Cutoff Scores in Neurocognitive Testing and Symptom Clusters That Predict Protracted Recovery From Concussions in High School Athletes

Brian C. Lau, BS*
Michael W. Collins, PhD‡
Mark R. Lovell, PhD‡

*University of Pittsburgh School of Medicine, Pittsburgh, Pennsylvania; ‡Department of Orthopedic Surgery, University of Pittsburgh Medical Center Sports Concussion Program, Pittsburgh, Pennsylvania

Correspondence:
Brian C. Lau, MD,
UPMC Sports Medicine,
3200 South Water St.,
Pittsburgh, PA 15203.
E-mail: blau10@gmail.com

Received, November 13, 2010.
Accepted, June 15, 2011.
Published Online, August 9, 2011.

BACKGROUND: Many studies address diagnosing concussions, but few look at predicting prognosis. A previous discriminant function analysis showed that symptom clusters derived from the Post-Concussion Symptom Scale and Immediate Post-concussion Assessment and Cognitive Testing composite scores used together improved predictions of protracted recovery after a sports-related concussion.

OBJECTIVE: To determine cutoff scores in neurocognitive and Post-Concussion Symptom Scale symptom cluster scores when classifying protracted recovery in concussed athletes.

METHODS: 108 male high school football athletes completed a computer-based neurocognitive test battery (Immediate Postconcussion Assessment and Cognitive Testing) within a median of 2 days after injury. Patients completed graded exertional protocols requiring athletes to be symptom free at rest and during increasing levels of activity and had recovery of neurocognitive scores before return to play. After return to play, athletes were classified as protracted recovery (>14 days, n = 58) or short-recovery (≤14 days, n = 50). Receiver-operating characteristic curves analyzed each of the neurocognitive (verbal, visual, processing speed, and reaction time) and symptom cluster (migraine, cognitive, sleep, and neuropsychiatric) scores.

RESULTS: Cutoffs for migraine cluster, cognitive cluster, visual memory, and processing speed were statistically significant. Cutoffs at 75%, 80%, and 85% sensitivity to predict protracted recovery for the migraine symptom cluster were 15 or greater, 18, 20; cognitive symptom cluster 18 or greater, 19, 22; visual memory 48 or less, 46, 44.5; and processing speed 24.5 or less, 23.46, 22.5, respectively. Eighty-percent sensitivity indicates that the corresponding cutoff correctly identify 80% of concussed athletes requiring protracted recovery.

CONCLUSION: Specific cutoffs may help to set numerical thresholds for clinicians to predict which concussed athletes will have a protracted recovery.

KEY WORDS: Concussion, Cutoffs, ImPACT, Prognosis, Receiver-operating characteristic curve, Return to play, Symptoms

Neurosurgery 70:371–379, 2012 DOI: 10.1227/NEU.0b013e31823150f0 www.neurosurgery-online.com

High-profile coverage of former professional football players reporting premature signs of memory loss and dementia has increased awareness of sports-related concussions. Emergency departments have also seen a tripling of visits for concussions in the 14- to 19-year-old age range between 1997 and 2007, and there is currently an estimated 3.2 million concussions per year in the United States.[1,2] In response, the sports community has increased scrutiny on the proper management of concussions.

ABBREVIATIONS: DFA, discriminant function analysis; **ImPACT,** Immediate Postconcussion Assessment and Cognitive Testing; **PCSS,** Post-Concussion Symptom Scale; **PPV,** positive predictive value; **ROC,** receiver-operating characteristic

A concussion is a unique type of injury because its effects are not as tangible to untrained observers as other sports-related injuries such as a brace for a torn anterior cruciate ligament. This may lead to pressure for concussed athletes to return to normal activities. Concussions, however, require the same attention to controlled rehabilitation, if not more, than any other sports-related injury. In the student athlete, a concussed brain may not be equipped to handle the concentration and memory requirements of school at the same level as before the injury.[3,4] An expectation of "snapping back" to preinjury cognitive levels may result in increasing frustration and worsening symptoms that lengthen recovery.[3,4] A recent clinical study by the Children's National Medical Center found that more than 80% of student athletes who experienced concussions reported a worsening of symptoms over the first 4 weeks after attempting to return to the classroom.[5,6] In addition, hasty return to play, particularly in younger athletes, has also been associated with delayed recovery time and potentially catastrophic consequences such as diffuse cerebral swelling or second-impact syndrome.[7,8] In light of these effects, all efforts should be made to prevent premature return to school or play when appropriate.

