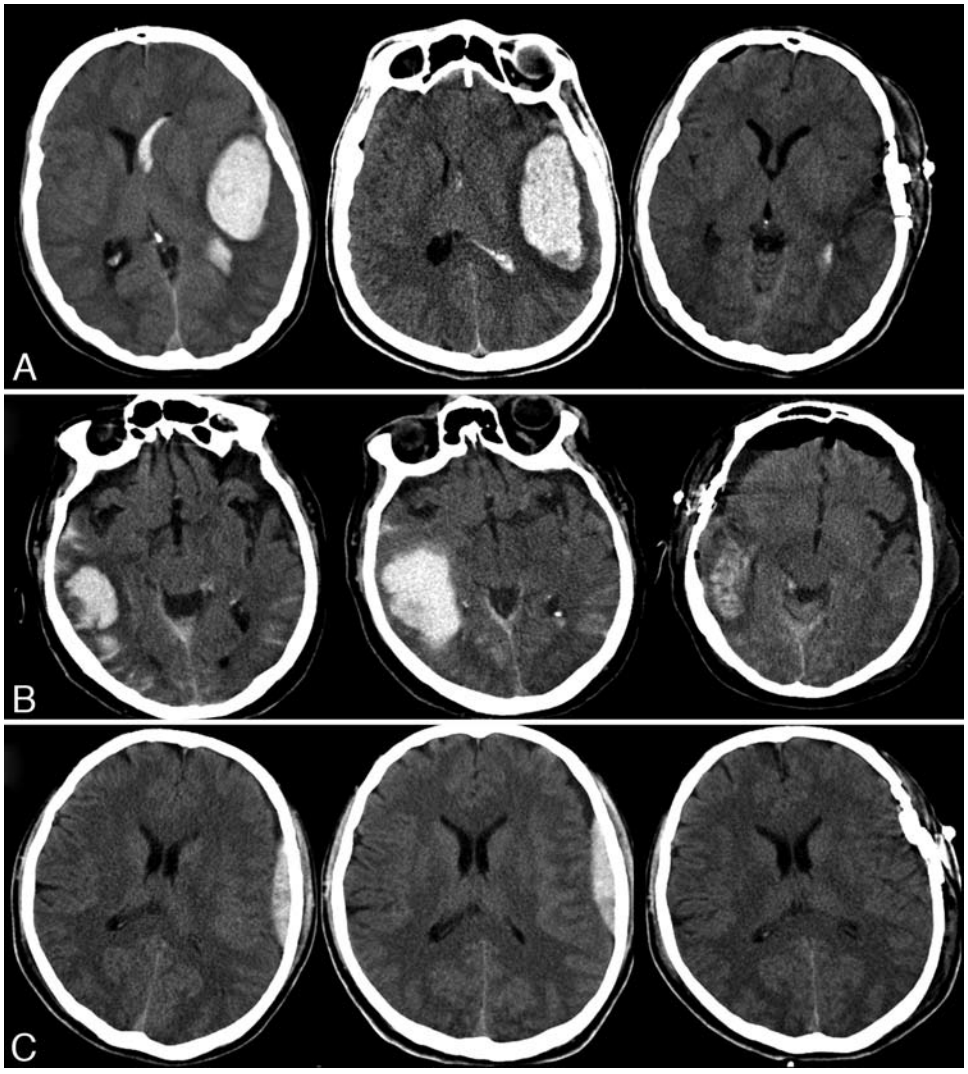

Fig. 2. Axial CT scans obtained in 3 of the patients who were initially observed with follow-up imaging and required surgical intervention at some point after the second CT. **A:** This 23-year-old man presented with headache and confusion (GCS Score 14) 3 days after assault *(left image)*. Given the extensive hematoma and intraventricular hemorrhage, a CT angiogram was performed, showing increased volume of contusion *(middle image)*. Based on this increase, surgical evacuation of the hematoma was performed (postoperative image on *right*). **B:** This 77-year-old man, who was in a motor vehicle collision, arrived confused but awake (GCS Score 13) with a left temporoparietal hematoma *(left image)*. On follow-up imaging, the hematoma showed expansion *(middle image)*; therefore, surgical evacuation was performed (postoperative image on *right*). **C:** This 27-year-old man was hit in the left temporal region by a falling tree branch. He was neurologically intact on arrival to UNM (GCS Score 15), and initial CT showed an EDH with an associated fracture extending into the middle fossa *(left image)*. The follow-up CT showed slight expansion *(middle image)*, especially in the temporal region, and so surgical evacuation was performed despite a lack of change in findings on neurological examination (postoperative image on *right*).

matic lesion of some type on CT,[8,10,17] < 1% of patients will require neurosurgical intervention.[13,16] Due to the fact that such a lesion is uncommon but potentially devastating if missed, much work has focused on accurate identification of these patients.[6,28]

The concept of patients whose condition is initially stable and then deteriorates has been well described,[15,22] and it seems that initial mass lesions such as parenchymal hematomas or contusions likely increase the probability of this potentially devastating consequence.[15] This was confirmed in our series with 2 of the patients requiring delayed surgery having relatively large temporal hematomas, though overall, due to the large number of small contusions on initial imaging, the finding did not reach significance with regard to the need for surgery. When specific criteria are applied to patients with mTBI (GCS Score 15, no loss of consciousness, amnesia, vomiting, or headache), the risk of developing a lesion requiring neurosurgical intervention is 0.1%–0.6%.[2,10,13] There are also clinical and radiographic factors that predict subsequent deterioration and need for neurosurgical intervention. Two attempts to formalize this system include the Canadian CT Head Rule and the New Orleans Criteria.[3,8,21,26–28] These systems have both proven to be highly sensitive in identifying high-risk patients and have been externally validated.[26] The New Orleans Criteria are likely more

TABLE 3: Characteristics of the surgical group (19 patients)*

Characteristic	Value
FU CT findings	
stable	1 (5.3)
worse	3 (15.8)
resolved	0 (0.0)
improved	0 (0.0)
postop	11 (57.9)
no FU or 1st was postop	4 (21.1)
mean LOS (in days)	7.63 ± 7.6
discharge from ED	0 (0.0)
discharge w/in 1 day	0 (0.0)
GCS score at discharge	
15	16 (84.2)
14	3 (15.8)
13	0 (0.0)
surgery after 2nd CT	4 (21.1)
surgery type	
EDH evacuation	7 (36.8)
SDH evacuation	6 (31.6)
fracture elevation	4 (21.1)
contusion evacuation	2 (10.5)

* Values represent numbers of cases (%) unless otherwise indicated.
Abbrevation: FU = follow-up.

sensitive for detecting significant CT lesions, but the Canadian CT Head Rule still seems reliable for identifying all patients who need neurosurgical intervention.[26,27]

The need for routine repeat head CT[30,31] as well as even neurosurgical consultation[12] has been called into question in patients with mTBI as emphasis is increasingly placed on cost savings in medicine. We recently performed a systematic review of the literature looking at the need for routine repeat head CT in patients with mTBI, and found an overall incidence of need for neurosurgical intervention of 2%. When CT was performed for neurological decline, the chance of needing surgical intervention was 58% compared with only 0.3% chance if the CT was done for routine follow-up, suggesting the importance of serial clinical examination as compared with routine imaging follow-up (unpublished data).

On review of the 4 cases with delayed need for neurosurgical intervention, all of the patients would have been defined as high risk based on either the Canadian CT Head Rule or the New Orleans Criteria. Furthermore, the findings on initial imaging were all sufficiently significant that the clinician would be unlikely to pass over the patients for observation at an outside facility. Two patients presented with relatively large temporal contusions (one 3 × 4 cm and one 4 × 5 cm) and likely due to a combination of evolution of the contusions and pericontusional edema progressed to the point of needing surgical evacuation. Though there are no established guidelines, and our data set is too small to make definitive conclusions, it seems reasonable that contusions (especially temporal ones) of significant size should be observed in a tertiary center with a neurosurgeon. The third case was that of a patient with a growing epidural hematoma associated with a fracture. These are well known to be dangerous lesions due to the potential for arterial laceration, and so all cases should probably be observed by a neurosurgeon. This is further supported by the significantly higher rate of patients with epidural hematomas who required surgical intervention based on the initial evaluation (that is, without delayed deterioration). The final case of deterioration was in a young patient with a relatively large subacute SDH with 6 mm of midline shift. This lesion was not a rapidly progressive one, but was evacuated due to the increasingly symptomatic condition of the patient. In all 4 of these cases the patients would probably not have been passed over for transfer, even with a very restrictive policy.

There was a second group of patients (including those with SDHs, EDHs, and depressed skull fractures) who required surgical intervention immediately on arrival. Given that these patients were all doing relatively well clinically on admission (GCS Scores 13–15), the decision to operate was made primarily on the basis of radiographic data. We assert that these patients also would have all been transferred to a neurosurgical service if this radiographic information was known. Based on our data, EDH and SDH are the lesions most significantly associated with a subsequent need for surgery, whether immediate or delayed. Many of these lesions were not progressive ones (fracture and chronic SDH), but it is possible that some of the remaining patients had expansion of the lesion in the period between the facility they were transferred from and the arrival at UNM. The imaging data from the other facilities were not available for these patients, though if such expansion occurred, it is possible that several more of these patients would have been considered in the "delayed deterioration" group.

This brings up the role of telemedicine in patient evaluation. The ability of a neurosurgeon to actually see the radiological images obtained in a patient is of critical importance—rather than simply making a decision based on a verbal report. Other neurological fields such as stroke therapy have made excellent process in implementing stroke systems to evaluate and treat these patients in outlying facilities.[25] Image transfer systems have been initiated across the world for many years specifically to address the need for neurosurgeons to evaluate images before the transfer of patients.[5,11,23,29] The effect of these systems, where available, has proved to be significantly beneficial in terms of mitigating cost of unnecessary transfer. One group in Italy found that only 23% of patients (with a mean GCS score of 11) who had images sent on a teleradiology system required transfer after the initial CT images were sent, and only 5% after follow-up CT.[24] A Level 2 trauma center in Israel found that with the implementation of teleradiology, 40% of patients with TBI were successfully treated at their facility, with only 2 patients requiring delayed transfer to a Level 1 center.[1] A recent evaluation of transfers in Germany showed that after image transfer, patient transfer was deemed unnecessary in 67% of potential neurosurgical cases, and the cost of the teleradiology system was amortized in 15 months

of use due to the cost savings.[14] With the recent rapid rise and availability of high-bandwidth wireless systems, the use of handheld devices in making determinations of the need for transfer may allow photographs and even short videos to be sent even from facilities with limited resources.[19,20,32] For more complex evaluation, systems of video consultation have been used to determine the need for interhospital transfer as well.[33]

With increasing trends toward the regionalization of care, the need for established guidelines for in-hospital treatment and transfer of patients to a higher level care facility are being increasingly developed and used. In Canada, a pilot project that simplifies and standardizes the treatment of patients with TBI has been implemented, using a simple poster with guideline-based decision tools for treatment of these patients.[9] This regionalization of treatment of mTBI is essential because it has been shown that early aggressive transfer and treatment of patients with severe TBI decreases mortality.[7] Decision rules to identify these patients have been developed.[18] The limited availability of beds and resources, therefore, must be prioritized to these severely injured patients.

The amount of potentially unnecessary transfers for mTBI was relatively high in this series. Though all of the included patients were transferred with some type of mTBI (concussion or decreased GCS), a relatively high number did not require any further diagnostic intervention upon arrival, many had negative findings on head CT, and many were discharged home from the emergency department or within a short stay. No standardized guidelines exist, and transfer of patients is based on the discretion of the accepting neurosurgeon, emergency physician, or trauma surgeon. In addition, if the referring health care provider is uncomfortable with a case, the patient may be transferred to another facility. No definitive statement regarding unnecessary transfers can be made on the basis of our series, because many of the patients needed other trauma or orthopedic intervention, some of whom might have been treated at the referring facility, and some of whom could not have been. Based on these data and the above-described studies, we propose a general algorithm for the treatment of patients referred from an outside facility. This algorithm takes into consideration the availability of telemedicine, the type of lesion seen on initial imaging, and factors such as patient age and anticoagulation therapy (Fig. 3).

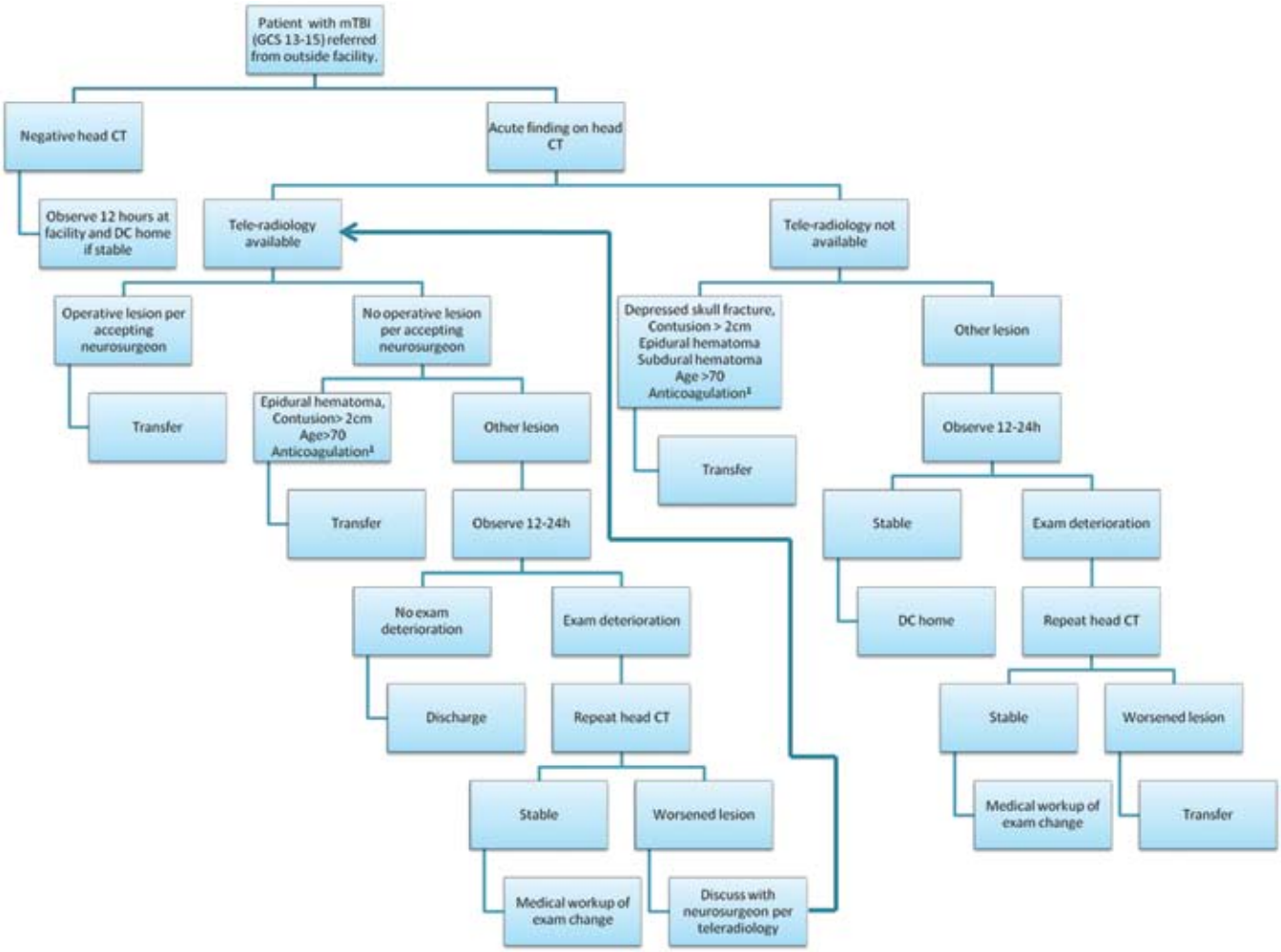

Fig. 3. Proposed algorithm for the treatment of patients referred with mTBI. Anticoagulation[1] refers to patients being treated with clopidogrel or with an international normalized ratio > 1.5. DC = discharge.

Other limitations of the current study include the lack of imaging data. Some patients may not have had an initial head CT if the facility at which they initially presented was a very small one without a CT scanner. In some other cases, an initial head CT might have been performed at the outside facility, but the CT was not available for review. This leads to the assumption that the initial CT study performed at UNM served as a baseline examination, though it is possible that some of the patients who were treated surgically may initially not have had a surgical lesion on imaging studies performed at the outside facility. If this were the case, the number of patients with delayed surgery could have been slightly higher. In addition, there was no set protocol during the study period for the need of repeat imaging, so follow-up imaging was variable. Data on the reason for ordering follow-up imaging was limited in the charts in terms of the patient's clinical status, so no statement can be made regarding the role of the clinical examination, except as described in the surgical cases.

