J Head Trauma Rehabil
Vol. 31, No. 3, pp. 159–166

Subconcussive Blows to the Head: A Formative Review of Short-term Clinical Outcomes

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Background: Given questions about "lower thresholds" for concussion, as well as possible effects of repetitive concussion and chronic traumatic encephalopathy (CTE), and associated controversy, there is increasing interest in "subconcussive" blows and their potential significance. **Objective:** A formative review with critical examination of the developing literature on subconcussive blows in athletes with an emphasis on clinical outcomes. **Methods:** Studies of biomechanical, performance and/or symptom-based, and neuroimaging data were identified via PubMed search and critically reviewed. Five studies of symptom reporting/performance and 4 studies of neuroimaging were included. **Results:** The relation between biomechanical parameters and diagnosed concussion is not straightforward (ie, it is not the case that greater and more force leads to more severe injury or cognitive/behavioral sequelae). Neuropsychological studies of subconcussive blows within a single athletic season have failed to demonstrate any strong and consistent relations between number and severity of subconcussive events and cognitive change. Recent studies using neuroimaging have demonstrated a potential cumulative effect of subconcussive blows, at least in a subset of individuals. **Conclusion:** Human studies of the neurological/neuropsychological impact of subconcussive blows are currently quite limited. Subconcussive blows, in the short-term, have not been shown to cause significant clinical effects. To date, findings suggest that any effect of subconcussive blows is likely to be small or nonexistent, perhaps evident in a subset of individuals on select measures, and maybe even beneficial in some cases. Longer-term prospective studies are needed to determine if there is a cumulative dose effect. **Key words:** *balance*, *cognition*, *concussion*, *mild TBI*, *neuropsychological*, *outcomes*, *subconcussion*

A "SUBCONCUSSIVE" BLOW is one that does not meet the criteria for clinical diagnosis of concussion or mild traumatic brain injury (TBI), yet is hypothesized[1] to have an adverse long-term effect in some individuals, particularly via repetitive occurrences. Subconcussive blows must be differentiated from mild TBI or concussions. *Mild TBI* is defined as disrupted brain functioning from any force to the head as evidenced by altered or lost consciousness, with various severity indices (length of coma, posttraumatic amnesia, or Glasgow Coma Scale score) that are of shorter duration or milder than more severe TBI. The most commonly utilized diagnostic criteria are those proposed by the American Congress of Rehabilitation Medicine.[2] The term "concussion" is sometimes used to refer to a milder subcategory of mild TBI,[3] particularly in the sports literature, but the term is typically used synonymously with "mild TBI." The vast majority of mild TBI cases have normal findings on clinical neuroimaging (ie, CT and structural magnetic resonance imaging [MRI]). Indeed, some clinical diagnostic criteria for concussion require normal acute neuroimaging.[4] The question then becomes whether "invisible" persistent structural injury is present.[5,6] Increasing resources have been directed at finding objective physiological evidence of injury and potential correlates with cognitive and neuropsychiatric symptoms through newer or experimental neuroimaging techniques and other biomarkers.

Severity of TBI is determined at the time of injury and not (as is often erroneously done) by level of functioning at some later time point. Severity of TBI is a continuum,

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The views expressed herein are those of the authors and do not necessarily reflect the views or the official policy of the Department of Veterans Affairs, Department of Defense, or US Government. This material is the result of work supported with resources and the use of facilities at the James A. Haley Veterans' Hospital.

The authors declare no conflicts of interest.

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DOI: 10.1097/HTR.0000000000000138

and the particular classification scheme used to designate a mild, moderate, or severe injury is somewhat arbitrary. As such, there has been much debate about how best to define concussion/mild TBI and the need for consistency in diagnostic criteria.[7] Because it is sometimes impossible to determine with certainty whether or not a person has sustained a mild TBI, some argue that broad and inclusive criteria should be used to identify those at greater risk and to ensure proper evaluation and treatment (eg, McCrory et al[3]; Scholten et al[8]) For example, a recently published consensus statement on sports concussion encourages assessment and management of athletes showing features of concussion, which includes postconcussive symptoms (eg, headache, emotional lability) and sleep disturbance.[3] Unlike moderate to severe TBI, diagnosis of mild TBI often cannot be corroborated with objective diagnostic tools used by medical or other health care personnel.