Studies have taken the next step from diagnosing sports-concussions to predicting the length of recovery from such injuries. Improved ability to predict prognosis would be extremely clinically useful. Such information could, in turn, be used to help in academic planning and predicting how long an individual may need to be removed from play or work. Iverson[9] revealed that athletes who took the computerized Immediate Postconcussion Assessment and Cognitive Testing (ImPACT) test battery and displayed reliable change deficits relative to baseline in 3 of 4 composite scores (verbal memory, visual memory, processing speed, reaction time) were 94.6% more likely to exhibit complex recovery, defined at the time by international consensus as greater than 10 days to recovery.[10]

Another study also used the simple and complex concussion distinction and applied it to the Post-Concussion Symptom Scale (PCSS).[11,12] The study used a previous factor analysis to categorize the PCSS into 4 distinct symptom clusters: migraine, cognitive, sleep, and neuropsychiatric and found that the athletes with complex (>10 days) concussions presented differently from those with simple concussions (≤10 days).[12,13] Multivariate analysis of variance and univariate analysis among groups showed that the migraine symptom cluster (P = .0019), sleep symptom cluster (P = .0133), and cognitive symptom cluster (P = .0238) were significantly more prominent in athletes requiring more than 10 days to recover.[12]

Subsequently, an international conference composed of leaders in the sports concussion field made a consensus statement not to endorse the 10-day distinction between simple and complex concussions and returned to a more individualized definition.[14] A recent study defined protracted recovery as greater than 14 days and quantified the ability of neurocognitive testing and symptom clusters to predict prognosis from sports-related concussion.[15] Fourteen days was chosen as protracted recovery because of findings in large population outcome studies that demonstrated that typical recovery from sports-related concussions was within 10 to 14 days of injury.[16-20]

There remains some question as to whether subacute neurocognitive testing used during follow-up had value added to following symptoms alone.[21] Discriminant function analyses (DFAs), using the 14-day protracted recovery distinction, sought to identify how accurately subacute ImPACT neurocognitive testing and symptom clusters used together could improve the accuracy to predict protracted recovery. It found that when used together, symptom clusters and computerized test scores as a whole had a 65.22% sensitivity and 80.36% specificity.[15] This compared with subacute neurocognitive testing (a combination of verbal memory, visual memory, reaction time, and processing speed) and symptom clusters (a combination of migraine cluster, cognitive cluster, sleep cluster, and neuropsychiatric cluster) used in isolation from each other had less sensitivity (53.20% and 46.94%, respectively) and specificity (75.44% and 77.20%, respectively) to identify athletes with protracted recovery. Overall, clinicians could have a 73.17% positive predictive value (PPV) in determining protracted recovery when evaluating with neurocognitive and PCSS scores used together within 2 to 3 days post-injury.[15] Canonical coefficient analysis of the combined DFA identified that the main contributors discriminating between short and protracted recovery were migraine symptom cluster, reaction time, visual memory, and verbal memory.[15]

The objective of this study was to directly build on the previous study that showed that a combination of symptoms and computerized neurocognitive data used together had a high PPV in classifying athletes requiring prolonged recovery from a sports-related concussion by identifying clinically objective cutoff scores of specific symptom cluster and neurocognitive test scores. Therefore, this study uses receiver-operating characteristic (ROC) curve analysis to determine optimal cutoff scores in ImPACT neurocognitive composite and PCSS symptom cluster scores when determining protracted recovery (>14 days) in concussed athletes.