Conclusions

In a series of patients transferred to a Level 1 trauma center for mTBI, only a small number will have delayed deterioration requiring neurosurgical intervention. In our case series, these patients presented with significant lesions, including large temporal contusions, SDH, and EDH with fracture, and probably would not have been passed over for transfer. Of the patients with mTBI who underwent a neurosurgical procedure, most had surgical lesions present at the outset. Our findings support the importance of teleradiology systems in patient evaluation for transfer. Most patients with mTBI can likely be triaged and observed without routine interhospital transfer to a Level 1 trauma center, and guidelines should be developed and implemented.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper. Statistical analysis was supported via a grant through the Clinical Translational Science Center at UNM.

Author contributions to the study and manuscript preparation include the following. Conception and design: Stippler, Kennedy, McLean. Acquisition of data: Stippler, Carlson, Ramirez, Kennedy, McLean. Analysis and interpretation of data: Carlson. Drafting the article: Carlson, Ramirez. Critically revising the article: Carlson, Kennedy. Reviewed final version of the manuscript and approved it for submission: Stippler, Carlson. Statistical analysis: Murray-Krezan.

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This article has been updated from its originally published version to correct sentences in the *Abstract* and *Discussion*.

See the corresponding erratum notice in the November 2010 issue for full details.

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A prospective study of physician-observed concussions during junior ice hockey: implications for incidence rates

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Object. The objective of this study was to measure the incidence of concussion (scaled relative to number of athlete exposures) and recurrent concussion within 2 teams of fourth-tier junior ice hockey players (16–21 years old) during 1 regular season.

Methods. A prospective cohort study called the Hockey Concussion Education Project was conducted during 1 junior ice hockey regular season (2009–2010) involving 67 male fourth-tier ice hockey players (mean age 18.2 ± 1.2 years, range 16–21 years) from 2 teams. Prior to the start of the season, every player underwent baseline assessments using the Sideline Concussion Assessment Tool 2 (SCAT2) and the Immediate Post-Concussion Assessment and Cognitive Test (ImPACT). The study protocol also required players who entered the study during the season to complete baseline SCAT2 and ImPACT testing. If the protocol was not followed, the postinjury test results of a player without true baseline test results would be compared against previously established age and gender group normative levels. Each regular season game was observed by a qualified physician and at least 1 other neutral nonphysician observer. Players who suffered a suspected concussion were evaluated at the game. If a concussion diagnosis was made, the player was subsequently examined in the physician's office for a full clinical evaluation and the SCAT2 and ImPACT were repeated. Based on these evaluations, players were counseled on the decision of when to return to play. Athlete exposure was defined as 1 game played by 1 athlete.

Results. Twenty-one concussions occurred during the 52 physician-observed games (incidence 21.5 concussions per 1000 athlete exposures). Five players experienced repeat concussions. No concussions were reported during practice sessions. A concussion was diagnosed by the physician in 19 (36.5%) of the 52 observed games. One of the 5 individuals who suffered a repeat concussion sustained his initial concussion in a regular season game that was not observed by a physician, and as a result this single case was not included in the total of 21 total concussions. This initial concussion of the player was identified during baseline testing 2 days after the injury and was subsequently medically diagnosed and treated.

Conclusions. The incidence of game-related concussions (per 100 athlete exposures) in these fourth-tier junior ice hockey players was 7 times higher than the highest rate previously reported in the literature. This difference may be the result of the use of standardized direct physician observation, diagnosis, and subsequent treatment. The results of this study demonstrate the need for follow-up studies involving larger and more diverse sample groups to reflect generalizability of the findings. These follow-up studies should involve other contact sports (for example football and rugby) and also include the full spectrum of gender, age, and skill levels. *(DOI: 10.3171/2010.9.FOCUS10186)*

Key Words • **concussion** • **ice hockey** • **incidence** • **Canada**

Current literature on ice hockey concussion incidence does not use a single agreed-upon definition or methodology. Very few studies use direct physician-based data collection, and an internationally agreed-upon return-to-play protocol.[19] This research inconsistency may result in a paucity of significant concussion incidence data and contribute to an underreporting of the true incidence of this important injury.

Sport concussions can have cumulative and long-lasting effects on memory, judgment, social conduct, reflexes, speech, balance, and coordination. Epidemiological studies have suggested an association between sport concussions and both immediate and later-life cognitive impairment.[4,5,12,13,19–21,26,27] For example, data from a small sample of retired professional football players demonstrated an increased risk and earlier onset of memory

Abbreviations used in this paper: HCEP = Hockey Concussion Education Project; ImPACT = Immediate Post-Concussion Assessment and Cognitive Test; MBESS = Modified Balance Error Scoring System; SAC = Standardized Assessment of Concussion; SCAT2 = Sideline Concussion Assessment Tool 2.

impairment, mild cognitive impairment, and Alzheimer's dementia.[12,13] Furthermore, anecdotal case reports have noted neuropathological evidence of chronic traumatic encephalopathy in some retired professional football players.[20] In 2009, there was a news release of 1 case of chronic traumatic encephalopathy in a former National Hockey League player.[27]

Investigation of the true incidence of sport concussions may require direct observation and diagnosis by an independent, trained physician. The primary goals of this study were to prospectively measure the direct physician-observed incidence of concussion (scaled relative to number of athlete exposures) and recurrent concussion within 2 teams of junior ice hockey players during 1 regular season (36 games), utilizing the concussion definition and return-to-play protocol from the 2009 Zurich consensus statement from the 3rd International Conference on Concussion in Sport.[19]

Methods

Participants and Sampling

Between September 2009 and February 2010, 67 male fourth-tier junior ice hockey players (mean age 18.2 ± 1.2 years, range 16–21 years), from 2 teams (Team A and Team B), consented to participate in the HCEP. Team A was observed during 34 of the 36 regular season games. Two games of Team A were not observed. One missed game occurred secondary to their baseline evaluations occurring after their first game. The second missed game resulted from suspension of the HCEP for 1 game after the improper return to play of a Team A player following an observed and diagnosed concussion incident. The HCEP was halted until an addendum was added to the protocol that addressed this type of event. The player involved was subsequently removed as a study participant.

Team B was observed during 21 of the 36 regular season games. Team B withdrew their participation after Game 21 of the season, because of an inability to comply with the HCEP protocol. After due process Team B was removed from the study, and ended its participation at Game 21 of the 36-game season.

Seventeen players from both teams played 5 regular season games or fewer.

Concussion Definitions

The definition of concussion for this study was derived from the 2009 Zurich consensus statement on concussions from the 3rd International Conference on Concussion in Sport.[19] Concussion was clinically diagnosed utilizing an observed or self-reported mechanism (such as a blow to the head or body), immediate or delayed neurological signs (player is unstable, lacks coordination, or is slow to return to play) or symptoms (player experiences headache, dizziness, or alteration of vision) and abnormal SCAT2 or ImPACT test results. A self-reported concussion was defined as a concussion that was not identified by the physician or nonphysician observers at an observed game. The players who self-reported concussions subsequently presented to the physician for diagnostic evaluation, either at the end of the game or in the days following that game.

Neuropsychological Measures

Two standardized concussion assessment tools, the SCAT2 and ImPACT, were administered to all players before the season began and to each player after a physician-observed and diagnosed concussion.

The SCAT2 is an accessible and free screening tool that was developed by the 3rd International Conference on Concussion in Sport held in Zurich, Switzerland, in 2008. The SCAT2 is an improved version of the original SCAT developed in 2005.[19] Although this tool has not yet been validated as a whole, individual components have been validated, such as the SAC, the Balance Error Scoring System, the Maddox Score, Glasgow Coma Scale, and the Concussion Symptom Inventory.

The ImPACT is a computerized concussion evaluation system and is (at the time of this writing) the most widely used, although it has not been independently evaluated. The ImPACT takes approximately 20 minutes to complete and measures multiple aspects of cognitive functioning in athletes including attention span, working memory, sustained and selective attention time, response variability, nonverbal problem solving, and reaction time.

At the ice hockey rink the SCAT2 Symptom Inventory, Modified Balance Error Scoring System (MBESS), and SAC were recorded during concussion evaluation by a physician. The SCAT2 utilizes the MBESS that is performed on the ground and does not use a secondary balance platform for the 3 balance positions. At the postinjury office evaluation the ImPACT as well as the aforementioned components of the SCAT2 were tested. The ImPACT results for the HCEP were independently evaluated by a remote certified neuropsychologist. Although the ImPACT is a commonly used and relatively accessible test, it is a psychometric test whether it is computer-generated or not, and calls for a refined level of understanding available to the registered psychologist with training in psychometrics and neuropsychological diagnostic skills.[28] The remote independent neuropsychological analysis of this diagnostic tool also eliminates possible bias that may exist when a team physician is interpreting the test for an athlete that he or she works with on a regular basis.

General Procedures

Each participant signed an informed consent form, and provided a release of medical information form at the outset of the study. Each team's board of directors and the participating league's board of directors gave consent for participation in the study. The executives of both teams were asked to inform the primary investigator when a player left the team roster or was added to the roster, so that appropriate baseline testing could be performed. The Health Sciences Research Ethics Board at The University of Western Ontario approved the study.

Procedure for Concussion Surveillance

Concussion surveillance was conducted at each regular season game of the participating teams by 1 indepen-

dent physician and 1 to 3 independent, nonphysician observers. There were 6 licensed physician observers, all of whom had experience as ice hockey team physicians and 5 of whom had sports medicine certification. There were 16 nonphysician observers (5 kinesiologists, 2 certified ice hockey coaches, 5 ice hockey executives, 1 physical therapist, 1 massage therapist, 1 chiropractor, and 1 former junior ice hockey player). Independent physician and nonphysician observers were defined as individuals who were not affiliated on a regular basis with the team or teams that they were evaluating. This independence allows for the elimination of possible identification and clinical decision-making bias that may affect the evaluation and return-to-play decision due to the familiarity with the athletes and team.

Before entering the study the physician and nonphysicians were verbally instructed for 20 minutes on their observation and reporting duties. Each observer was asked to complete a 23-question descriptive form to document each observed and diagnosed concussion. The physician and the observers were placed at elevated and well-balanced positions around the ice rink, so as to have direct views of the play from a variety of vantage points. Communication between the physician and nonphysician observers, as well as the physician and team therapist/first responder/trainer was by walkie-talkie. Practice sessions were not directly observed during this study. A flowchart concerning the methods of concussion identification, treatment, and return-to-play protocol is provided in Fig. 1.

In the event of an on-ice extended period of loss of consciousness, or situations in which the player experienced neurological signs or symptoms (such as severe neck pain, limb motor/sensory changes, or seizure), play was suspended, an emergency 911 call was made, and the player was maintained with neck stabilization and trauma support until paramedics arrived for transport to the nearest hospital emergency department.

For an observed concussion that did not result in an emergency department evacuation, the team therapist/first responder was asked by the physician observer to remove the player from the game. The player was then immediately evaluated by the physician away from the locker room and ice surface, while other observers remained in place. Clinical evaluations of the player with a suspected

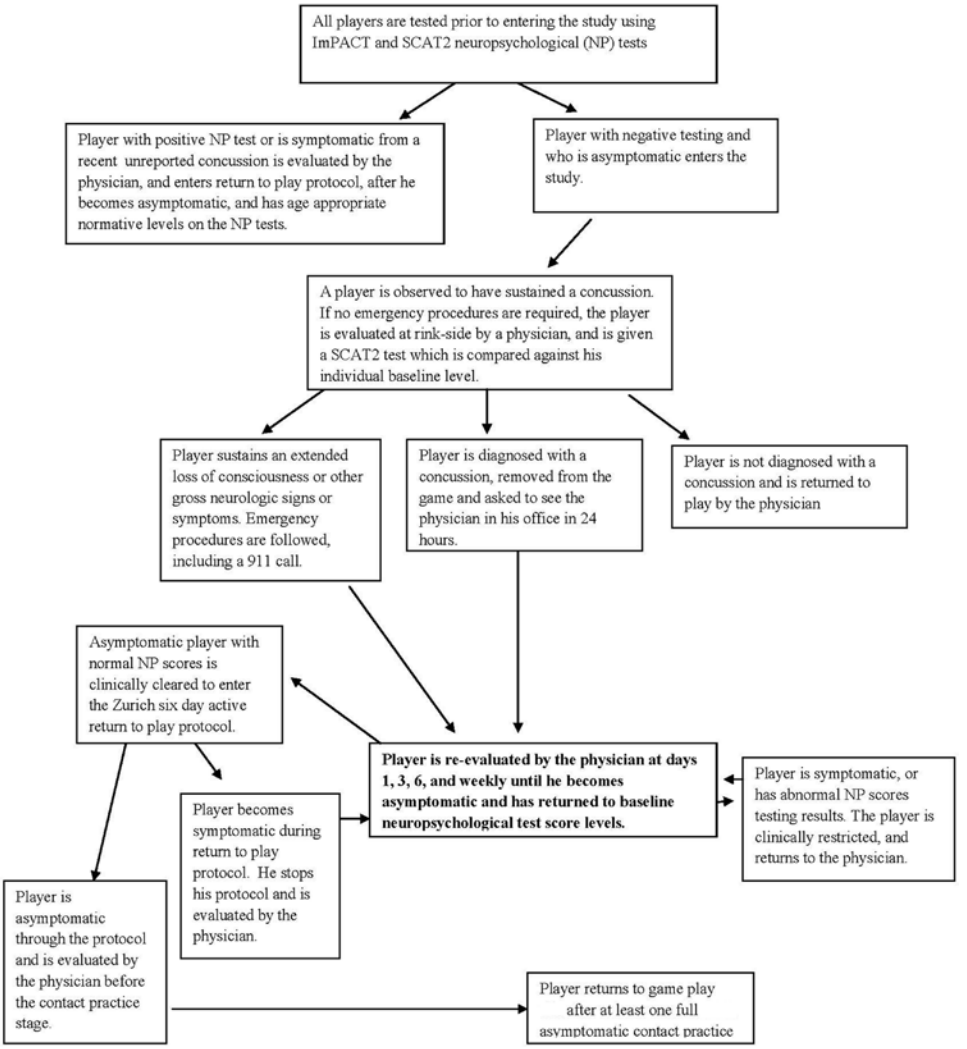

Fig. 1. Flowchart of the methods of concussion identification, treatment, and return-to-play protocol.

concussion included SCAT2 testing at the rink. If a concussion diagnosis was made, instructions regarding precautions were given to both the player and a responsible adult (such as a coach or parent). Both individuals were requested to attend a follow-up evaluation the next day in the office of the primary investigator who is a physician.

All players involved in on-ice fights who were observed to sustain a blow to the head were removed from the game and after a "cool-down" period of 30 to 60 minutes were clinically assessed by the game physician, involving a neurological examination and SCAT2. These players were also asked to complete an ImPACT the following day at the medical office of the primary investigator. Clinical office evaluations (after the rinkside diagnosis of the concussion) were performed on Days 1, 3, and 6, and then weekly as needed until the player was cleared to return to play.

Clinical Definition of Return to Play

All return-to-play decisions were made by the primary investigator on the basis of clinical judgment. The physician also drew upon the results of the SCAT2 objective components and ImPACT scores to determine when test results returned to the previously recorded baseline levels. If a baseline ImPACT had not been performed, the athlete was compared against established age-group normative levels. After clinical and neuropsychological clearance was obtained, each injured player returned to competitive play only after successfully completing the 6-day progressive and active return-to-play protocol defined in the consensus statement of international expert opinion at the 3rd International Conference on Concussion in Sport.[19] Teams that played in opposition to an HCEP-observed team and game officials were made aware of the physician at each game, and of their availability to evaluate any injuries. Two players from opposing HCEP teams were identified, diagnosed, and treated by the game physician for concussion during the 52 observed games. In both cases the physicians had to actively offer their services to the opposing team after the observed injury. Concussions identified in this fashion were not included in the incidence calculations.

Statistical Analysis

The incidence of concussion was calculated as the number of observed or self-reported concussions occurring during observed games, divided by the total number of athlete exposures. Athlete exposures were defined within this sample as the sum of all games played, and were summed for all players. This method of determining the denominator for the incidence calculation is deliberately conservative, and includes all athlete exposures, regardless of the length of time played within any given game.