If the lower boundary of concussions is unclear, defining a "subconcussive blow" or a "subconcussion" is even more problematic. How does a "subconcussive blow" differ from any blow to the head? What force would be required to be designated a "subconcussive blow" as opposed to a less severe and nonclinical impact to the head? Furthermore, given that concussions may go undiagnosed at the time of the impact, when and how would subconcussive blows be diagnosed? Therefore, "head impacts" or "head impacts not associated with diagnosed concussion" are more accurate terms. Because a subconcussion cannot clearly be defined, it is largely an elusive theoretical construct at this point.

There is growing concern that repetitive head trauma, both those associated with diagnosed concussions and those not so associated, may cause brain pathology and lead to chronic traumatic encephalopathy (CTE). Chronic traumatic encephalopathy denotes a histopathologically defined condition, which has been proposed to be a secondary consequence of repetitive head trauma and to represent a degenerative condition that causes pronounced behavior changes and cognitive dysfunction.[9] Its diagnosis is very controversial. Historically, the term "dementia pugilistica" or "punch drunk syndrome" denoted a similar entity, described in boxers with repetitive head trauma.[10] Pathologically, the hallmark of CTE is tau-immunoreactive neurofibrillary tangles.[11] However, in contrast to Alzheimer disease, the neurofibrillary tangles are unevenly distributed with a predilection for the depths of the sulci and around blood vessels,[12] particularly early in the disease. Furthermore, deposition of beta-amyloid (Aß) plaques occurs in fewer than half the cases of traumatic encephalopathy reported to date.[9]

Just as there is controversy over the lower severity boundary for concussion, there also are no consensus criteria for the neuropathological or clinical criteria of CTE. The 2 prominent laboratories in this line of research have promulgated partially overlapping but different criteria.[12,13] Similarly, anecdotal links among concussion, CTE, and clinical outcomes have yet to be scientifically established. For example, despite highly publicized cases suggesting a link between suicide and concussion, a recent review of the evidence concluded that "the current state of the science indicates that suppositions invoking a relationship between CTE and suicide must be viewed as speculative at this point in time."[14] Iverson notes[15] that there are no published cross-sectional, epidemiological, or prospective studies showing a relation between contact sports and risk of suicide.

Despite the definitional and diagnostic problems with "subconcussions," given the debate about the "lower threshold" of concussion and how inclusive versus restrictive one should be, there is increasing interest in "subconcussive" blows to the head. Concerns about the possible effects of repetitive head trauma and the development of CTE add to the importance of developing a clear scientific understanding of these issues. Does a blow that does not necessarily alter consciousness, either alone or repetitively, have some type of adverse impact, either in the short- or in the long-term? This would obviously have significant implications for those who participate in sports, particularly those with a higher rate of such blows (eg, boxing, football, soccer, etc), as well as for military veterans who have been exposed to repeated physical trauma (or potentially even high pressure blast waves) to the head. It might also suggest the need to lower the threshold of what constitutes a concussion.

Animal models suggest that a single blow with a level of force that typically does not cause cellular damage can nonetheless cause damage when repeated several times within short periods.[16,17] Shulz et al[16] used a paradigm wherein a "subconcussive" lateral fluid percussive force of 0.5 to 0.99 atmosphere (atm) was used based on previous work suggesting that forces of 1.00 to 1.50 atm caused concussion with functional impairments. They found that a single mild lateral fluid percussion injury administered with this lower level of "subconcussive" force did not produce significant differences between "subconcussive injured" rats and sham injured rats on axonal injury measures or on measures of cognitive, emotional (ie, validated measures of anxiety on the elevated plus maze, based on rodents' aversion to open spaces), or sensorimotor functioning. However, there was evidence of an acute neuroinflammatory response in the subconcussive group in the form of increased microglia/macrophages and reactive astrogliosis. Slemmer and Weber[17] found that a 10% subthreshold stretch paradigm (which results in membrane deformation and axial strain or stretch) eventually caused damage when repeated multiple times within short periods (2-minute intervals). Notably, 5 or 6 insults were needed to cause damage, and damage was not associated with repetitive blows administered at longer intervals (ie, 1 hour). There were also significant increases in neuron-specific enolase after 6 consecutive injuries, a marker of brain injury, but no corresponding increase in S-100h protein (another biomarker of injury). As such, there is some evidence that repetitive, "subthreshold" force can cause injury but only with a certain number of repetitions in short succession.