Results

Twenty-one concussions were physician observed or self-reported and subsequently physician diagnosed in 52 physician-observed regular season games, yielding an incidence of 21.52 concussions per 1000 athlete exposures. A concussion was diagnosed in 19 (36.5%) of 52 observed games. The data from the study (Table 1) demonstrated a general trend of decreasing severity and normalization of the objective measures (SCAT2 symptom inventory, MBESS, SAC score, and ImPACT evaluation) toward the injured player's baseline levels over time.

Seventeen players suffered a physician observed or self-reported physician-diagnosed concussion during a physician-observed game, and 5 (29%) of these 17 players also suffered a second concussion during the study period. One of the 5 individuals who suffered a repeat concussion sustained his initial concussion in a regular season game that was not observed by a physician, and as a result this single case was not included in the total of 21 total concussions. This initial concussion of the player was identified during baseline testing 2 days after the injury and was subsequently medically diagnosed and treated. The mean time interval between the first and second concussions of these 5 players was 78.6 days (median 82 ± 39.8 days), and the mean time between the return-to-play date of the first and second concussions was 61.8 days (median 60 ± 39.7 days).

Eighteen (53%) of the 34 potential concussions identified by the physician and nonphysician observers were positively diagnosed by the physician at rinkside. Three of the diagnosed concussions were not directly identified in an observed game, and were self-reported to the physician either at rinkside or within the next 48 hours. The remaining 16 (47%) of the concussions that were initially identified by the observers were returned to play after a negative clinical and SCAT2 evaluation by the physician.

A total of 67 players competed in at least 1 game during the 2009–2010 regular season. Forty-six (69%) of these 67 players completed baseline SCAT2 and ImPACT testing at the start of the season. No further baseline testing was completed for players entering the study after initial testing was completed, as a result of team and individual noncompliance with the study protocol agreement.

Fifty-three of the 67 players provided a medical history of previous concussions prior to the start of the study. There was no concussion history provided by the remaining 14 players. Thirty-one (58%) of these 53 players denied sustaining any previous concussions. Thirty-four percent (18 of 53) admitted to sustaining 1 to 2 previous concussions. Four (8%) of these 53 players admitted to sustaining 3 or more previous concussions.

Fifteen (88%) of the 17 players with a diagnosed concussion admitted to having experienced at least 1 concussion in the past. Two of the 17 players who suffered a concussion during the study admitted that they had concealed a concussion sustained during the current season to keep playing. Three of the 17 players who sustained a concussion identified themselves to team officials. All 3 players were medically diagnosed with a concussion, and were treated appropriately. Two of the 17 players with the diagnosis of a concussion suffered associated injuries. One player suffered a separated shoulder and another player suffered a dislocated shoulder.

Fifteen (22%) of all 67 participating players played 5 regular season games or fewer. Three of the 15 players who participated in 5 regular season games or less were diagnosed with a concussion. These 3 players eventually returned to play: 1 player was medically cleared to return

TABLE 1: Objective-measure results for the 17 HCEP players who sustained concussions during a physician-observed game*

Case No. (Test)†	CRTP Interval (days)	Baseline	Day of Injury	Office Visit No. 1	2	3	4	5	6	7	8
1	refused FU, out of study			refused FU							
SCAT2		NP	0/0								
SAC			25/30								
MBESS			24/30								
2	refused FU, out of study			refused FU							
SCAT2		NP	10/17								
SAC			30/30								
MBESS			21/30								
3	10			PID 4							
SCAT2		0/0	7/8	0/0							
SAC		25/30	28/30	29/30							
MBESS		27/30	NP	21/30							
IC/IR		IC		IC							
4	16			PID 3	PID 10						
SCAT2		NP	0/0	1/1	0/0						
SAC			28/30	25/30	28/30						
MBESS			NP	27/30	30/30						
IC/IR				IC	IC						
5a	10			PID 1	PID 4						
SCAT2		0/0	1/4	0/0	0/0						
SAC		24/30	24/30	25/30	25/30						
MBESS		26/30	NP	NP	25/30						
IC/IR		IC		IC	IC						
5b	no CRTP clearance for remainder of season		0	PID 1	PID 5	PID 18	declined further testing				
SCAT2		0/0	12/26	6/10	3/4	3/4					
SAC		24/30	21/30	25/30	26/30	27/30					
MBESS		26/30	23/30	26/30	21/30	22/30					
IC/IR		IC		IR	IR	IC					
6 (SRP)	28			PID 2	PID 4	PID 8	PID 18				
SCAT2		14/35	NP	17/38	17/27	5/5	0/0				
SAC		30/30	SRP	27/30	28/30	28/30	29/30				
MBESS		27/30		28/30	27/30	24/30	30/30				
IC/IR		IR		IR	IC	IC	IC				
7a (SRP)	29			PID 2	PID 6	PID 11	PID 18	PID 23			
SCAT2		3/4	NP	10/14	1/1	0/0	0/0	0/0			
SAC		27/30	SRP	25/30	27/30	27/30	28/30	27/30			
MBESS		27/30		NP	24/30	28/30	28/30	28/30			
IC/IR		IC		IR	IR	IR	IC	IC			

(continued)

TABLE 1: Objective-measure results for the 17 HCEP players who sustained concussions during a physician-observed game* *(continued)*

Case No. (Test)†	CRTP Interval (days)	Baseline	Day of Injury	Office Visit No. 1	2	3	4	5	6	7	8
7b	9			PID 3							
SCAT2		3/4	0/0	0/0							
SAC		27/30	29/30	29/30							
MBESS		27/30	NP	28/30							
IC/IR		IC		IC							
8a	15			PID 2	PID 4	PID 9					
SCAT2		6/30	5/7	2/2	0/0	0/0					
SAC		28/30	27/30	27/30	24/30	29/30					
MBESS		25/30	NP	18/30	23/30	30/30					
IC/IR		IC		IR	IR	IC					
8b	8 (delayed due to shoulder injury)			PID 2							
SCAT2		6/30	0/0	1/2							
SAC		28/30	28/30	29/30							
MBESS		25/30	26/30	25/30							
IC/IR		IC		IC							
9a	12			PID 3	PID 6						
SCAT2		13/14	4/5	2/2	0/0						
SAC		24/30	20/30	23/30	24/30						
MBESS		30/30	NP	28/30	27/30						
IC/IR		IC		IC	IC						
9b	refused FU, out of study			refused FU							
SCAT2		13/14	0/0								
SAC		24/30	29/30								
MBESS		30/30	24/30								
IC/IR		IC									
10	10			PID 1	PID 5						
SCAT2		8/10	9/13	3/3	1/1						
SAC		24/30	25/30	29/30	30/30						
MBESS		19/30	12/30	30/30	27/30						
IC/IR		IC		IR	IC						
11	9			PID 3							
SCAT2		NP	3/4	1/1							
SAC			26/30	26/30							
MBESS			26/30	23/30							
IC/IR				IC							

(continued)

TABLE 1: Objective-measure results for the 17 HCEP players who sustained concussions during a physician-observed game* *(continued)*

Case No. (Test)†	CRTP Interval (days)	Baseline	Day of Injury	Office Visit No. 1	2	3	4	5	6	7	8
12	7			PID 1							
SCAT2		4/6	0/0	0/0							
SAC		28/30	25/30	26/30							
MBESS		28/30	NP	NP							
IC/IR		IC		IC							
13	sent to ER for evaluation on Day 1, refused FU, out of study			PID 1	PID 3	refused further FU					
SCAT2		NP	8/23	22/60	13/30						
SAC			23/30	21/30	28/30						
MBESS			23/30	NP	24/30						
IC/IR				NP	IR						
14	7			PID 1							
SCAT2		2/2	2/4	0/0							
SAC		22/30	28/30	23/30							
MBESS		27/30	NP	28/30							
IC/IR		IC		IC							
15	15			PID 2	PID 6	PID 9					
SCAT2		9/19	18/49	8/8	3/3	0/0					
SAC		27/30	20/30	26/30	26/30	27/30					
MBESS		29/30	18/30	21/30	27/30	26/30					
IC/IR		IC		IR	IC	IC					
16	no CRTP clearance for regular season or playoffs, neurosurgical consult			PID 2	PID 5	PID 8	PID 16	PID 20	PID 33	PID 55	PID 75
SCAT2		4/9	NP	3/3	1/1	14/25	19/47	7/8	9/10	3/3	5/7
SAC		24/30		29/30	30/30	28/30	29/30	28/30	NP	28/30	NP
MBESS		28/30		30/30	27/30	23/30	29/30	25/30	NP	27/30	NP
IC/IR		IC		IR	IR	IR	IR	IR	IR	IR	IR
17	7			PID 1							
SCAT2		0/0	0/0	0/0							
SAC		28/30	26/30	29/30							
MBESS		22/30	NP	28/30							
IC/IR		IC		IC							

* CRTP = clinical return to play; ER = emergency room; FU = follow-up; IC = ImPACT neuropsychological-based clearance given by neuropsychologist; IR = ImPACT neuropsychological-based restriction given by neuropsychologist; NP = not performed; PID = postinjury day; SRP = self-reported concussion.

† MBESS score (max 30); SAC score (max 30); SCAT2 symptoms (max 22)/symptom severity score (range 0–6, max 6 × 22 = 132).

to play in 11 days, the second player was medically cleared to return to play in 15 days, and the third player returned to play high school ice hockey in 7 days against medical advice.

The forward position suffered the most diagnosed concussions (12 of 17 patients, 71%), while defensemen were diagnosed with 29% of the concussions. No goalies suffered a concussion. Fifty-seven percent (12 of 21 patients) of diagnosed concussions occurred in the third period, while 29% (6 of 21) occurred in the second period, and 14% (3 of 21) occurred in the first period. Seven (30%) of the 21 diagnosed concussions were not associated with immediate self-declared symptoms (0–6 Likert scale) on the SCAT2 inventory by the athlete. Inclusive of those athletes who did not declare immediate symptoms, the mean number of symptoms reported was 5.5 ± 5.8 (range 0–18 symptoms). The most common self-disclosed symptom was headache (mean score 1.9 ± 0.74, range 1–3/6, 10 patients). The second most common symptoms were "don't feel right" (mean score 2.7 ± 1.6, range 1–4, 9 patients) and fatigue/low energy (mean score 1.8 ± 1.1, range 1–4, 9 players). The third most common symptom reported by the players was sensitivity to light (mean score 1 ± 0, range 0).

There were 2 players who demonstrated an observable period of loss of consciousness (10–15 seconds). One individual required the physician to come onto the ice surface and initiate emergency assessment and cervical stabilization. This player did not require an activation of the 911 system. Both of these individuals were taken out of the game, diagnosed with a concussion, and followed up with the physician for appropriate evaluation and sequential care. A careful review of the files demonstrated that 7 other players recalled a possible momentary loss of consciousness (on secondary or tertiary historical questioning) associated with their diagnosed concussion.

One of the 17 players who was diagnosed with a concussion was sent to the hospital for emergency evaluation secondary to severe and increasing concussion symptoms. This player was released the same day. Two of the players were disqualified from return to play for their teams for the remainder of the regular season and playoffs due to persistent concussion symptoms. One of these 2 players continues to remain clinically symptomatic, while the other declined further follow-up.

Twenty-four percent (5 of 21) of the HCEP concussions occurred in players who were directly involved in a fight immediately prior to their diagnosis. Three of the 4 players who sustained a concussion as a result of involvement in a fight refused follow-up with the primary investigator and were taken out of the study. Sixty-nine percent of the HCEP observers' reports (29 of 42) documented that the point of contact of the majority of hits documented as causing a concussion was the head. Eighty percent of these observer reports (33 of 41) also documented that the hit causing the concussion was purposeful versus incidental. The difference in the number of observer reports is accounted for by the varied (1–3) number of nonphysician observers who attended each game.

Discussion

This is the first study of its kind to document an incidence of concussion in fourth-tier junior ice hockey players based on the 2009 Zurich consensus statement on concussions from the 3rd International Conference on Concussion in Sport.[19] The literature reports the incidence of concussion in terms of level of play, age, and sex of participants. The most common denominators for incidence calculation are player hours, athlete exposures, and games played.[1–3,8–10,16,17,24,25,29] Flick[10] reported an incidence rate of 3.1 per 1000 athlete exposures for Division 1 university ice-hockey players in 1 season. Wennberg and Tator[29] reported an incidence of concussion in the National Hockey League that ranged from 1.81 per 1000 athlete exposures in 1998–1999 to a low of 1.04 per 1000 athlete exposures in 2005–2006. Our rate per athlete exposure (21.52 per 1000) was 7 times higher than the highest rate reported by these authors, and our rate of concussions observed per game (36.5%) was also far higher than the National Hockey League game rate (3.1%) reported by Keating.[17]

The reasons for the differences in incidence may be multifactorial. There are several possible reasons for these differences. First, prior studies have not incorporated prospective, direct, physician-based diagnosis and follow-up. The majority of prior studies depended on either the retrospective self-reporting of the athlete, or the judgment of a certified team trainer or first responder.[6,7,11,14,15,18,22,31] Second, the elevated and multisite points of observation used in our study provided improved ability to view the events occurring on the ice surface. Because our observers were specifically looking for concussions prospectively, as opposed to collecting these retrospectively or using historical injury data previously collected, we likely observed and recorded more events than otherwise might have been detected by team staff who have a multitude of other duties. Our observers often reported that team trainers, despite not being engaged with other duties at the time of the event, did not either see or react to an observed concussion event. The team therapist/first responder then had to be prompted to evaluate a player with a suspected concussion. Third, it is possible that the threshold for diagnosis using our observers and the Zurich statement was more sensitive than prior diagnostic systems. Fourth, player recognition of concussions may be improving, despite obvious barriers and resistance. Three of our players who were diagnosed with a concussion initially self-reported their injury. And finally, there could be a true increase in the rate of concussion based on increased speed and aggression of players. Some of these players were motivated to play as physically as possible in hopes of attaining upper level junior or collegiate status, and may have taken more risk than players in previous studies.

Five (24%) of 21 individuals who sustained a concussion were directly involved in a fight immediately prior to their concussion diagnosis. The majority of hits causing a concussion were to the head (29 of 42 observer reports, 69%). Eighty percent of the observer reports (33 of 41) described the hit that was perceived to cause the concussion as purposeful. These observations demonstrate the need for a closer examination of preventable hits to the head in ice hockey and other sports. Although the intention of an aggressor in ice hockey is difficult to determine, it is im-

portant to objectively and directly document these events in this manner. Future studies may use video surveillance as well as human surveillance to provide an improved historical record and analysis of each event.

We did not specifically monitor practices, and no concussions that occurred in practices were reported by either team during the study. Previous sport concussion studies demonstrated that concussion predominantly occurs in game situations.[1–3,10,30]

Gerberich et al.,[11] a commonly cited retrospective study on recurrent concussions, states that the relative risk of concussions is 4 times higher than for individuals without this history. A prospective survey study of US high school and college football athletic trainers by Guskiewicz et al.[15] found that players who had sustained 1 concussion were 3 times more likely to sustain a second concussion than those players who had not sustained a previous injury. A large prospective study by Zemper[31] indicates that the risk of sustaining a cerebral concussion is 6 times greater for individuals with a history of concussion than for individuals with no such history.

Recurrent concussions may be related to the fact that players are often prematurely returned to play.[23,30] Guskiewicz et al.[14] found that of the 12 incidents of repeat concussions that occurred within the same season, 11 (97%) occurred within 10 days of the first injury, and 9 (75%) occurred within 7 days of the first injury.[14] The time interval between the first and second concussions found in the HCEP differed significantly from the findings of Guskiewicz et al. The HCEP findings demonstrated a mean time interval between the first and second concussions of these 5 players of 78.6 days (median 82 ± 39.8 days), and the mean time between the return-to-play date of the first and second concussions was 61.8 days (median 60 ± 39.7 days). The difference in these findings may be attributable to the direct surveillance and strict adherence to the Zurich return-to-play protocol used in the HCEP.

In our opinion, the singular results of standardized tools such as SCAT2 and ImPACT should not be considered independent decision-making instruments. Rather, these tools can supplement clinical information, but not override physician judgment. In 3 of the 17 cases (18%) of diagnosed concussions in which medical follow-up was obtained, the athletes scored either in the normal range or were within their baseline ImPACT score, but still declared significant symptoms. In 2 of the 17 (12%) diagnosed concussions which underwent medical follow-up, the athletes declared no symptoms, yet demonstrated cognitive deficits when compared to their their baseline ImPACT score, or age-/gender-matched normative scores.

Baseline standardized testing served to identify 1 athlete who had been concussed in a game 2 days earlier and did not report his injury or resulting symptoms. This athlete was withheld from play until he recovered from his injury. A second player was less fortunate. He had a positive symptom inventory on his baseline SCAT2 testing from a nondisclosed prior concussion, and was permitted to play on the basis of a normal ImPACT result when compared with age-group means. This player suffered 2 subsequent concussions (a second nondeclared and 1 physician identified) during the 2009–2010 season, and was forced to retire permanently secondary to persistent postconcussion syndrome.

In retrospective analysis, 12 of the 17 athletes who were diagnosed with a concussion demonstrated a positive symptom inventory or abnormal SAC score (< 25/30) at baseline, despite the fact that their baseline ImPACT scores were reviewed and found not to be outside their expected age-related normative range. These athletes were not clinically examined, retested, or withheld from competition. Improved vigilance concerning interpretation of abnormal baseline test results is suggested for future studies, to identify individuals who may be suffering from a nondisclosed concussion at baseline testing.

A limitation of this study was the lack of compliance of athletes with requested neuropsychological evaluations. Five of the players who were diagnosed with a concussion did not complete their baseline SCAT2 and ImPACT testing prior to entering the study. A second example of noncompliance was the resistance to the recommended physician evaluation for medical release to game play. The lack of compliance made it difficult to document a complete data set of the measurements for comparison purposes.

Complaints by coaches, players, and parents concerning the inconvenience of multiple physician visits for serial testing and evaluation were common. The reluctance to report concussion symptoms and to follow such protocols likely results from certain cultural factors such as athletes asserting their masculinity by playing through the discomfort of an injury, and the belief that winning is more important than the athlete's long-term health.

Future studies should focus on improved education and compliance of the athlete, coaching staff, medical/training staff, club executives, and parents concerning adherence to a direct surveillance protocol. The complete SCAT2 data should be collected and compared across the population to assist in validating and improving this screening tool. Studies should also be performed on larger populations, in other contact sports, across sexes, across different levels of play, and across different countries to assess the generalizability of these findings.

Conclusions

Physician observation and diagnosis using current internationally agreed-upon diagnostic criteria and standardized assessment tools showed that the incidence of concussion in fourth-tier junior ice hockey players was significantly greater than has previously been reported in the literature for this age group. The results of this study demonstrate the need for follow-up studies involving larger and more diverse sample groups to reflect generalizability of the findings. These follow-up studies should involve other contact sports (for example football and rugby) and also include the full spectrum of gender, age, and skill levels.

Disclosure

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Return to play after an initial or recurrent concussion in a prospective study of physician-observed junior ice hockey concussions: implications for return to play after a concussion

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Object. The authors investigated return-to-play duration for initial and recurrent concussion in the same season in 2 teams of junior (16–21-year-old) ice hockey players during a regular season.

Methods. The authors conducted a prospective cohort study during 1 junior regular season (2009–2010) of 67 male fourth-tier ice hockey players (mean age 18.2 ± 1.2 years [SD], range 16–21 years) from 2 teams.

Prior to the start of the season, every player underwent baseline assessments that were determined using the Sideline Concussion Assessment Tool 2 (SCAT2) and the Immediate Post-Concussion Assessment and Cognitive Test (ImPACT). The study protocol also required players who entered the study during the season to complete a baseline SCAT2 and ImPACT. If the protocol was not followed, the postinjury test results of a player without true baseline test results were compared with previously established age- and sex-matched group normative levels.

Each game was directly observed by a physician and at least 1 neutral nonphysician observer. Players suspected of suffering a concussion were evaluated by the physician during the game. If a concussion was diagnosed, the player underwent clinical evaluation at the physician's office within 24 hours.

The return-to-play decision was based on clinical evaluation guided by the Zurich return-to-play protocol (contained in the consensus statement of international expert opinion at the 3rd International Conference on Concussion in Sport held in Zurich, November 2008). This clinical evaluation and return-to-play protocol was augmented by the 2 tests (SCAT2 and ImPACT) also recommended by the Zurich consensus statement, for which baseline values had been obtained.

Results. Seventeen players sustained a physician-observed or self-reported, physician-diagnosed concussion during a physician-observed ice hockey game. The mean clinical return-to-play duration (in 15 cases) was 12.8 ± 7.02 days (median 10 days, range 7–29 days); the mean number of physician office visits by players who suffered a concussion (15 cases) was 2.1 ± 1.29 (median 1.5 visits). Five of the 17 players who sustained a concussion also suffered a recurrent or second concussion. One of the 5 individuals who suffered a repeat concussion sustained his initial concussion in a regular season game that was not observed by a physician, and as a result this single case was not included in the total of 21 concussions. This initial concussion of the player was identified during baseline testing 2 days after the injury and was subsequently medically diagnosed and treated. The mean interval between the first and second concussions in these 5 players was 78.6 ± 39.8 days (median 82 days), and the mean time between the return-to-play date of the first and second concussions was 61.8 ± 39.7 days (median 60 days).

Conclusions. The mean rates of return to play for single and recurrent concussions were higher than rates cited in recent studies involving sport concussions. The time interval between the first and second concussions was also greater than previously cited. This difference may be the result of the methodology of direct independent physician observation, diagnosis, and adherence to the Zurich return-to-play protocol. *(DOI: 10.3171/2010.9.FOCUS10210)*

Key Words • **concussion** • **return to play** • **traumatic brain injury** • **sports injury** • **ice hockey**

The direct independent medical assessment and protocol-guided return to play after an athlete has sustained a medically diagnosed concussion is believed to be essential in the acute concussion care.[19,23] This approach may decrease the frequency of short- and long-term sequelae (such as postconcussion syndrome; mild cognitive impairment; chronic traumatic encepha-

Abbreviations used in this paper: HCEP = Hockey Concussion Education Project; ImPACT = Immediate Post-Concussion Assessment and Cognitive Test; MBESS = Modified Balance Error Scoring System; SAC = Standardized Assessment of Concussion; SCAT2 = Sideline Concussion Assessment Tool 2.

lopathy) related to this injury.[4,5,8,9,19,20,22,25,26] It may also improve the return-to-play data on which individual decisions are determined. Previously published return-to-play concussion-focused studies have been difficult to compare, as they have been based on different surveillance and return-to-play protocols.[1,10,12,14–16,18,24,28]

The primary goal of the present study was to prospectively measure the duration of medical restriction from play (return-to-play period) after each physician-observed and -diagnosed concussion or recurrent concussion, by direct clinical evaluation augmented with the SCAT2 and ImPACT neuropsychological tools. We studied players from 2 teams of junior ice hockey players during a single regular (36-game) season using the Zurich return-to-play protocol.[19]

Methods

This study was part of a larger surveillance and reporting study also published in this issue.[6] The experimental sample described herein was collected during the 2009–2010 junior ice hockey regular season, and it included 67 male fourth-tier ice hockey players (mean age 18.2 ± 1.2 years, range 16–21 years) from 2 teams.

Prior to the start of the season, every player underwent baseline assessments that were determined using the Sideline Concussion Assessment Tool 2 (SCAT2) and the Immediate Post-Concussion Assessment and Cognitive Test (ImPACT). The study protocol also required players who entered the study during the season to complete a baseline SCAT2 and ImPACT. If the protocol was not followed, the postinjury test results of a player without true baseline test results were compared with previously established age- and sex-matched group normative levels.

Each game was directly observed by a physician and at least 1 neutral nonphysician observer. Players suspected of suffering a concussion were evaluated by the physician during the game. If a concussion was diagnosed, the player underwent clinical evaluation at the physician's office within 24 hours.

The return-to-play decision was based on clinical evaluation guided by the Zurich return-to-play protocol (contained in the consensus statement of international expert opinion at the 3rd International Conference on Concussion in Sport held in Zurich, November 2008). This clinical evaluation and return-to-play protocol was augmented by the 2 tests (SCAT2 and ImPACT) also recommended by the Zurich consensus statement, for which baseline values had been obtained. Mean results are presented ± the SD.

For a complete and detailed description of the methods used in the HCEP please see Echlin and colleagues' article, "A prospective study of physician-observed concussions during junior ice hockey: implications for incidence rates," in this issue of *Neurosurgical Focus*.[6]

Results

In 15 players who suffered a concussion, the mean interval before clinical return to play was 12.8 ± 7.02 days (median 10 days, range 7–29 days); the mean number of physician office visits by 15 players who suffered a concussion was 2.1 ± 1.29 (median 1.5 visits).

These calculations exclude 1 player (an outlier who was out for the season and did not return to play [more than 75 days]), 5 players who refused follow-up, and 4 HCEP players with a physician-diagnosed concussion in whom the event had occurred outside the parameters of the study (2 players in the first round of the playoffs and 2 players in games that were not being observed).

The mean return-to-play duration of players with a reported medical history of concussion were as follows: 11.5 ± 7.60 days in 8 players with 0 previous concussions; 10.7 ± 2.94 days in 6 players with 1–2 previous concussions; more than 28 days in players with more than 3 previous concussions (1 case) (excluding the 1 outlier player and the 5 players who refused to follow-up with the physician).

Eighteen (53%) of the 34 potential concussions identified by the physician and nonphysician observers were positively diagnosed by the physician at rinkside. Three of the diagnosed concussions were not directly identified in an observed game, and were self-reported to the physician either at rinkside or within the next 48 hours. The remaining 16 (47%) of the concussions that were initially identified by the observers were returned to play after a negative clinical and SCAT2 evaluation by the physician.

Five (29%) of 17 players who suffered a concussion also sustained a recurrent concussion during that interval. One of the 5 individuals who suffered a repeat concussion sustained his initial concussion in a regular season game that was not observed by a physician, and as a result this single case was not included in the total of 21 concussions. This initial concussion of the player was identified during baseline testing 2 days after the injury and was subsequently medically diagnosed and treated. The mean interval between the first and second concussions in these 5 players was 78.6 ± 39.8 days (median 82 days), and the mean span between the return-to-play date of the first and second concussions was 61.8 ± 39.7 days (median 60 days).

The concussion diagnosis and return-to-play decision of the athlete were augmented by the use of the ImPACT and the SCAT2. The linear neurocognitive recovery trend over time (number of office visits) of the SCAT2 symptoms, the SAC score, and the Modified BESS score are presented in Figs. 1–3.

Discussion

This is the first study to use independent on-site physicians to diagnose and then determine a player's return-to-play status according to the Zurich protocol.[19] Among the published concussion studies, the lack of a single standardized methodology involving documentation of return to play makes direct comparison of results difficult and allows only trends to be discussed.

In the present study, the mean clinical return-to-play duration of the participants who suffered a new or recurrent concussion during the observed season was 12.8 days. Seven (33%) of the 21 athletes diagnosed with a concussion required more than 12.8 days before returning to play. This calculation includes 2 players who were unable to return to play for the rest of the season due to ongoing symptoms. Previous studies have demonstrated that athletes tend to recover from perceived symptoms

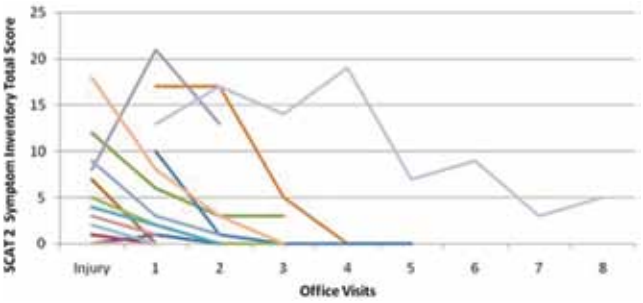

Fig. 1. Graph demonstrating change of the SCAT2 symptom inventory total during the recovery period.

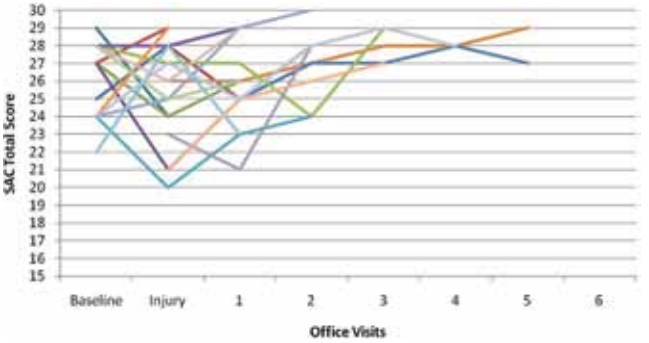

Fig. 2. Graph showing SCAT2 SAC total scores for concussed athletes during the recovery period.

and their neurocognitive performance normalizes within 3–10 days, with a smaller percentage of individuals that require more time to recover.[1,12,14–16,18]

Previous studies have also demonstrated that players who sustained a concussion in a season were 3 times more likely to sustain a second concussion in the same season compared with uninjured players.[11,29] Five (29%) of 17 players who sustained a concussion in this study also sustained a second concussion in the same season. Three of these 5 players who suffered a repeat concussion had a medical history of sustaining at least 1 concussion prior to the beginning of the season.

The mean clinical return-to-play duration for individuals who reported never previously suffering a concussion before the start of the observed season (8 players) was 11.5 days; this value was greater than the mean clinical return-to-play duration (10.7 ± 2.94 days) for individuals (6 players) who reported having between 1 and 2 previous concussions.

The literature documents lengthened recovery times in individuals who reported suffering 3 or more prior concussions.[3,7,10,13] There were 2 HCEP players who reported 3 or more previous concussions and who sustained a concussion during the study. In both players a significantly longer duration for recovery from symptoms and objective neurocognitive measurements was demonstrated. One player, who reported 5 previous concussions, had a significantly longer return-to-play duration (28 days), and the second player who reported 4 previous concussions was unable to return to play and had to retire permanently due to ongoing symptoms. Individual concussion history data may be underreported due to individual bias and to the interpretation of the definition of concussion.

Recurrent concussions may be related to the fact that players are often prematurely returned to play.[24,28] This was not found in the results of the HCEP, as the mean interval between the first and second concussions in the same season (in 5 players) was 78.6 ± 39.8 days (median 82 days). These results differ from the 10-day period in which the second or recurrent concussion most frequently occurred in previous studies.[10,17] The difference in these findings may be attributable to the direct surveillance and strict adherence to the Zurich return-to-play protocol used in the HCEP, and the small sample size used in this study.

The present study used neurocognitive tools such as SCAT2 and ImPACT to augment clinical decision making. These tools should not be considered independent decision-making instruments. Rather, they can supplement clinical information but not override physician judgment. In 8 (38%) of 21 cases of concussions diagnosed and sequentially followed, the athletes scored either in the normal range or within their baseline ImPACT score but were clearly still symptomatic. In 2 (10%) of 21 concussions evaluated, the player would be symptom free and would exhibit cognitive deficits on SCAT2 or ImPACT. These findings of inconsistent results in the objective neuropsychological tools may be attributed to operator error, the learning effect of the participant athlete, or the lack of sensitivity of the test itself.[24,27]

This study concurs with previous studies in the literature that conclude that there is currently no single direct measure of recovery after concussion and that clinical decisions should be made based on multifactorial input including concussion history, symptoms, balance, and cognitive function.[2,14,21]

A limitation of this study was the lack of compliance of HCEP participants with objective baseline testing and retesting at the requested intervals. Although general trends in the objective testing data demonstrated the utility of the objective testing tools, the lack of participant compliance made it difficult to document a complete data set of the objective measurements for comparison purposes. A second limitation of this study was the absence of a matched control group of individuals not involved with the participating teams.

Future studies should focus on improved compliance of participant baseline and postinjury testing. The complete SCAT2 data should be collected and compared across the population to assist in validating and improving this screening tool compared with the components that were

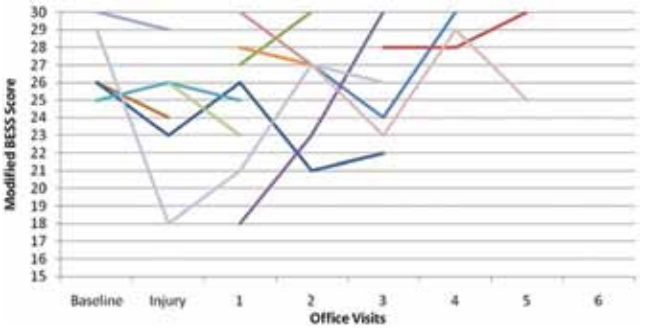

Fig. 3. Graph demonstrating changes of SCAT2 Modified BESS total scores for concussed athletes during the recovery period.

used in this study. Future studies should also be performed in larger populations, in other contact sports, across sex, across different levels of play, and across different countries to assess the generalizability of these findings.

Conclusions

The mean rate of return to play after a single and recurrent concussion was higher than the rate in recent studies involving sports-related concussions. The interval between the first and second concussions was also greater than previously cited. This difference may be a result of the present methodology, including independent direct physician observation and adherence to the Zurich return-to-play protocol.