On the contrary, other experimental animal research suggests that repetitive "subconcussive" blows may actually be protective in some circumstances. For example, Allen et al[18] found that administering repetitive concussive insults (repetitive mild TBI was induced by dropping a weight from 2.5 cm above the dural surface 3 times with 3 days intervening each time) before inducing a severe TBI insult caused significant reduction in motor deficits compared to those observed in animals with severe TBI alone. These authors hypothesize that activation of some neurons and astrocytes in certain regions following repetitive injury may play a role in cortical reorganization and/or creation of alternate pathways in the brain. There is other evidence that a very mild "subconcussive" blow might actually be protective in some cases. For example, a "subconcussive" injury (3.4 mm) applied to mice hippocampal cells administered 24 hours before a "mild" injury (5.5 mm) significantly decreased S-100h protein (but not neuron-specific enolase).[17] However, there may be differences in effects between glia and other cells in this type of paradigm (see Arundine et al, 2003[19]). Further research on "preconditioning" is necessary. These findings at least suggest the possibility that there may be a period when a subconcussed brain is rendered better able to recover from a subsequent injury. As a whole, the animal literature suggests that any effect of repetitive subconcussive blows is likely to be complex, with many factors to consider including time between impacts, number of impacts, type of impact/force, type of outcome potentially affected, etc. The longer-term effects are also unknown.

Translating animal experimental findings to humans is difficult. Nevertheless, the animal literature cited above certainly raises the possibility that head impacts not associated with a diagnosed concussion can have some type of effect in human beings. Posttraumatic perturbation of metabolism resolves within 7 to 10 days in rats (which corresponds to the typical functional recovery in athletes after concussion[20]) but can last 2 to 4 weeks in humans.[21] In general, human recovery is slower than that of rats.[22] The questions about subconcussive blows then become as follows: how frequent, how close in time must they occur, how powerful the minimal force required, and how many blows are needed to sustain structural damage? In addition, what might the long-term consequences be, if any? This line of research in humans is really in its infancy and might best be studied via controlled study of athletes, particularly soccer players, who endure both "subthreshold" and concussive injuries. A meta-analysis[20] examining "exposure" due to sports (ie, heading frequency in soccer or number of bouts in boxing) found a small but significant adverse impact of exposure on neuropsychological functioning ($d = 0.31$) overall. However, the majority of the studies in that analysis included participants with prior head injury, so the effect is likely inflated with respect to evaluating the potential effect of repetitive "subconcussive" impacts.

A recent review of the subconcussion literature[1] in humans concluded that subconcussive blows can have a deleterious neurological effect over time. However, that review did not focus primarily on clinical outcomes and did not discuss in detail some contradictory findings in the literature to date. The purpose of the current review is to critically examine the extant literature on subconcussive blows with an emphasis on more short-term clinical outcomes because we are unaware of any studies of long-term outcomes. In addition, given the paucity of data on this emerging topic, only a formative, rather than systematic, review was possible.

METHOD

PubMed was searched using the following terms: subconcussion, subconcussive, impact/concussion, and threshold/concussion. In addition, reference sections of known journal articles on the topic of subconcussive blows were searched. Only studies with human participants and studies that addressed clinical outcomes were included.

RESULTS

Twenty-two potential studies on clinical outcomes were identified, 9 of which were ultimately deemed relevant to the purpose of the review: 5 studies on symptom reporting/performance and 4 studies on neuroimaging. Thirteen studies were discarded because they either were conducted with animals or did not address clinical outcomes. All included studies were conducted with athletes. In addition, 9 studies on biomechanics of concussion are briefly reviewed below to provide context for the clinical findings.

Biomechanical data

Not surprisingly, human data in subconcussion studies come primarily from football players, who endure an average of 652 impacts to the helmet per season at the high school level with variability due to position (ie, linemen tend to have the most impacts).[23] With respect to forces sustained to the head, Schnebel et al[24] reported a range of 90 to 120*g*s in collegiate football players. Pellman et al[25] found that a force in excess of 98*g*s is 75% specific to concussion in the National Football League. In contrast, others have found that the magnitude of impact to the helmet does not necessarily correlate with the probability of sustaining a concussion,[26] suggesting that there is no "threshold effect" (or a certain force necessary) for concussion. Overall, most studies have found a wide range of impact magnitudes associated with concussion. Furthermore, rather than magnitude of force, a combination of biomechanical variables tends to better predict concussion (ie, linear acceleration, rotational acceleration, head injury criterion, impact location).[27] However, Eckner et al[28] compared cumulative impact histories prior to concussive impacts to the cumulative impact histories prior to the 3 largest magnitude nonconcussive impacts in the same athletes and found that the cumulative impact burden history prior to concussion was no different than the burden produced by impacts that did not result in concussion. This was true no matter what variable was examined–number of hits, cumulative force, or type of force (ie, linear vs rotational). Furthermore, there was no evidence of a window of vulnerability vis-à-vis nonconcussive impacts. Similarly, Guskiewicz et al,[29] in a prospective study of 88 college football players with helmet telemetry over 5 seasons, found no relations between diagnosed concussion; linear or rotational impact magnitude (or impact location); and changes in postural stability, cognitive performance, or self-reported symptoms following injury. The authors concluded that something other than just force (both in terms of magnitude and location) determines the occurrence of concussion and subsequent cognitive/behavioral sequelae. On the contrary, Beckwith et al[30–32] found that football players were hit more often and with greater impact on days when they were diagnosed with a concussion; when the concussion was diagnosed immediately after impact, the magnitudes of a variety of kinematic measures associated with the injury were elevated relative to those associated with the delayed diagnosis of concussion, though it is unclear to what extent delayed diagnoses were accurate. Clearly the role of prior head impact burden and the relation between biomechanical parameters and diagnosed concussion are not simple.