Disclosure

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A prospective study of concussion education in 2 junior ice hockey teams: implications for sports concussion education

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Object. The aim of this study was to evaluate the effectiveness of an educational intervention on concussion knowledge within a sample of junior fourth-tier ice hockey players.

Methods. A prospective cohort study, called the Hockey Concussion Education Project, was conducted during 1 junior ice hockey regular season (2009–2010) with 67 male fourth-tier ice hockey players (mean age 18.2 ± 1.2 years, range 16–21 years) from 2 teams. All participating players were randomized into 3 concussion education intervention groups (DVD group, interactive computer module [ICM] group, or control group) before the beginning of the season. Each individual received a preintervention knowledge test prior to the intervention. The DVD and ICM groups received a posttest after the completion of their intervention. All participants were offered the same knowledge test at 15 games (50 days) and 30 games (91 days) later.

Results. In the concussion education intervention component no significant group differences were observed at baseline between individuals in the control group and between individuals within the interventional group. At the 15-game follow-up, however, the difference between groups approached significance ($F [1, 30] = 3.91$, $p = 0.057$). This group difference remained consistent at the 30-game follow-up.

Conclusions. This study demonstrates a positive trend concerning concussion education intervention and knowledge acquisition with either the ICMs or the educational DVD. Both forms of intervention produced a positive and sustainable improvement that approached statistical significance when compared with the control group. The control group demonstrated a negative longitudinal trend concerning concussion knowledge.
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Key Words • concussion • ice hockey • education • Hockey Concussion Education Project • Canada

Failure to recognize and report concussions noted in previous publications in the literature may be the result of a lack of a standardized knowledge base among athletes, coaches, trainers, and parents regarding the signs and symptoms of concussion.[1,3,6,12,13,16,17,24,25,,27] Such underreporting is likely associated with undertreatment, which may also have very significant immediate and long-term social and health implications.[7,8,14,15,18,19,20,22,23] The primary goal of this study is to evaluate the effectiveness of different types of educational interventions on improving concussion knowledge and retention of that knowledge within a sample of junior fourth-tier ice hockey players. This study did not investigate behavioral changes resulting from the educational intervention.

Abbreviations used in this paper: HCEP = Hockey Concussion Education Project; ICM = interactive computer module.

Methods

Patient Population

This study was part of a larger surveillance and reporting study (see other papers in this issue). The experimental sample described herein was collected during the 2009–2010 junior ice hockey regular season, and included 67 male fourth-tier junior ice hockey players (mean age 18.2 ± 1.2 years, range 16–21 years) from 2 teams.

Concussion Knowledge and Education Component

At the beginning of the season all participating players were randomly assigned to 1 of 3 concussion education intervention groups: the Thinkfirst[1] concussion DVD (Concussion Clinic for Hockey Coaches; 16 players); the ICM group (20 players); or a control group that did not receive any educational intervention (22 players). Although a total of 67 players participated in the study, only 58 players participated in the baseline testing session. Due to individual and team noncompliance with study protocol, no other baseline tests were performed. The ThinkFirst Foundation of Canada is a national nonprofit organization dedicated to the prevention of brain and spinal cord injuries. Each individual received a preintervention knowledge test prior to the intervention to establish a baseline level of for all participants.

This 26-question multiple choice and true/false test was based on the ThinkFirst DVD content and the recent Zurich consensus guidelines concerning concussion injury knowledge and treatment protocol.[18] The concussion information tested was given to the intervention groups in the DVD and ICM formats. An identical concussion knowledge test was administered after 15 games, and again after 30 games. At each time period, the concussion knowledge test was administered under the supervision of study personnel.

The DVD and ICM groups received their interventional education only once at the start of the study. The 2 intervention groups (DVD and ICM) completed their educational interventions in the same computer lab, supervised by several study officials. A postintervention knowledge test was completed immediately after the completion of the intervention. All participants were offered the same knowledge test at 15 games (50 days) and 30 games (91 days) later. All interventions were completed under supervision by study personnel. For a complete and detailed description of the methods used in the HCEP please see Echlin and collegues' article, "A prospective study of physician-observed concussions during junior ice hockey: implications for incidence rates," in this issue of *Neurosurgical Focus*.

Statistical Analysis

The rates of missing data were unacceptably high in the posttest time period and the 30-game follow-up session. The control group did not participate in the postintervention test and the exclusion of 1 team at Game 21 left few participants in the sample for follow-up comparisons. Accordingly, all statistical analysis presented herein will be based on the pretest data and the 15-game follow-up data.

The effects of educational intervention were tested within 3 separate ANOVA designs, each of which was evaluated against a probability level of 0.05. In the first analysis, the effects of intervention type were tested within a 3 × 2 split-plot ANOVA, with group (control vs ICM vs DVD) as the between-subject variable, and time (pretest vs 15-game follow-up) as the within-subject variable. In the second analysis, the 2 educational interventions were collapsed into a single group, and the overall effects of education were tested within a 2 × 2 split-plot ANOVA, with group (control vs intervention) serving as the between-subject variable, and time (pretest vs 15-game follow-up) serving as the within-subject variable.

Results

No significant difference was found among groups at baseline, nor were there significant differences on test scores of concussion knowledge among groups who received either type of educational intervention or those who received no intervention, at the pretest time period or at the 15-game follow-up. There was no significant interaction between group and time ($F [2, 29] = 1.95$), and no significant main effect for either group ($F [2, 29] = 0.80$) or time ($F [1, 29] = 1.23$). When the educational intervention is evaluated without considering the type of intervention, the interaction between group and time approaches significance at an alpha level of 0.05 ($F [1, 30] = 3.91$, $p = 0.057$). This result suggests that there may be a meaningful effect of concussion education on concussion knowledge (Fig. 1).

The test consisted of 26 questions as stated in the *Methods* section. The scores were based on the number correct out of 26. Means and standard deviations for the concussion education results are summarized for each group in Table 1.

The effect of contamination of the data caused by exchange of information between the groups was not found to be significant. Given that random assignment to treatment groups was performed within teams, it is possible that team members shared information among themselves, thereby diffusing the effectiveness of the independent variable. This diffusion of the treatment effect would reduce the potency of the independent variable in this study, which suggests that these results are likely to be a conservative estimate of the effects of education on concussion knowledge.

Discussion

The Zurich consensus statement on concussions recognized that education of the athlete, referee, administrators, parents, coaches, and health care providers is a mainstay of progress in this field.[18] There has been some moderate success using computer-/video-based educational interventions.[4,5,10,11] These interventions have demonstrated an improvement in testable knowledge levels. Very few studies have attempted to actively educate the athlete concerning concussions and then prospectively

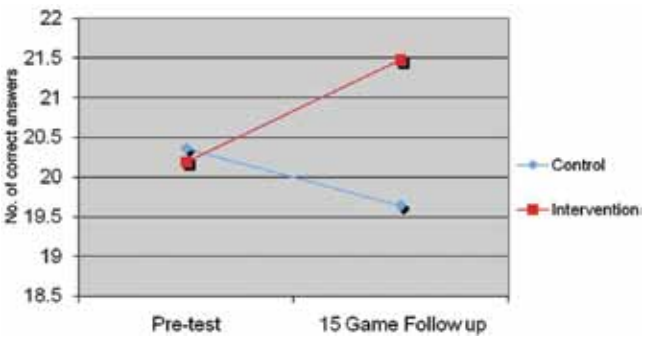

Fig. 1. Line graph showing interaction between group (intervention vs control) and time (pretest vs 15-game follow-up).

TABLE 1: Pretest and 15-game follow-up test scores according to experimental group*

Group	Pretest Score	15-Game FU Score
control	20.36 (1.80)	19.64 (4.01)
ICM	19.71 (3.99)	21.14 (2.77)
DVD	21.14 (2.04)	22.14 (1.77)
combined†	20.19 (3.47)	21.48 (2.48)

* All values given as means (SDs). Tests consisted of 26 questions. Abbreviation: FU = follow-up.
† Combination of the ICM and DVD groups (individuals were in either the ICM or the DVD group).

examine the retention of that knowledge or measure the effects of that knowledge on behavior.[5] Only 1 study has attempted to assess the effect of the educational program on behavior: ThinkFirst's "Smart Hockey" program was shown to reduce specific body checking penalties.[5] Educational research has demonstrated that interactive educational tools that force an individual to be involved in the process often have an improved success rate compared with passive noninteractive systems.[2]

A recent study of concussion knowledge of ice hockey athletes, coaches, trainers, and parents demonstrated a significant lack of knowledge concerning concussive injuries.[6] The documented lack of concussion knowledge has been demonstrated by Delaney et al.[9] who found that only 20% of those professional athletes who were experiencing a concussion actually realized that they had suffered this injury. There have been several studies that investigated the concussion knowledge of athletes and coaches. The majority of these studies have been retrospective cross-sectional survey designs.[1,3,5,6,12,13,16,24,25] Williamson and Goodman[26] found that studies based solely on administrative records or reports may not account for all concussions. These investigators believed that their findings indicated the importance of prospective study of the sport-induced injury.[26]

Provvidenza and Johnston[21] found that although there are a variety of concussion education resources currently available such as interactive educational modules and passive noninteractive video-based resources, there is no evidence to indicate which modality is the most appropriate as resources are rarely compared with each other within the same study. These researchers identified the need to evaluate and determine the most effective resources that will promote optimal learning of concussions within each group (physicians, physiotherapists, coaches, trainers, therapists, and athletes).[21]

In a prospective cohort study the HCEP evaluated the concussion knowledge level and retention of concussion knowledge using consistent definitions. The intervention groups demonstrated a trend toward significance (α = 0.057) concerning the retention of concussion knowledge when their knowledge scores were compared with the control group at the 15-game point in the season.

The education and compliance of the athlete, coaching staff, medical/training staff, club executive, and parents concerning the importance of the protocol as well as the cooperation of the team coaching and training staff is essential to fulfill the proper implementation of concussion knowledge education. The trend of knowledge retention among the athletes who underwent the intervention (vs controls) was a small but important finding, and is worthy of repeating in a larger study with better compliance control to determine validity and reliability. The base question that the primary investigator sought to discover was the level of knowledge that the participants began the study with and then the level of retention that occurred over time. In this study only the players were tested concerning their baseline knowledge of concussion. It is important in future studies to test and retest all of the aforementioned individuals associated with the sport to provide a broad-based acceptance of concussion identification, care, and prevention.

The cause and effect relationship of the knowledge and resultant behavior was beyond the scope of this study. If a larger study demonstrates that most players have a reasonable understanding of concussion (including definition, treatment, and long-term effects) then the other more complex questions to consider would be why this behavior continues to occur at such a high incidence level. Consideration of this relationship is difficult and multifactorial and has many significant social components that need to be evaluated and documented, and should form the basis of future studies.

Concussion prevention and incidence reduction involves all individuals (athlete, coaching staff, medical/training staff, club executives, and parents) involved in the particular sport that is under study. The cultural background must be investigated, as it is often influenced by the overwhelming result-oriented pressures at all levels, and the acceptance of previous patterns of behavior concerning this "invisible injury." The resistance to change cultural patterns prevents individuals with a knowledge of concussion from utilizing that knowledge for the benefit of themselves and others. This resistance was demonstrated in the noncompliance with the baseline knowledge and neuropsychological testing components of the protocol by the participating individuals and the teams, other than the initial preseason baseline sessions.

A limitation of this study included the size of the population that received the educational intervention, to provide true significance of the intervention. A second limitation was the lack of a matched control group that was independent of the ice hockey teams involved in this study. Future studies involving larger randomized cohort groups should be conducted to validate the findings of this study. Future studies may also attempt to correlate the use of a concussion education intervention to determine if there is an effect upon the measured direct and documented incidence of concussion.

Conclusions

This study demonstrates a positive trend toward significance concerning concussion education intervention and knowledge acquisition using either the ICMs or the educational DVD. Both forms of intervention produced

a positive and sustained improvement over time that approached statistical significance when compared with the control group. The control group demonstrated a negative longitudinal trend concerning concussion knowledge.

Disclosure

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Editorial

Concussion education, identification, and treatment within a prospective study of physician-observed junior ice hockey concussions: social context of this scientific intervention

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The Hockey Concussion Education Project (HCEP) is a prospective study in which education and surveillance interventions of 2 junior (16 to 21–year-old) fourth-tier ice hockey teams took place during the 2009–2010 season.

The HCEP originated from the observation of inadequate and inconsistent concussion care in junior ice hockey. The precipitating event occurred when a junior-level coach overruled a team physician on a return-to-play decision of a player with a concussion. The coach allowed the player to return to play against medical advice. When confronted by the physician concerning the risk to the player, the team, and the league, the coach responded, "Who needs a doctor anyway?" This incident convinced me to undertake further scientific study of concussions and to advocate for consistent medical care of athletes who sustain them.

This editorial will outline multiple observations that came out of the HCEP. Some of these observations are subjective and most pertain to the sociological context in which hockey is played. The cases and case examples discussed mainly represent individuals from the HCEP. A few individuals from the author's practice identified as not participating in the prospective study are also described. The 3 associated scientific articles published in this issue of *Neurosurgical Focus* contain scientific research on concussion incidence, education, and return-to-play findings that resulted from the HCEP.

A review of previous concussion studies shows many different protocols and guidelines gathered under varying levels of expertise. Direct, independent, scientific evidence of the true incidence of concussions, gathered by physicians according to a single internationally agreed upon protocol, is needed.

The 2009 Zurich consensus statement on concussions resulted in a protocol guideline from a 10-year international, cooperative, and multidisciplinary consensus of current evidence and expert opinion. The Zurich statement was used as the basis for the HCEP definition of concussion, identification/diagnosis, treatment, and return-to-play guideline.

The HCEP was composed of an educational component and a surveillance component. Players in the study were tested for their baseline concussion knowledge and were then randomized into 1 of 3 groups: 2 groups received different forms of concussion education and 1 group was the control. The intervention groups were given concussion education and were tested postintervention. All the groups were then sequentially tested at Game 15 and Game 30 of their regular hockey season to determine the change in their knowledge of concussions.

The surveillance intervention component of the HCEP consisted of having a qualified sports medicine physician and neutral trained observers attend the regular season games of the 2 teams. A probable concussion was initially identified by the medical and neutral observers during the game. A suspected concussion was recorded, and the player was medically evaluated in a vacant dressing room. If the medical evaluation was positive for a concussion, the player was removed from the game and was requested to follow up with the HCEP physician the following day for reevaluation and appropriate treatment. If the player's immediate evaluation was negative for concussion, he was returned to play. For a complete and detailed description of the methods used in the HCEP please see Echlin and colleagues' article, "A prospective study of physician-observed concussions during junior ice hockey: implications for incidence rates," in this issue of *Neurosurgical Focus*.

In Canada, ice hockey is a major cause of sport-related concussion.[9] Senior hockey players can travel at speeds of up to 48 km/hour (30 miles/hour) when skating and up to 24 km/hour (15 miles/hour) when sliding. These athletes can make contact with numerous hard surfaces such as the boards, glass, ice, goal posts, and fellow players. It is not surprising that a concussion is the most common athletic injury and that hockey rates among the highest of all contact sports for concussion rates per player exposure.[1] Research has documented the significant effect that concussion may have on the individual and society.[4–7,11–14]

Despite long-standing concerns in the medical community, concussion has received little attention from the general population or from the athletes.[16] Cultural and social obstacles may prevent the seriousness of this brain injury and its long-term effects from being appropriately recognized.

To effect a cultural change concerning concussion,

widespread education is needed for all individuals involved in contact sports. Improved identification, treatment, and prevention of concussion should be based on prospective standardized evidence.

The athlete and the individuals who surround the athlete (parents, coaching staff, club and league executives, trainers, and physicians) are key to taking responsibility for concussion identification, treatment, and prevention.

Our shared social responsibility concerning concussion care of the athlete will be discussed in this editorial.

The Athlete

The athlete who sustains a concussion is often forced to suffer in silence with this "invisible" injury. This silence reflects both a lack of understanding and cultural resistance.

Concussion is popularly perceived to be a benign and temporary injury, euphemistically described as a "bell ringer" or "dinger." A player who sustains this type of injury is often encouraged to believe that suffering from concussion is a "rite of passage." Competitive athletes learn at a young age to please those who support them. They do not readily admit to weakness or injury. These athletes may believe that this behavior pleases coaches and parents, enhances their image with their peers, and allows them more playing time.

According to the Zurich statement, athletes suffering concussion-related symptoms should be immediately removed from the field of play and medically assessed. An athlete whose symptoms have resolved must complete a minimum and progressive 6-day stepwise activity-based return-to-play process.[11] This is the guideline of the Zurich Conference on Sport Concussion.