Performance and symptom reporting data

Other investigators have pursued clinical outcome studies of the neurological/neuropsychological impact of subconcussive blows. Broglio et al[33] studied 95 high school football players over 4 seasons using a head impact telemetry system to record impacts to the helmet. In that time, there were a total of 101,994 impacts recorded and 19 athletes sustained a total of 20 concussions. Both cognitive and symptom reporting measures (using "ImPACT" computerized assessment[34]) were completed preseason and again within 24 hours of injury in those who sustained a concussion. The concussed athletes demonstrated acute declines in cognitive performance and increases in symptom reporting. However, there were no significant relations between changes in performance on cognitive tests and any of a number of impact exposure variables (including number of impacts, peak or cumulative linear acceleration, peak or cumulative rotational acceleration, impact severity or cumulative profile, time from game start until injury, or time from the previous impact), nor was there a relation between self-reported symptom severity and these impact exposure variables. Of nearly 100 statistical comparisons, there was only 1 marginally significant relation between the force of the injurious impact and change in impulse control, though it was not significant when corrections for multiple comparisons were applied.

Gysland et al[35] studied 46 collegiate football players with cognitive, sensory, balance, and symptom self-report measures both before and after a single season during which a telemetry system recorded head impacts. Changes in performance were mostly independent of prior concussion history as well as the total number, magnitude, and location of sustained impacts over 1 season. Specifically, head-impact variables (including the total number of impacts, the total number of impacts greater than 90*g*, the total cumulative magnitude of impacts, and the total number of impacts to the top of the head) did not predict neurocognitive performance over time on the Automated Neuropsychological Assessment Metrics[36] or the Standardized Assessment of Concussion[37], nor did they predict changes in balance on the Sensory Organization Test[38] or total symptom severity. Another measure of balance (the Balance Error Scoring System[39]) produced counter-intuitive and contradictory findings. That is, a higher number of impacts and higher number of prior concussions predicted improved balance over the course of the season, while a higher cumulative magnitude of head impacts predicted declining balance. Finally, while total symptom severity was not related to head impact variables, an increase in the number of symptoms reported was related to a higher number of severe head impacts (over 90*g*) and a higher number of impacts to the top of the head. As the authors point out, the increase in the number of symptoms reported over the season (0.90-1.45 symptoms) is less than 1 point and likely not clinically meaningful. This study, of course, does not address the potential effects of lifetime impact dose, though the authors did find that the amount of college football exposure (based on number of years played) was associated with poorer balance and increased symptom reporting. Miller et al[40] similarly assessed 76 collegiate football players at preseason, mid-season, and postseason on neuropsychological measures and found no significant declines throughout the season on the Standardized Assessment of Concussion or ImPACT, despite likely repeated subconcussive impacts. These researchers did not measure head impacts so the relation between magnitude and number of blows was not directly assessed.

Finally, McAllister et al[41] followed 214 collegiate football and hockey players from pre- to postseason and compared them to 45 noncontact sport athletes assessed at the same intervals. None of the athletes sustained a diagnosed concussion during the study period. They used a more extensive battery than prior studies, including the ImPACT battery (including self-reported symptom severity) as well as 7 other neuropsychological measures. They found no significant between-athlete group differences by time on a variety of cognitive measures, despite the contact athletes sustaining an average of 469 head impacts over the season with a maximum acceleration of 132 *g*s. They concluded that the number of head impacts does not have a widespread short-term detrimental effect. However, these authors did additional analyses to examine if there was a subset of individuals who did worse than expected at postseason, based on the noncontact athletes' preseason performance and test-retest interval. After conducting multiple comparisons, they found that a statistically significantly higher percentage (24% vs 3.6%) of athletes in the contact sport group performed below predicted performance on the learning trials of the California Verbal Learning Test, Second Edition,[42] a verbal memory measure. However, performance on the California Verbal Learning Test was not significantly correlated with head impact exposure, though performances on 2 measures of speeded attention/psychomotor function were correlated with exposure (ie, Trails B and ImPACT reaction time). None of the other neuropsychological measures revealed any differences between groups.