Current clinical and empirical evidence demonstrates that the failure to act and restrict the player diagnosed with a concussion from further immediate play may place the athlete at a significant risk of short- and long-term cognitive disability. A concussed player often ignores concussion symptoms and resists being evaluated. He or she returns to play while suffering from symptoms and is more vulnerable to sustaining another concussion with the associated post-concussion syndrome. Post-concussion syndrome involves a prolonged period of recovery and sometimes lifetime disability from symptoms such as headache, dizziness, fatigue, irritability, light and sound sensitivity, and memory and concentration impairment. The incidence of post-concussion syndrome is poorly documented, and poorly understood, but it is widely reported.

The most catastrophic and lethal brain injury resulting from sport-related trauma is called second impact syndrome, or SIS, which occurs when an athlete sustains a second head injury before the first has resolved. The pathophysiology of second impact syndrome is thought to involve a swelling of the brain induced by the initial brain injury. This swelling can lead to brain herniation through the skull base, causing respiratory failure and death. The prevalence of second impact syndrome is low, although it is more common than previously suspected.[9]

Recently, retired football players from the National Football League and the Canadian Football League endeavored to raise awareness of concussion. These athletes are beginning to speak out about long-term cognitive disabilities, as well as the pathological link between repetitive concussions and chronic cognitive impairments including chronic traumatic encephalopathy.[6,7,12,13]

A concussion is often not suspected unless the individual loses consciousness. Frequently athletes are allowed to return to play in the same game while actively suffering from concussion symptoms. One of the primary difficulties in obtaining data on the incidence of concussions has been athletes' lack of self-reporting of symptoms, which are headaches, blurred vision, and difficulty with concentration and memory lapses.

The reluctance to report a concussion most commonly occurs because the athlete is either unaware of the seriousness of this brain injury or fears that he or she will be restricted from play.[2,3,8,10,15] Kaut et al.[8] found that 30.4% of the athletes admitted to continuing to play while experiencing symptoms after being hit in the head, with football players exhibiting a high incidence of this behavior (61.2%). Only 43% of all athletes surveyed stated they had some knowledge of concussions.

The HCEP protocol used an "against medical advice" form during the study. This action was taken when a player was diagnosed with a concussion resulting from a fight and refused to follow the established HCEP protocol. Athletes diagnosed with a concussion often have mixed feelings about the diagnosis, frequently wishing to minimize its seriousness. However, some athletes express relief at being given permission to stop playing, to rest, and to avoid further debilitating injury. These mixed feelings may be due to the fear of further injury combined with both internal and external pressure to continue to perform.

The lost playing time and status resulting from a concussion represent a common fear that has been reported by injured athletes. An athlete may fear the loss of the identity he or she has derived from sport. Players frequently may place themselves at risk of further injury by ignoring concussion symptoms in order to avoid loss of status and playing time.

Case Examples

Player A. When this player in the HCEP was diagnosed with a concussion after a fight and appeared at the office the next day for further testing and treatment, he asked, "Doc, I was wondering why I hadn't been called in previously, as I have had other concussions this year. The only reason that I came in was that I am tired of living with these headaches and other symptoms." Player A admitted to sustaining concussions twice before the initial evaluation and that he had failed to report his symptoms in an effort to keep playing and please his teammates.

Player A reported that he was having difficulty in his university classes, and he feared he would not be able to obtain the grade point average needed for graduate school admission. He admitted that he felt pressure from a team executive who had promised him a letter of recommendation for graduate school.

As part of his treatment process, Player A was given

medical academic deferral and accommodation from the university until his recovery was complete. He reported that his club's management continued to pressure him to return to play despite the full knowledge of his diagnosis, treatment plan, and ongoing academic difficulties.

Player B. This player in the HCEP study was concussed by an opposing player and was returned to play by his trainer. Subsequently he took himself out of the game due to blurred vision and headache symptoms. He remarked on the lack of sportsmanship and respect demonstrated by his opponents. The opposing team had berated the injured player while he lay face down on the ice and chided him for leaving the game despite injury. He remarked on the frustrating lack of respect from opposing players, many of whom he had known and competed against over many years. During his evaluation, the player admitted to failing to report a concussion 1 week earlier. He returned himself to play against medical advice, despite extensive education and warnings concerning the dangers of returning to play before he had recovered.

See the *Appendix* for the case histories of 10 athletes who, in their own words, describe the effects of concussion on their own lives.

The Parents

Parents and the support that they provide are essential to the success of a competitive athlete, but parents may become overly invested in their child's success. They have been observed to reinforce the athlete's fears about losing "ice time" and falling behind their peer group if they admit to the symptoms of a concussion. In many of the concussion cases during the HCEP, the athlete's health did not seem to be a priority.

Case Examples

Parent V (parent of a clinical patient not involved in the HCEP). This father of a 14-year-old concussed hockey player stated that he could understand the parents of players with concussions wanting to ignore their children's medically diagnosed brain injury. He said that parents had a significant amount of time and money invested in the child, and if there was nothing visibly wrong, he should be on the ice with his teammates.

Parent W (parent of a clinical patient not involved in the HCEP). This father of another 14-year-old hockey player digressed from a discussion of his son's concussion symptoms to a complaint about the amount of money that he had invested in his son's hockey equipment, personal trainer, psychologist, and private schooling.

General Remarks. On 2 separate occasions, HCEP players diagnosed with concussion by the physician at their respective games refused appropriate follow-up and specialized care, obtaining instead a return-to-play note from their family doctors. When the family doctors of these individuals were contacted and properly informed concerning the initial diagnosis and care offered, the physicians stated that players and parents deliberately deceived them concerning the injury. In one of these cases, the parent had urgently enrolled his child in the long-term care of a physician to provide his son with a return-to-play note. The management of the club and the league were aware of this deception but took no action.

Parents X and Y. Parent X of an HCEP athlete said, "The doc is a quack, and he is providing an unsafe playing environment for my son…He needs to play on instincts, and can't be worried about getting a concussion every time he goes into a corner." Parent Y of another HCEP athlete said, "I know my son and he seemed like himself at breakfast, so I see no reason why he should not be out there at practice."

General Remarks. Four further cases of minor hockey players presented to the clinic for diagnosis and management of a concussion. The parents of these young athletes similarly declined to continue with appropriate treatment when they were informed of the diagnosis and the possibility of extended medically supervised absence from sport.

Parent Z. In contrast to the aforementioned parents, this parent of an HCEP athlete exhibited a positive parental intervention. Parent Z's son initially refused medical evaluation after a suspected concussion. The coaching staff actually encouraged him not to be evaluated by the physician. The parent of this player intervened and convinced him to be evaluated before returning to play.

Parent Z said, "It's only a game, and it is not worth the risk of a significant injury." After the physician had evaluated and in this case returned the player to play, Parent Z apologized to the physician for his son's behavior.

The Coaches

Coaches have a significant responsibility to be become informed about concussion and to educate and protect the players under their supervision. In study by Sye et al.,[15] concerning the players' understanding of concussion and return-to-play guidelines, the authors found that players predominantly obtained their information from coaches/teachers, and this was followed by medical personnel and then other players.

Coaches can experience conflict between the pressure to win and the protection of the long-term health interest of the player. In a recent study by Cusimano et al.,[3] 22 of 34 minor league coaches refused to have their teams watch a video about concussion prevention because they thought that it would make their players less aggressive and less successful as a team. Traditionally, sporting culture has rewarded athletes who "play through" or feign toughness for the benefit of the team.

Hockey coaches are responsible for the on-ice success of the team and distribution of playing time among players. If players feel that their playing time will be reduced or they will be "punished" with less ice time if they admit to concussion symptoms, they may often not report the symptoms, despite the possibility of long-term brain injury.[2]

Case Examples

Coach A (not an HCEP coach). This coach stated that

before the season he opposed having someone else make player-related decisions, even with respect to concussions. At the end of the season, Coach A stated that despite struggling with this issue of player control, he was relieved not to have to make medical decisions and that a qualified individual was present to perform that function.

Coach B. This coach also said that at the start of the season he was opposed to having decisions concerning players taken out of his hands. He explained that by going through the injury and rehabilitation process twice in the same season with his son, he now supported and understood the importance of the medical intervention. Despite this important education-based insight from the study, Coach B said, "The medical management of concussion will not be accepted easily by the current social structure of the game."

During the playoffs, Coach B's son suffered an apparent third concussion of the season. The therapist/first responder informed Coach B of the injury, and that he should be restricted from further play until appropriate medical evaluation. Nevertheless, Coach B's son was permitted to play the rest of the game without the suggested medical evaluation.

An example of the fear that exists in the social structure of hockey concerning concussion was recently apparent at the university level. A request for involvement of a major Canadian university to participate in an HCEP educational and surveillance study was proposed and accepted at all levels including the athletic director, head athletic therapist, and the team physicians.

When the coach was approached, he declined the opportunity. His reasons were that he was uncomfortable with the neuropsychological testing tools and that he did not think he could fit a 3-hour testing period for education and preseason neuropsychological testing into his team's schedule. The coach was supported in this decision by the administrative and medical staff.

League and Team Executives

The league and team executives are responsible for enforcing the rules of the game and providing a safe environment for the players. The executive level can provide an important layer of player protection.

The team executives are commonly observed to defer the responsibility for player injuries and health to the coaching and training staff, focusing instead on the elements of the team and the outcome of the game.

A powerful example of lack of understanding and appropriate executive leadership occurred when one team executive removed his team from the HCEP and direct emergency medical supervision halfway through the season. This incident highlighted the effect that an executive can have on players who are dependent on these individuals to protect them. This withdrawal occurred despite the fact that the HCEP was a physician-instituted concussion study that the club had been fully informed about and had agreed to participate in.

The executive stated he would only allow his club to return to the study under the condition that the protocol be changed to prevent the physician from examining a suspected concussion until after the game and with the permission of the trainers, coaches, and players. This executive wished to prevent his players with a suspected concussion from being evaluated immediately by a qualified, experienced sports medicine physician.

A formal meeting was held to inform the league and the participating clubs that no changes would be made in the HCEP study under the existing University of Western Ontario ethics committee–approved protocol. The executive was asked to directly inform the primary investigator of the team's intentions to continue under the existing protocol. The team executive failed to comply, and the team was removed from the HCEP.

Executives on both HCEP teams resisted fully implementing the project by refusing to perform baseline tests in new players added to the team during the season. One executive complained of ongoing player resistance to the project. The manager stated that he feared a *"mutiny"* among the players concerning postinjury testing and that his team would lose players as a result.

A trainer asked HCEP Player C why he refused the evaluation request after an observed concussion by a physician. The player said that he had already passed the screening test several months before during his recovery from his first concussion of the season, and he did not understand why he had to be tested again.

The team executive was asked to explain to Player C that he had to be evaluated and the executive refused, indicating he *did not* want to cause disruption in the locker room by arguing with the player. He said he would like to remove the player from the study.

Player C was observed to sustain multiple hits to the head in subsequent games and to have reduced reaction time necessary to escape the hits. Sadly, this player sustained an intentional elbow to the head 3 games later, which resulted in a documented concussion. He was removed from the game and was evaluated for a concussion by the HCEP physician. This player was unable to compete for the rest of the season as a result of the concussion and the post-concussion syndrome.

Player D, who left the HCEP after refusing evaluation following a suspected concussion, was also observed in subsequent games to sustain a disproportionate number of direct and indirect head traumas. After an observed head hit, Player D exhibited a loss of emotional control, yelling, slamming his stick and the bench door repeatedly for several minutes in front of a large crowd.

The general manager confronted Player D and his parent about this aberrant behavior. The general manager, who understood that the player's behavior might have resulted from a concussion, suggested the player take time off for "bumps and bruises" *instead* of undergoing appropriate medical evaluation. The player's father responded to this suggestion by stating that the general manager was "making a mountain out of a molehill" and there was no need for any further action.

The Team Therapist

The team athletic therapist/first responder (previously

known as the trainer) ideally has sports medicine and first responder knowledge, and should be able to identify a suspected concussion injury and refer the player to a qualified physician for a medical diagnosis. Athletic therapist certification requires extensive post-secondary education to achieve qualification. According to the Zurich statement protocol, the therapist should remove the player from the game if a concussion is suspected and refer him/her for secondary medical diagnosis and treatment.

The team therapists at lower junior and minor hockey levels are usually volunteer first responders who have minimal knowledge of protocols for identification and treatment of concussion or long-term consequences of concussion. Despite the efforts of national certification and league regulatory bodies to improve the acceptable safety standards, this deficiency has been observed to currently exist. Lack of appropriate sports medicine knowledge, confidence, or independence may contribute to a trainer's inability to remove a player with a suspected concussion from the game. The many responsibilities of the team therapist often prevent this individual from observing a concussion when it occurs and may require the intervention of other team members.

Therapists have reported pressure to please coaches, parents, players, and management. They also report an inability to sustain the scrutiny of their decisions for excluding injured players from play.

Case Examples

Therapist A (not an HCEP therapist). This HCEP therapist stated that he was uncomfortable working with his own son's team because he feared that other parents would suspect that taking players out for suspected injuries would favor his own son with increased ice time.

Therapist B. This therapist, who worked professionally in an associated medical field, allowed himself to be seen and identified as the team "doc." In private, however, he said that he was relieved to have a doctor at the game because he was not comfortable behind the bench and feared his ability to cope with a real trauma.

Therapist C. This trainer admitted that he was uncomfortable speaking out and taking a stand against his team's lack of concern about concussions. He felt he could be blackballed by his ownership or might not be able to find a position with another team in the future.

Prior to removal of Team B from the HCEP, Team B had 8 players who were diagnosed with a concussion; at that time, 6 players had been diagnosed with a concussion on the paired Team A. At the conclusion of the study, Team B reported that no further regular season concussions had occurred. Team A, however, during the same period, reported an additional 7 observed and diagnosed concussions (total 13).

The disparity between the numbers of observed and diagnosed concussions involving Team A and B players after Team B was removed from the study may demonstrate an example of underreporting and undertreatment of this injury.

The Physician

The physician has the primary role in diagnosing and managing the treatment of players with concussion in sports. The specialty-trained sports medicine physicians involved in the HCEP encountered frequent resistance to identifying and evaluating athletes suspected of concussion. Furthermore, athletes rarely reported their own injury. The reluctance of the athletes to self-report and their observed inclination to mask concussion symptoms is often a result of their fear of lost playing time during the recovery process.

Some of the HCEP sports medicine physicians also reported experiencing a conflicting empathy for the athlete with a suspected concussion, despite their duty to remove the individual from play and provide appropriate evaluation. The team physician's first duty is to protect the patient/athlete by providing independent medical care. The struggle with team-related bias may occur due to the regular involvement with the team and intimidation within the sports environment.

As a result of specialty training, the sports medicine physician has the opportunity to educate and formalize the training of all individuals involved in contact sports, including other physicians. Concussion education is most important for the physician's medical peers, who may not have received the same level of exposure and training pertaining to this injury. It is important for the sports medicine physician to be involved in promoting concussion prevention, which involves reviewing the way games are played to decrease the incidental incidence of these injuries and eliminate their intentional causes.

The word concussion must be openly and accurately defined. The true incidence of concussion must also be accurately documented and available for review.

Opinion Statement from Author

Scoreboard results and sports culture sometimes lead the athlete, coach, manager, and even team medical personnel to ignore the long-term health of the player in favor of a short-term goal.

Consider this remark made by a general manager who acknowledged that 3 of his players were not able to play in a crucial playoff game because of concussions: "…not great news at all, but it is what we have to deal with. Our backs are against the wall down 3–1 and shorthanded. I can't wait until the other teams are on an even playing field and not playing with injured players as I'm sure our team isn't the only team getting concussions. I just have to be content that at least our players are playing *somewhat* safe."

The pressure to win the next period, game, or series is an important and overriding factor that blinds many of those who should be protecting our young athletes. The fact is that hockey is only a game, as previously stated by a hockey parent, who persuaded his son to be evaluated for a concussion that placed his son's long-term health at risk. Hockey and other contact sports should always be respected as a game, not a life-and-death battle that places the participants at needless risk for future disability.

The athlete has to be educated about the long-term seriousness of concussion and encouraged to self-report. Sport culture must permit the athlete to report the injury and seek appropriate treatment without fear.

The adults who surround the athlete must take the leadership in promoting respect for the game and the long-term health of its participants. The identification, treatment, and prevention of concussion must be seen as a priority.

The parent, team trainer or therapist, coaches, club and league executives, and physician must become better educated in the identification and management of concussion, as well as the shared responsibility that it demands.

It is the responsibility of league or governing sport bodies to enforce rules that protect the health of the player, to recognize deficiencies in current concussion knowledge, and to institute preventative measures based on accurate data.

We can no longer claim that we do not know how to identify or evaluate this injury. Nor can we say that we do not know what the consequences of this injury are. We know they can be significant and life altering. It is everyone's responsibility to see and to act.

The personal testimonials of individuals who have suffered from concussion, and who desired to share their personal and powerful insights, are included in the appendices of this article. *(DOI: 10.3171/2010.10.FOCUS 10222)*

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Appendix

The following case histories were contributed by patients treated by the author. The treatments reflect the author's specific practice and his approach to concussion management. The testimonials were the athletes' way of sharing their experience with concussion and post-concussion syndrome.

Case 1: A 20-Year-Old Male Hockey Player

January 2009: I was diagnosed with post-concussion syndrome, from the accumulation of concussions that went undetected after 10 years of hockey and lacrosse. October 2009: I have had headaches and a changed lifestyle. I was playing goalie for [name of team removed] when I was run, and the back of my head hit the post and then the ice. The goal counted with only ten seconds left in the second period while it is believed I lay unconscious. I remem-

ber seeing all black lying on my back trying to catch my breath. I opened my eyes and slowly regained my breath. I was required to go to the bench for the remainder of the 2nd period because I was down for too long to remain in the game. My coach and trainer repetitively asked, "Are you okay to play?" I decided to return to play in the 3rd period, after becoming very emotional telling my team to protect me. Any competitive athlete questioned if they are okay to play will always say yes; I wish I was either given no option or was more in tune with how I felt. The third period seemed to drift by with cloudy vision, which I had experienced playing hockey on and off for about 6 years, not knowing it was the sign of a concussion. The following day at school I didn't feel right with a constant migraine and went to the hospital. I was told I had had a concussion, not to play hockey until the headache was gone and going to school would not be harmful.

After 4 months of trying to determine what was wrong with me, practising with the team once and making numerous trips to the hospital, I was living as normal as possible. In school and work I had felt achy, tired, headachy, and frustrated. Family and friends had noticed me becoming easily irritated. I remember sitting in my room itching to do something, usually resulting in me getting into a fight with mom, or my siblings. Co-workers had noticed my lack of memory repetitively forgetting about my shifts, which was extremely uncharacteristic. Once getting in touch with Dr. Echlin in January, I was shut down from my grade 12 year immediately not knowing when I would return or if I would be graduating or going to university with my classmates. The worst part about the entire situation [was that I] did not know when I would be back to normal, when I could play hockey, and when I could go back to school. Once being "shutdown" I was limited to no TV, computer, Xbox, was on a regimented sleep schedule, and didn't attend school or do work, and was limited to what felt like no life. As an outlet I tried watching my team play, the noise, lights, and watching what I was missing out on was too hard to take. My coach and trainer showed very little understanding and must have sought legal advice as they removed themselves from the situation. I ultimately became disconnected from the team entirely, which was tough to do as I had always prided myself on being a team player. Other symptoms I had developed were sensitivity to light and sound. I could only watch half a period of hockey on TV before developing a migraine. I had also become extremely emotional; I remember absolutely bawling my eyes out on occasion for extended periods of time, losing complete control of my emotions. Once again this was uncharacteristic of my normal behaviour. Depression was there, and thoughts of suicide crossed my mind on a few occasions. This was a scary time in my life; I had never lost touch with my emotions and thoughts to such an extent. I also had headaches so bad I couldn't sleep; I was put on sleeping pills, which slowly became addicting and I tried to sleep without them.

It was not until late February, early March I was taking two classes in school, and one night school course in order to finish my final year. My weekly schedule was basically attending night school twice a week, go into school once a week for the social aspect and to collect work for the week. Weekends I would rarely see friends; if I did I was out until 10 and felt I was missing out on one of the best years of my life. These were some of the darkest days of my life. Every morning there was basically nothing to look forward to except my girlfriend, friends, and the hope of playing hockey again. Thanks to my family, friends and the cooperation of teachers, I managed to graduate with honours. The summer was a good shut down period with no work, and little stress. Over the summer I decided to attend university with a reduced course load although my doctor was not entirely in agreement with the idea, I felt it would be more detrimental to watch all my friends go away and feel even more disconnected than to partake in classes part-time. I believe I definitely made the right decision. I rested up over the summer to take three courses as opposed to five in each semester. My university was extremely willing to work with me, supplying numerous accommodations. I am taking my core courses and tacking on electives at the end of my university career, or as I can handle to take them.

Throughout this entire experience it has been a struggle to deal with my emotions, headaches and entirely new lifestyle. I will never forget absolutely breaking down the day I was told I would probably never play contact sports again. Removing sports from my lifestyle has been extremely difficult; it feels like I completely lost my identity as a person. The hardest part through all of this is the fact that as much as people can try to understand no one knows what it's like until they go through it. Through my experiences the emotional side of the injury has been tougher to deal with compared to the daily headaches. My doctor, girlfriend and family are extremely conscious of what I am going through and are very understanding in the toughest of times. For the most part friends and other outsiders do not see my injury like they would a broken leg; it's an invisible condition. Friends may make comments if I can't come out, or when they feel like I have an unfair advantage writing exams with accommodations. One outlet I find relieving is talking to other people with PCS [post-concussion syndrome], and other brain injuries sharing experiences. Through university I have definitely had some fun and have learned not to push it, which took a long time after training myself to constantly push as an athlete. I am slowly coming to terms with my condition; I have learned to cope with it as much as possible. It has been almost a year and a half now of headaches; I am slowly losing hope [of] a one hundred percent recovery. Although I would love some answers as to when I am going to get better, I am taking it day by day hoping for the best. Another question I would love answered is what if I had never played in the third period—would things be different today? Unfortunately there is no answer to these questions. Lately I have had little sign of improvement with only a month remaining in the school year. I am hoping another summer of shutting down will be the cure.

Case 2: An 18-Year-Old Female Former High School Wrestler

On December 6th, 2008, everything about my life had changed. It was a Saturday afternoon at a high school

wrestling tournament that ended up teaching me one of life's greatest lessons the hard way. Looking back almost a year and a half later, I recognize that I have learned a lot about myself and the severity of brain injuries that are often overlooked. I hope one day I am able to look back at this experience with enough accumulated knowledge to help me look out for myself and others who are going through similar experiences.

During the second match of my first and last official wrestling tournament, I was pulled over my opponent's shoulder and slammed onto the mat head-first. I can remember feeling an odd sense of pain behind my eyes and yelled out "my head!" When this happened the referee and my coach came over to see if I was all right, as I had trouble opening my eyes and standing up because I was feeling dizzy and nauseous. The two of them thought I was okay because the fall didn't look out of the ordinary and I had not lost consciousness. My peers and coaches encouraged me to continue on with the second match and onto another one after that. Although I mentioned how I didn't think I should keep wrestling, my desire to succeed seemed more important than the pain I was feeling at the time. I can remember feeling extreme pressure inside my skull and how all I wanted to do was sleep.

Up until I had landed on my head during my first wrestling tournament, I had had no knowledge of what a concussion really was or the dangerous signs people need to look out for. Throughout my short lifetime, I have participated and competed in many different types of sports, so the feeling of extreme exhaustion was not unusual for me. On the night of the tournament, I honoured previous commitments by spending the night babysitting, which I found to be unusually frustrating and confusing. The couple I was babysitting for could tell something was wrong with me and ended up calling my parents a few days later to see if everything was okay.

On the Monday back to school I went on a field trip that I had been looking forward to for days, with the Social Justice Committee I was a part of at school. Despite how important the trip was for me, I cannot remember a single thing that happened except for the fact that the day ended with me getting sick in the washroom. After the trip, we returned back to school just in time for my wrestling practise. During practise, I was not able to prevent myself from falling asleep so my coaches sent me home thinking I was extremely overtired. On my second day back at school after the tournament weekend, I was even more confused and unable to remember where my classes were. After being told to call my mom, she picked me up from school and took me to see a doctor that one of her friends had told her about. The doctor we had seen informed us that landing on my head during the wrestling match had left me with a serious concussion that could take many months to heal.

After seeing the doctor, I was no longer allowed to watch TV, go to school, listen to music, spend a lot of time alone, sleep for long periods of time, read, use my cell phone, go on the computer, work out, or go out with any of my friends. This was extremely frustrating for me during the times when I was able to process that everything in my life had been taken away, at least until most of my symptoms had subsided. My doctor and parents were trying to make my daily life as simple as possible in order to allow my brain to heal. It was not until I started to break out of the daze I was in, that I started to feel angry and hurt about not being able to live the way I used to. I felt really alone, anxious and depressed because I could not do all of the things my friends were doing during senior year. Living in my house with two active younger siblings was also really hard for me because I was always jealous that they were able to continue on with their many sports, and were able to live independently.

There were times when I would understand and agree with what my doctor had to say but other times I would be in complete denial that anything was wrong and would try to get away with things such as going out for runs. I only ended up going on a few runs though, because after each one I would get sick and have really bad migraines. Many months after the injury, I still cannot find a way to sort out and describe everything that happened because all of my memories seem like blurry pieces of information. I sometimes get choked up and stressed out by the fact that I cannot remember so much of the last year such as my eighteenth birthday, and often wonder how this all could have been avoided. I think about how, if I had been taken out of the tournament immediately after I hit my head and not continued on to another opponent, everything could have turned out differently. Since my injury, I have learned that once you have a concussion, your brain is even more sensitive and prone to further damage. It bothers me to think that I might not have had to sit on the sidelines of my life for a year if someone at the tournament had known the repercussions of undetected brain injuries.

It is a fact that people who have had concussions suffer from not having control over their emotions. While I was off school I had frequent mood changes that often frustrated the people around me. When these people became angry at me for my emotions, they didn't realize that I was already hurting and feeling ten times more frustrated than they were. Not being able [to] explain, control, or even understand why I was feeling and acting the way I was was confusing and alienating. I felt as though no one was really able to understand what I was going through so eventually, I gave up on trying to maintain relationships with some of my friends. Many of my friends couldn't understand that even though I looked okay, I still couldn't go out and do things the way I used to until all of my symptoms had gone away. There were times when my friends would say to me out of frustration, that I seemed fine so I should stop looking for an easy way out of school work. This continues to anger me because I may have seemed okay, but I was not getting an easy way out of anything. My concussion set me back a year, causing me to miss my high school graduation with all of my friends and classmates, a moment I will never get to relive. I realize now that my friends cannot be blamed for not understanding my situation because they were never really given any information about serious concussions. All throughout my years of playing sports and schooling, I never knew how important it really was to protect your head and to step in and pull someone out of the situation immediately after they hit their head, winning

or not. I feel strongly that it is highly important for parents, athletes, teachers, spectators, and especially coaches to learn more about brain injuries and the consequences for failing to recognize the seriousness of hitting one's head.

Today I appreciate just how lucky I was to have had the doctor I did throughout this entire ordeal. He is the only person who took the time to tell me over and over again that he understood, I was going to be okay, and what I was going through happened to others. I found great comfort in his understanding and reasoning, despite the fact that on some days it was the last thing I wanted to hear about. The most important thing that he taught me that will stick with me forever is that: a brain injury is just like any other injury; you just cannot see the cast and bandages. Despite not being able to see the cast on your brain, it still needs the same type of nurturing and care as a broken arm or leg. You cannot fully immobilize your brain, but you have to find a way to allow it rest and relaxation until it is healed. This process was difficult for me to master and I wish I had done a better job of it a year ago. Although I ended up winning the wrestling match that gave me my concussion, I ultimately ended up losing. I hope the idea of never being able to play again is enough motivation for athletes to let themselves lose a game in order to sit out and recover correctly so that they are able to continue on with all aspects of their lives.

Case 3: A 25-Year-Old Female Former Hockey Player

[Date of injury removed] The last 5 years have been the hardest, most challenging years of my entire life. I was assaulted in a hockey game, which resulted in a head injury that turned my world upside down. Before this incident I always succeeded in everything I put my mind to and surpassed all expectations and challenges put before me. I was always described as a vibrant, driven, focussed and friendly person. After I got injured it left me with such dramatic changes in my abilities that I was almost a different person. I slowly and steadily went into a shell. I still can't recall or retain information very easily. When I listen to people speak or when I try reading, it is very frustrating because by the second sentence I have already forgotten the first. I am in pain with bad headaches almost every day and jaw pain that is getting worse. There is often numbness in my legs that makes it very difficult for me to walk properly or stand for very long. I have also been suffering from insomnia. I would be past the point of exhaustion, but I can't sleep. My anxiety is debilitating and I have a dizzy nauseous feeling most of the time. When I shut my eyes, my head spins and my body almost always falls sideways. I can't take a shower without holding onto something or I will fall.

I couldn't understand at the time why my friends (all but one!) were not around to support me. Shortly after the injury my boyfriend of almost 2 years broke up with me. My teammates never even invited me to the Award Banquet that year. My mother woke up one morning to find my trophy hanging in a bag from my door knob. People were treating me differently and I couldn't take it. It made me angry, sad, and misunderstood. I had been quite popular and had a lot of friends, but almost overnight people stopped calling me to do things with them. I didn't have the organizational skills to coordinate get-togethers like I used to so my social life deteriorated.

I wasn't in a position to ask for help and I didn't know where to turn. One doctor that I went to at a sports injury clinic wanted to help, so she sent me to a doctor at rehabilitation hospital that was supposed to help her with a diagnosis and a treatment plan. He spent five minutes with me asking me what happened. He told me at that time that it was very "interesting" that I was able to recall details of what happened during the assault. He said that he couldn't understand why I was sent to him and it was wasting his time. That was the end of my endeavours, at that time, to seek medical help.

Before my injury I was working as an Accredited Pharmacy Technician while attending night school to earn extra credits that would benefit me when I went off to college that September. I was awarded an academic scholarship in the Bachelor of Science Nursing Program [name of university removed]. I suffered my concussion 6 months before I was to start school. With the lack of understanding on how to treat a brain injury we were misinformed by the family doctor, who told us that like reconditioning the body after an injury, the brain also requires exercise. I attended school that September, but was unable to continue in my program. I tried to attend Nursing School again the next September (thinking by now I should be over this concussion). I had to quit and return home in October. I was unable to proceed because of the inability to retain information and because of the severe symptoms of my pain. After I returned home I tried working a couple of times but I was UNABLE to commit to be a reliable employee. I was sick, tired, confused and in severe pain. I was dependent on my family and that was hard because I had always been a very independent person. They were suffering too, watching me go downhill.

I became very depressed. I was a person that was "programmed to succeed" so I couldn't help feeling like a failure. I started to alienate myself from people so I wouldn't have to explain why.

I was slowly losing everything instead of moving forward like other young adults my age. I was in so much pain physically and emotionally that I felt relief from pain medication, but that also started to become a problem. I was losing HOPE, but I was sensible enough to know that masking my pain wasn't the answer.

I have recently been diagnosed with post-concussion syndrome and have learned that there is a treatment plan that should help with a lot of my continuing symptoms. I'm learning that resting my brain...instead of exercising it will help my injured brain to heal. This has taken away a lot of my shame and guilt.

Now, when I rest I try not to tell myself "I'm lazy." I try saying, "You are healing an injury."

Case 4: A 20-Year-Old Male Hockey Player

I have being playing hockey since I was four years old and one thing that has always been consistent for both me and my fellow players: the basic idea of playing through pain. As hockey players, we all learn at a young age that we have to be able to take the bumps when they come or else we won't last very long in the game. This

ideology is an awesome metaphor for life in general because we learn to push through the hard times. The only problem is, pushing through head pain and acting like it isn't there doesn't make you stronger—it gradually breaks you down.

I've had some random injuries in my life that, in some instances, have ended seasons for me. I got used to avoiding doctors if possible because they were frequently the bearers of bad news. This meant that I never once went to a doctor when I had head pains, particularly this season—the doctor had to contact me the last time, to ensure I would go in. I used to play a fairly physical game, and though that certainly wasn't the only aspect of my game, I really loved contact. When I was in Grades 8 and 9, I was one of the smallest players and as such, wanted to prove myself by always going after the biggest guy on the other team. Then, as I grew into one of the bigger guys, the physical aspect of my game became more intense.