Overall, studies employing cognitive/neuropsychological assessment within a single season have failed to demonstrate any strong and consistent relations between number and severity of subconcussive blows and cognitive changes. There are just a few studies at this point, and they are not directly comparable. Gysland et al[35] found an effect for total symptom severity and contradictory balance findings but included athletes who sustained concussions during the study season, while McAllister et al[41] had 1 cognitive finding and did not include people with concussions during the study season (though it is unclear if this difference may have been due to differences in prior concussion history). As was suggested by the animal literature, human studies to date suggest than any effect of subconcussive blows is likely to be small and possibly nonreplicable, perhaps evident in a subset of individuals on select measures, and perhaps even beneficial in some cases. Further longer-term prospective study is needed to determine whether there is a cumulative dose effect. The difficulty, of course, is finding athletes with no history of concussion who nonetheless endure repeated subconcussive blows.

Neuroimaging data

Recent studies that have included a neuroimaging component have demonstrated a potential cumulative effect of subconcussive blows, at least in a subset of individuals. Specifically, in a prospective study of 21 high-school football players who were assessed pre- and postseason (with some assessed in-season as well), 4 of the 8 nonconcussed players with subconcussive blows who were reassessed in-season had significant reductions on verbal and/or visual memory scores on the ImPACT battery and significantly decreased fMRI activation levels in the dorsolateral prefrontal cortex and cerebellum[43] during working memory tasks. Furthermore, these players' cognitive and fMRI data were at least as impaired as 3 players who sustained a concussion during the season, although different areas of activation were noted via fMRI. All ImPACT scores were near ceiling during each assessment for all athletes. The 4 nonconcussed players with positive findings had a greater total number of collision events throughout the season than the concussed and nonconcussed (with no decline in cognitive performance) groups. Furthermore, while the total number of blows differentiated the groups, the median peak linear acceleration did not.[44] The number of impacts experienced in the week immediately preceding in-season reassessment was significantly correlated with changes in fMRI activation in all players. Interestingly, the group with no concussion and no changes on cognitive measures had more collisions per player in each location on the helmet than the concussed group, suggesting that concussion was due to a particularly damaging single or smaller number of blows rather than a lowered concussion threshold from a cumulative subconcussive effect. These authors did not report pre-post season comparisons by group, nor did they report whether total season head impact variables correlated with cognitive performance variables. It is puzzling that ubiquitous "near ceiling" performance on cognitive testing nonetheless resulted in group differences. Thus, while there may be a subset of individuals who show acute clinical changes related to recent subconcussive impacts, the longer-term (or even season-specific) and functional implications remain unclear.

Recent work has also employed diffusion tensor imaging to investigate subconcussive blows. In a prospective cohort of 9 football/ice hockey high school athletes and 6 controls (some with minor orthopedic injuries, some without), changes in white matter, as detected using diffusion tensor imaging within 24 hours of injury, were most apparent in the 1 concussed athlete, followed by the nonconcussed athletes (with repetitive impacts), followed by the controls.[45] Increases in symptom reporting over the study period correlated with the proportion of white matter voxels showing some kind of significant change (whether increased or decreased) in fractional anisotropy (FA) and mean diffusivity (MD), both markers of white matter integrity. The number of self-reported head hits was also significantly correlated with the proportion of white matter voxels showing some kind of significant change. However, the changes in FA and MD were in both directions (both increased and decreased), making interpretation difficult. However, the "subconcussive group" did not report more symptoms than the control group and did not perform any differently than controls on the ImPACT cognitive assessment battery (and in fact outperformed them on visual motor speed and reaction time). Thus, the subconcussive-relevant findings seem restricted to white matter changes of unclear structural or functional meaning. Unfortunately, this study relied on retrospective self-reported diaries for its assessment of subconcussive blows, further limiting interpretability. History of prior concussions in either group is also unknown in this study. Again, given that this study followed the athletes for only 1 season, the longer-term implications are unknown.