In November of 2009, a team trainer asked me if I had ever had a concussion (perhaps suspecting as much). I told him that I had never been diagnosed with one by a physician, so no. Later that same month, my team was playing an away game and I was playing very well (probably my best since I had returned from surgery on my wrist six games prior). The third period was getting pretty physical and it was a tight game. One of the other team's better defenceman and I had been at each other most of the night but we were both too worried about the score, so it was nothing more than chirping and hitting. He ran me once when I was getting a pass on the boards in my zone but it didn't work out—all that ensued was more chirping. The next time the puck went to him on the point, I ran him and he got his elbow up enough to give me a little daze—I didn't even think twice about that because it happened all the time. The puck was fired down the ice and I beat him back to his zone to pick it up. With the puck on the boards, he hit me enough from behind that my head bounced off the glass, and the next thing I remember was both of us with our helmets off and a fight. I knew the time remaining in the game and the score, and also realized right away that this was not the time to be fighting. I tried just holding on to bring the linesmen in so that we wouldn't get fighting majors, but that was a bad idea. My opponent pulled up on my leg and I fell back and I hit my head on the ice, hard.

More embarrassed by my stupid actions than anything, I left the ice to go get changed. I had a bad headache but was sure it was nothing and was way more concerned about what my coaches would say to me when they came in—they wouldn't be happy that their Captain was in the dressing room instead of helping the team get a much needed goal at the end of the game. I did a concussion test with the doctor that was at the game and told her I was fine and that all I wanted was some food. I went home and thought that with a good sleep, I'd be all set for class the next morning.

The next day I had a really hard time concentrating in class, but I didn't think anything of it because that had been par for the course for most of this year (which was a much different experience than in previous years). I got a call after class from my manager saying that Dr. Echlin wanted to see me and I told him that I was fine. Dr. Echlin insisted that I come in just so that I could prove to him that I was perfectly fine. I was having a real problem trying to read my work off of my computer screen so I agreed to go—getting out of the library and taking a drive could only do me well, right? Dr. Echlin told me that I was concussed and that he could not clear me to play until everything cleared up. I can't say that I was surprised but I was disappointed for sure!

After going through and discussing some of the games that I had played before I saw a doctor, we figured out that I had probably had at least two or three concussions since the start of September before this last one. Stacking the concussions just made it harder and harder to ignore and hide the symptoms and this one tipped the scale for sure.

For the next month and a half, I could hardly read. If I did an hour of work, I'd have to take a two-hour nap. Walking to class began to get difficult because of the head rushes. I went from being a hard-working student and athlete to someone that couldn't be either. Everyone related to hockey wanted to know when I was coming back and I couldn't give them a straight answer because I didn't know. Rightly so, they wanted answers that I couldn't provide because of the situation I was in. As it was, I had to postpone all of my Christmas exams, causing me further stress. My parents weren't worried about me playing hockey again (though they would have loved to see me well enough to get back on the ice); they were more worried about school and my future. They told me that I had my whole life to live and that I only had one brain…so don't mess it up! I trusted them and agreed but I was determined to turn things around for myself. I would have a couple of good days in a row and be able to do work and maybe a little bit of exercise, and then I would call my coach and tell him I was coming back—thinking that if I believed I was going back right away, I could make myself get better. It took until the middle of January before I realized that my season was over. Admitting defeat is tough and I hated the fact that I had promised so many people that I would get back on the ice but I wasn't going to be able to pull through on that promise. I felt guilty, frustrated, and honestly, devastated by all that had happened.

Concussions are an odd injury. Through all my wrist surgeries, no one ever questioned if I could play again because they could see the cast or the fresh scars and realize that I wasn't ready yet. With a concussion, only a few people like my parents or girlfriend could tell that something was off when they were talking to me—anyone who didn't know me as well had no idea that I had a brain injury. No one can see a concussion when they look at you, so you have the appearance of being fine. Most people don't understand concussions and it is very hard to get people to buy into the fact that there is something actually wrong.

It has been more than five months since my last concussion and my symptoms are starting to get better. Reading and memorization were a real problem for quite a while but now things are getting a lot easier. I am down to four classes at university in hopes of keeping my marks close to where they used to be. The physical change was huge after the concussion, as I lost 25 lbs fairly quickly

because I was unable to exercise or train. This experience taught me a lot: I am NOT invincible… and my brain is something very worth protecting.

Case 5: A 19-Year-Old Male Hockey Player

The following is the player's direct, first-person description of the concussion:

When I first got hit I didn't know what was going on. I lost my sight and tried to follow the boards back to the bench. My legs felt weak, like it was hard to keep my balance. I got the puck along the boards and tried to stick handle but I had no control over it. I tried passing the puck but I could barely see it and could get nothing on it. It was the same with the shot that I took. I couldn't see the goalie and couldn't get anything on the shot. Then I scored and I had to follow my teammates back to the bench.

Case 6: A 23-Year-Old Female Elite Cyclist

In the summer of 2009 I was injured in a crash in a cycling race in Canada. I do not remember the crash, or about five to ten minutes after it, although I am told that I was talking the whole time (but repeating myself over and over and not lucid). The last thing I remember before the crash was climbing a hill in the race. The next thing I remember is climbing into the ambulance.

Once I arrived at the hospital, which took approximately 30 minutes by ambulance, I was rushed into a private room where I was attended to by nurses and a doctor. The doctor found that I had injured my shoulder, needed stitches for a laceration to my head, and directed the nurses to clean up and cover my wounds. I suggested the possibility that I may have had a concussion, but he was not convinced this was the case. He instructed me to go home and be sure to take it easy, and if I had any vomiting or blacking-out that I should come back to the hospital immediately.

That night I moved into the [team masseuse's room] and her job became to take care of me. I still wanted to be part of the team, and despite a bit of neck pain and being really tired I didn't think anything was seriously wrong, so I continued to follow the team as they raced, resulting in long days and early mornings. As the days went by it became more obvious that something was very wrong. I was able to sleep for many hours multiple times during the day on top of my usual evening sleeps, and was still getting headaches, nausea, and significant neck pain.

I finally flew back [home], as planned, four days later, where I met my parents who had helped me set up an appointment with my family doctor. Since it was summertime, many doctors were away which further complicated matters. I ended up seeing two family doctors and three sport medicine doctors, without anyone really knowing what to do except prescribe rest.

In the cycling world, many people had heard about my crash, and one person I remember specifically said, "You're lucky it was *just* a concussion"! To this day I think of that comment and it reminds me how little is understood about this injury. Within two weeks of the crash, fellow cyclists started to question my injury, as most think of a concussion as a 24-hour to 1-week-long injury. Many doubted that I was *actually* still injured. Having a concussion is an invisible injury. If nobody asks how you're feeling, it's very hard for them to see that anything is wrong. I believe it was only when I had to give up my spot on the Pan American Championship team that others realized that I really couldn't ride and that I was still seriously injured.

The next few months were probably the hardest for me: not knowing how long the recovery would take, having others doubt what I was going through, and me myself not truly understanding what I was dealing with.

When I first got injured, friends noticed how upset I was and suggested I contact a sport psychologist. Apprehensive about the idea of going to a psychologist, but open to any option that might help, I decided to contact a local sport psychologist. This was perhaps one of the best things I ever did. Despite not having any specific background in concussions, his support was tremendously helpful. He helped me to take everything one step at a time, and continue to look at my past accomplishments and make little baby-step goals towards the future. He helped me to stay relaxed through the use of mindful meditation, and creating daily logs of my recovery progress.

Dr. Echlin was very helpful. He helped to arrange an appointment for me to visit Dr. Johnson in Toronto, and more importantly helped me to contact other athletes who have been through serious concussions and successfully re-entered into their competitive sport.

Over 10 months later, I am still dealing with my head injury on a daily basis. I have learned many of the triggers of my headaches, and how to best avoid them. I still get headaches rather frequently, and am only able to exercise at low intensities every few days. However, when I look back on where I was last June, I see that I have improved.

From all that I have learned, I think the most useful thing for me was talking to others who had been through serious long-term concussions. There is a lot of cynicism from the public about post-concussive syndrome, and many moments it even caused me to doubt myself. However, it is a real condition that mostly just takes time and "taking it easy" to heal. Although ten months can seem like forever, I am confident that I am almost healed. Every week I feel that I can add a bit more to my life. One of the more positive results of this injury is through this whole process I decided to quit my job and go back to school to pursue a master's degree in a field I have been fascinated with my whole life: sport psychology.

Case 7: A 20-Year-Old Male Hockey Player

Recently I have suffered from post-concussion syndrome. I had received a second concussion within a few weeks of a previous hit to my head. Before, I would hear on TV and the news of players suffering from concussions but I never really took it too seriously, thinking that the player would be fine and bounce back, no problem. I learned that receiving a concussion is a big deal after I got my last one.

[In] 2009, I was hit with an elbow to my head playing in a Junior A hockey game. I do not remember the game, preparing for the game, nothing. I remember sitting in the dressing room with a paramedic, not knowing what hap-

pened. The next few months consisted of headaches, light sensitivity, sensitivity to noise; even just walking around too much seemed to cause those severe headaches! It puts you into a state of depression and you feel like you have a long road back to recovering. Luckily, I saw Dr. Echlin and he kept a close watch on my progress. If I hadn't seen him, I would most likely have rushed back into playing within a few weeks and run into more trouble with more concussions. That is a big problem these days: players, coaches, trainers, all rush concussion victims back into action too quickly!!!

If I could give a concussion victim any advice, it would be simple. Get help, see a specialist, and DO NOT RUSH! You have the rest of your life to live!!!

Case 8: A 20-Year-Old Ex-Hockey Player

Concussions were never something I took serious until I had to quit hockey because of them. I am currently 21 years old and haven't been able to play contact sports for more then 5 years. I was playing high level hockey when I received my 8th concussion. I have had concussion many different ways, playing on monkey bars, roller blading, wrestling with friends and playing hockey and lacrosse. My last and most serious concussion I suffered in a hockey fight. I had post-concussion syndrome, which then turned into a daily chronic headache which lasted for years. Concussions are such a scary thing because they are not like a broken arm; they can't just be healed with a cast or medication. The brain is such a complex thing. After I had to quit hockey the headaches and the lack of physical activity led to depression. Since I couldn't play the sport I loved I felt like I no longer fit in. Since I wasn't able to work out or do any physical activity for a long time I put on weight, which made me feel even worse. I began to no longer find joy in hanging out with friends or being social. It made tasks such as school and work much harder to deal with. The years I should have been having the most fun, I was dealing with this problem. Concussion [is] not just a minor injury; it can lead to so many other major issues, whether physical or emotional. Concussions are too often ignored because it is an injury you do not see. I know how easy it is to tell yourself you don't have a concussion when you really do. I told myself that a few times. Doing serious damage to your brain is not worth playing that extra game or those few extra shifts. Concussions can lead to so many other serious problems that I personally experienced and would not wish upon anybody. They are a very serious injury and should be treated that way.

Case 9: A 54-Year-Old Ex-Professional Football Player

Circa 1984, one of many concussion experiences:
Player [talking to self]: Where am I?
Oh yeah, we're in Calgary.
What happened?
Oh yeah. Got knocked out. Again.
I am still laying flat on my back. Wow.

I can see the trainer and doctor coming towards me. The game has stopped. TV timeout. Hey, at least I get some air time.

They're here. First, they check to see if I have sensation in my extremities (feet and hands). I check out. NOTE TO SELF... Thank God!

Doctor: "OK. We are going to have to ask you a couple of questions to see if you're alright (translation: if you can go back to play). We believe you may have suffered a concussion."

Player: "Well, whatever. I did get knocked out but I am OK now. I am good to go."

Doctor: "I still need to ask you a few questions."

Player [talking to self]: I need to answer these questions, even if I stretch the truth... I NEED to get back into the game.

Doctor: "Where are we?"

Player: "McMahon Stadium. Calgary."

Doctor: "Who are we playing?"

Player: "You kiddin'? If we're in Calgary, we're playing the Stampeders."

Doctor: "What is the score?"

Player: "We are losing 14-7."

Doctor: "What is the time in the game?"

Player: "Move your fat ass so I can see the score clock."

Doctor: "No, without looking?"

Player: "OK, somewhere in the second quarter."

Doctor: "What happened?"

Player: "I hit my head on the turf, while tackling the quarterback."

Doctor: "You seem okay, but let's take it slow. We'll walk back to the sideline, and see how things go over the next few minutes."

Player Commentary

The first thing I do when I get back to the sideline (bench) is hide. I need to follow the old adage "out of sight out of mind." I take a knee at the end of the bench, where the big boys (O lineman) hangout, as they provide the best cover. They never look over here.

The game is back on.

([I look] around). Hey, how did we get onto the field? I don't even remember entering the stadium. I feel empty... and, truth be told, frightened. I have no idea how we're going to leave the stadium.

(Next series, back on field.)

(Afterwards):

As it turns out I had a great game. But I did not remember anything after the concussion.

Thank God for game film.

Background

Back in the day, a man would return to the field after being knocked out. That was the sign of a *real* ball player. As a pro, you *always* went back.

Just grab some smelling salts...and off you go!

Going back into the game was a personal victory. You could always tell *that* story in the locker room or the bar. Heck, lots of players didn't remember anything about the game until they saw the game film. You just grabbed your *huevos* and got back out there. It was a different era of sport. Real sports. When a man was a man.

Unfortunately, today there are still times we cannot remember that last play in our daily lives. With no cameras we rely on someone else—a friend, a family member, and maybe a wife (usually a second or third)—to tell us about it.

As players, we lived our dreams, but now some live our nightmares.

(The nightmare of anger, alcohol and/or substance abuse, depression, memory loss, spousal abuse [both ways], dramatically reduced life expectancy [56], etc.)

As a Canadian I lived my dream, but with it came a cost. Any regrets? HELL NO!

Case 10: A 43-Year-Old Ex-Professional Hockey Player

I played hockey since the age of 5. I not only was good at the sport but I truly enjoyed practicing, which in turn made me better. I began to suffer concussions during my Junior A career. It was all extremely new to me—the effects at the time of injury and just how to make this unnatural feeling "go away." There was never any thought about tomorrow. It may sound extremely primitive, but my trainer would give me warm cups of water and over twenty minutes or so things would improve. We didn't know what we were dealing with. I had not been "knocked out" but rendered "off," "dizzy," and "spacey." This made a diagnosis and future game plan difficult back then. My trainer wanted the best for me as I obviously did for myself, but where were the answers?

Time has played a critical role in the acknowledgement and understanding of concussions. For the most part, no longer is a player or person looked at as being soft or not up for the task. However at the professional level, that problem is still prevalent. Many times it is the player who is not being perfectly honest with the doctors and trainers for fear of losing his position on the team. Compounding this is the stigma of a concussion history that attaches itself to a player whereby opponents make cheap and unnecessary attempts to make a name for themselves at the price of one's health. In a weird and twisted way they are rewarded for their actions. These players are rarely the ones who make a difference on the score sheet but those that become coveted by opposing teams and their contracts reflect it.

Concussions will always occur. In a high paced, contact sport like hockey with strong, powerful men skating at high speeds, it is inevitable for this unfortunate aspect of the game to [be present]. One would just like to think that players would respect their opponents and avoid doing the unnecessary in deliberate fashion. In the event that a player does suffer from "concussion like symptoms" get real and acknowledge that it is a concussion and make sure the proper steps are taken to assist the PERSON back to proper health. The one remedy that I have always found to be the best is simply time. In that, I find it ironic that it has taken this long for the injury of suffering a concussion to be talked about more openly and honestly than ever before. The use of the "C" word should not be whispered. On that same note, one would hope that all advances in this field are being shared and funding is being used appropriately.

See the corresponding article, **DOI:** 10.3171/2010.9.FOCUS10186.

Erratum

A prospective study of physician-observed concussions during ice-hockey:implications for incidence rates

To The Editor: Thank you for publishing our paper, "A prospective study of physician-observed concussions during ice-hockey: implications for incidence rates" (*Neurosurg Focus 29(5):*E4, 2010; DOI: 10.3171/2010.9.FOCUS10186).

On the eve of publication I found 2 errors in our paper, but it was too late to correct them before the paper was posted online. The first error appeared in the *Conclusions* section of the *Abstract* (page 1). The incorrect sentence was: "The incidence of game-related concussions (per 1000 athlete exposures) in these fourth-tier ice hockey players was 3.3 times higher than the highest rate previously reported in the literature." This sentence has now been corrected to state the following:

> The incidence of game-related concussions (per 100 athlete exposures) in these fourth-tier junior ice hockey players was 7 times higher than previously reported in the literature.

The second error appears in the first paragraph of the *Discussion* section of the article (page 8, second column): "Honey[16] reported incidence rates of 4.2 per 1000 athlete exposures for university-age players, and 6.6 per 1000 athlete exposures for players on fourth-tier amateur teams." This sentence has now been corrected to state the following:

> Flick[10] reported an incidence rate of 3.1 per 1000 athlete exposures for Division 1 university ice-hockey players in 1 season.

I am pleased to have the opportunity to correct these errors. The corrections were made online as of November 5, 2010.

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