A larger study[46] of the effects of exposure to repetitive head impacts over a single season on diffusivity measures compared 80 collegiate varsity football and ice hockey players who wore instrumented helmets and who did not sustain a concussion during the index season to 79 noncontact sport athletes (with no history of reported concussion). A significant ($P = .011$) athlete group difference was found for MD in the corpus callosum. Postseason FA differed ($P = .001$) in the amygdala (0.238 vs 0.233). Measures of head impact exposure correlated with white matter diffusivity measures in several brain regions including corpus callosum, amygdala, cerebellar white matter, hippocampus, and thalamus. In a group of both contact and noncontact athletes with poorer performance on a measure of verbal learning and memory, the magnitude of change in corpus callosum MD at postseason was greater than in those who did not perform poorly. The authors interpreted their findings as consistent with relations among head impact exposure, white matter diffusion measures, and cognition over the course of a single season, even in the absence of diagnosed concussion.

CONCLUSION

Although there is not a straightforward relation between various kinematic parameters and the probability of sustaining a diagnosed concussion, there is recent interest in the potential cumulative impact of repeated "subconcussive" blows. Evidence from human studies of the neurological/neuropsychological impact of subconcussive blows is currently quite limited. Findings to date suggest that any effect of subconcussive blows is likely to be small and perhaps only evident in a subset of individuals on select measures. Even in this subset, it is unclear if differences are clinically meaningful and/or enduring. The neuroimaging studies reviewed showed some functional and structural changes in a subset of individuals that seem to correlate with head impact exposure, but findings are not consistent across studies. Neuroimaging findings associated with subconcussive blows have shown FA and MD changes occur in both directions (both increased and decreased) and are poorly correlated with functional and symptom changes. Thus, as with the purely cognitive studies, the neuroimaging studies reveal that while there may be a subset of individuals who show acute clinical changes related to recent subconcussive impacts, the longer-term (or even season-specific) and functional implications remain unclear.

Given the small number of studies, and the disparate methodologies used, it is difficult to draw any firm conclusions at this point. Important methodological issues when studying the cumulative impact of subconcussive blows include controlling for prior concussion history (or preferably not including people with any history of concussion), using consistent protocols across studies, and comparing results within certain age ranges, given the possible differences in recovery by age.[47] If effects are small and potentially dependent on moderating factors, inconsistent findings are likely. Measuring changes in cognition and symptoms has been challenging in the larger concussion literature. As discussed earlier, given the recent focus in the media on concussion and the concern about CTE (despite the lack of a clear and universally accepted operational CTE definition), it is important to proceed cautiously. Large prospective studies are needed to elucidate both the immediate and long-term effects of cumulative subconcussive head impacts. Certainly, research on the elderly suggests that positive neuroimaging findings and even brain pathology do not always correspond well with functional abnormalities. In 2 large epidemiological clinical-pathologic aging studies, brain pathology accounted for only 40% of the variance in cognitive decline.[48] To be sure, any potential acute and possibly transient effects due to the cumulative effect of subconcussive blows, seen both within the brain and through behavior, may or may not have longer-term impact, depending on what is likely to be a large number of variables. Caution is warranted in interpreting and publicizing "brain injury" secondary to subconcussive blows, due to the huge implications for society as a whole. Prospective, controlled epidemiological study is needed to clarify the incidence of subconcussive blows and their short- and long-term effects.

REFERENCES

1. Bailes JE, Petraglia AL, Omalu BI, Nauman E, Talavage T. Role of subconcussion in repetitive mild traumatic brain injury. *J Neurosurg.* 2013;119(5):1235–1245.
2. American Congress of Rehabilitation Medicine. Report of the Mild Traumatic Brain Injury Committee of the Head Injury Interdisciplinary Special Interest Group. *J Head Trauma Rehabil.* 1993;8:86–87.
3. McCrory P, Meeuwisse WH, Aubry M, et al. Consensus statement on concussion in sport: the 4th International Conference on Concussion in Sport held in Zurich. *Br J Sports Med.* 2013;47(5):250–258.
4. Department of Veterans Affairs and Department of Defense. VA/DOD clinical practice guideline for management of concussion/mild traumatic brain injury. http://www.healthquality.va.gov/mtbi/concussion_mtbi_full_1_0.pdf. April 2009; Accessed November 2012.
5. Belanger HG, Vanderploeg RD, Curtiss G, Warden D. Recent neuroimaging techniques in mild traumatic brain injury: A critical review. *J Neuropsychiatry Clin Neurosci.* 2007;19(1):5–20.
6. Shenton ME, Hamoda HM, Schneiderman JS, et al. A review of magnetic resonance imaging and diffusion tensor imaging findings in mild traumatic brain injury. *Brain Imaging Behav.* 2012;6(2):137–192.
7. Carroll LJ, Cassidy JD, Holm L, Kraus J, Coronado VG. Methodological issues and research recommendations for mild traumatic brain injury: the WHO Collaborating Centre Task Force on Mild Traumatic Brain Injury. *J Rehabil Med.* 2004;43 (suppl):113–125.
8. Scholten J, Cernich A, Hurley RA, Helmick K. Department of Veterans Affairs's traumatic brain injury screening and evaluation program: promoting individualized interdisciplinary care for symptomatic veterans. *J Head Trauma Rehabil.* 2013;28(3):219–222.
9. McKee AC, Cantu RC, Nowinski CJ, et al. Chronic traumatic encephalopathy in athletes: progressive tauopathy after repetitive head injury. *J Neuropathol Exp Neurol.* 2009;68(7):709–735.
10. Bazarian JJ, Cernak I, Noble-Haeusslein L, Potolicchio S, Temkin N. Long-term neurologic outcomes after traumatic brain injury. *J Head Trauma Rehabil.* 2009;24(6):439–451.
11. Mez J, Stern RA, McKee AC. Chronic traumatic encephalopathy: where are we and where are we going? *Curr Neurol Neurosci Rep.* 2013;13(12):407.
12. McKee AC, Stern RA, Nowinski CJ, et al. The spectrum of disease in chronic traumatic encephalopathy. *Brain.* 2013;136(pt 1):43–64.
13. Omalu B, Bailes J, Hamilton RL, et al. Emerging histomorphologic phenotypes of chronic traumatic encephalopathy in American athletes. *Neurosurgery.* 2011;69(1):173–183; discussion 183.
14. Wortzel HS, Shura RD, Brenner LA. Chronic traumatic encephalopathy and suicide: a systematic review. *Biomed Res Int.* 2013;2013:424280.
15. Iverson GL. Chronic traumatic encephalopathy and risk of suicide in former athletes. *Br J Sports Med.* 2014;48(2):162–165.
16. Shultz SR, MacFabe DF, Foley KA, Taylor R, Cain DP. Subconcussive brain injury in the Long-Evans rat induces acute neuroinflammation in the absence of behavioral impairments. *Behav Brain Res.* 2012;229(1):145–152.
17. Slemmer JE, Weber JT. The extent of damage following repeated injury to cultured hippocampal cells is dependent on the severity of insult and inter-injury interval. *Neurobiol Dis.* 2005;18(3):421–431.
18. Allen GV, Gerami D, Esser MJ. Conditioning effects of repetitive mild neurotrauma on motor function in an animal model of focal brain injury. *Neuroscience.* 2000;99(1):93–105.
19. Arundine M, Chopra GK, Wrong A, et al. Enhanced vulnerability to NMDA toxicity in sublethal traumatic neuronal injury in vitro. *J Neurotrauma.* 2003;20(12):1377–1395.
20. Belanger HG, Vanderploeg RD. The neuropsychological impact of sports-related concussion: a meta-analysis. *J Int Neuropsychol Soc.* 2005;11(4):345–357.
21. Bergsneider M, Hovda DA, Lee SM, et al. Dissociation of cerebral glucose metabolism and level of consciousness during the period of metabolic depression following human traumatic brain injury. *J Neurotrauma.* 2000;17(5):389–401.
22. Giza CC, Hovda DA. The neurometabolic cascade of concussion. *J Athl Train.* 2001;36(3):228–235.
23. Broglio SP, Schnebel B, Sosnoff JJ, et al. Biomechanical properties of concussions in high school football. *Med Sci Sports Exerc.* 2010;42(11):2064–2071.
24. Schnebel B, Gwin JT, Anderson S, Gatlin R. In vivo study of head impacts in football: a comparison of National Collegiate Athletic Association Division I versus high school impacts. *Neurosurgery.* 2007;60(3):490–495; discussion 495–496.
25. Pellman EJ, Viano DC, Tucker AM, Casson IR. Concussion in professional football: location and direction of helmet impacts—Part 2. *Neurosurgery.* 2003;53(6):1328–1340; discussion 1340–1321.
26. Guskiewicz KM, Mihalik JP. Biomechanics of sport concussion: quest for the elusive injury threshold. *Exerc Sport Sci Rev.* 2011;39(1):4–11.
27. Greenwald RM, Gwin JT, Chu JJ, Crisco JJ. Head impact severity measures for evaluating mild traumatic brain injury risk exposure. *Neurosurgery.* 2008;62(4):789–798; discussion 798.
28. Eckner JT, Sabin M, Kutcher JS, Broglio SP. No evidence for a cumulative impact effect on concussion injury threshold. *J Neurotrauma.* 2011;28(10):2079–2090.
29. Guskiewicz KM, Mihalik JP, Shankar V, et al. Measurement of head impacts in collegiate football players: relationship between head impact biomechanics and acute clinical outcome after concussion. *Neurosurgery.* 2007;61(6):1244–1252; discussion 1252–1243.
30. Beckwith JG, Greenwald RM, Chu JJ, et al. Timing of concussion diagnosis is related to head impact exposure prior to injury. *Med Sci Sports Exerc.* 2013;45(4):747–754.
31. Beckwith JG, Greenwald RM, Chu JJ, et al. Head impact exposure sustained by football players on days of diagnosed concussion. *Med Sci Sports Exerc.* 2013;45(4):737–746.
32. Beckwith JG, Greenwald RM, Chu JJ, et al. Biomechanical basis for mild traumatic brain injury: head impact exposure sustained by football players on days of diagnosed concussion. *Med Sci Sports Exerc.* 2013;45(4):737–746.
33. Broglio SP, Eckner JT, Surma T, Kutcher JS. Postconcussion cognitive declines and symptomatology are not related to concussion biomechanics in high school football players. *J Neurotrauma.* 2011;28(10):2061–2068.
34. Lovell MR, Collins MW. Neuropsychological assessment of the college football player. *J Head Trauma Rehabil.* 1998;13(2):9–26.
35. Gysland SM, Mihalik JP, Register-Mihalik JK, Trulock SC, Shields EW, Guskiewicz KM. The relationship between subconcussive impacts and concussion history on clinical measures of neurologic function in collegiate football players. *Ann Biomed Eng.* 2012;40(1):14–22.
36. Bleiberg J, Kane RL, Reeves DL, Garmoe WS, Halpern E. Factor analysis of computerized and traditional tests used in mild brain injury research. *Clin Neuropsychol.* 2000;14(3):287–294.
37. McCrea M, Kelly JP, Kluge J, Ackley B, Randolph C. Standardized assessment of concussion in football players. *Neurology.* 1997;48:586–588.

38. Nashner LM, Peters JF. Dynamic posturography in the diagnosis and management of dizziness and balance disorders. *Neurol Clin.* 1990;8(2):331–349.
39. Riemann BL, Guskiewicz KM, Shileds EW. Relationship between clinical and forceplate measures of postural stability. *J Sport Rehabil.* 1999;8:71–82.
40. Miller JR, Adamson GJ, Pink MM, Sweet JC. Comparison of preseason, midseason, and postseason neurocognitive scores in uninjured collegiate football players. *Am J Sports Med.* 2007;35(8):1284–1288.
41. McAllister TW, Flashman LA, Maerlender A, et al. Cognitive effects of one season of head impacts in a cohort of collegiate contact sport athletes. *Neurology.* 2012;78(22):1777–1784.
42. Delis DC, Kaplan E, Kramer JH, Ober BA. *California Verbal Learning Test.* 2nd ed. San Antonio, TX: Psychological Corporation; 2000.
43. Talavage TM, Nauman EA, Breedlove EL, et al. Functionally-detected cognitive impairment in high school football players without clinically-diagnosed concussion. *J Neurotrauma.* 2014; 31(4):327–338.
44. Breedlove EL, Robinson M, Talavage TM, et al. Biomechanical correlates of symptomatic and asymptomatic neurophysiological impairment in high school football. *J Biomech.* 2012;45(7):1265–1272.
45. Bazarian JJ, Zhu T, Blyth B, Borrino A, Zhong J. Subject-specific changes in brain white matter on diffusion tensor imaging after sports-related concussion. *Magn Reson Imaging.* 2012;30(2):171–180.
46. McAllister TW, Ford JC, Flashman LA, et al. Effect of head impacts on diffusivity measures in a cohort of collegiate contact sport athletes. *Neurology.* 2014;82(1):63–69.
47. Dougan BK, Horswill MS, Geffen GM. Athletes' age, sex, and years of education moderate the acute neuropsychological impact of sports-related concussion: a meta-analysis. *J Int Neuropsychol Soc.* 2013;20:1–17.
48. Boyle PA, Yu L, Wilson RS, Schneider JA, Bennett DA. Relation of neuropathology with cognitive decline among older persons without dementia. *Front Aging Neurosci.* 2013; 5:50.