METHODS

Participants

A total of 177 Western Pennsylvania male high school football athletes sustained a concussion between the 2002 and 2006 seasons and completed the ImPACT battery within a median of 2 days after injury. All athletes at participating schools were referred to the university's concussion clinic regardless of type or severity of symptoms. Patients were primarily seen for clinical purposes and continued to be followed until returned to play. All athletes with any concussion-related deficits were required to obtain clearance to return to play from the same concussion specialist who followed their recovery before returning to the playing field. The study only included athletes who sustained concussions during preseason and regular season football activity, a total of 11 games. Of 177 athletes who sustained a concussion, 108 met inclusion criteria and were eventually cleared to play. Athletes were excluded if their concussions were sustained during postseason playoffs, they did not return to football, or they were lost to follow-up before clearance to return to play. In addition, data collection ended at the conclusion of the 2006 season. Unfortunately, individual reasons for athletes not cleared to return (eg, graduation) to play were not recorded.

Diagnosis and Management of Concussions

Athletic trainers and/or physicians present on the sidelines after a direct or indirect collision diagnosed concussions. The basis for diagnosis was on-field presentation of 1 or more of the following signs/symptoms: any noticeable change in mental status, loss of consciousness, disorientation, amnesia, or any self-reported symptoms such as headache, dizziness, visual changes, and balance difficulties.

After international return-to-play standards, athletes were managed with the graded exertional activity protocol that required athletes to be symptom free at rest and during subsequently increasing level of activity. Specific details of the protocol may be found in international concussion consensus and previous studies.[9,10,12,14,15,22]

Four additional criteria were used to clear athletes for return to play.

1) Total PCSS scores of concussed athletes must have been less than 7. The symptoms listed in the PCSS are not specific to concussion, and even noninjured athletes may report these at baseline. A previous study by Iverson et al[23] found that 76% of noninjured participants had a total score of 6 or less on the PCSS, thus, the decision to use 7 as a threshold.
2) The athletes must not have had more than one ImPACT neurocognitive composite score statistically worse than their baseline performance or age-normative data. In this study, 77% of the total sample, 82.75% of short recovery and 72% of protracted recovery athletes had baseline scores. When baseline data were not available, athletes' scores were compared with age-normative data. A previous study revealed that only 3.6% of noninjured athletes had 2 composite scores below baseline. In other words, 96.4% of noninjured athletes had 1 or fewer composite scores below baseline or age-normative data.[23] The values needed for a score to be significant at 80% confidence interval were 9 points for verbal memory, 14 points for visual memory, 0.06 seconds for reaction time, and 3 points for processing speed.[23]
3) Athletes must have all 4 ImPACT neurocognitive composite scores above the 10th percentile for age-normative data. The only exception was if the patient's baseline before injury was below the 10th percentile. A previous study used this percentile in the management decisions of patients with a concussion.[10] Additionally, scores below the 10th percentile, according to ImPACT normative data, are considered unusually low. The rationale is to ensure that athletes return to age-normative cognitive functioning before return to play while preventing the criteria from inappropriately holding athletes who possibly have far below normal preinjury/baseline testing scores from returning to play.
4) Regardless of their PCSS score, no athlete was returned to play if he was experiencing headache pain or other symptoms such as dizziness or balance dysfunction that was clearly linked to the diagnosed concussion.

All physical activities were monitored by their athletic trainers or team physicians, and athletes were not returned to practice or game situations until they were evaluated by clinical staff and met all mentioned criteria and international return-to-play criteria. After clinically returned to play, athletes were grouped into either protracted recovery (>14 days, n = 58) or short recovery (≤14 days, n = 50).

Outcome Measures

The computerized neuropsychological testing modules of ImPACT consist of 6 separate tests to yield 4 composite scores: verbal memory, visual memory, processing speed, and reaction time. The individual tests and the construction of composite scores were as described previously.[10,12,15,23-25] In addition, ImPACT includes a 22-item symptom inventory, the PCSS. The concussion symptom inventory includes a 7-point Likert-type scale in which 0 is complete absence of symptoms and 6 is most severe symptoms.[11] A previous factor analysis grouped the PCSS into 4 symptom clusters: migraine, cognitive, sleep, and neuropsychiatric (Table 1).[13,15] The entire test requires a computer mouse and monitor and takes approximately 20 minutes to complete.

ImPACT has been previously shown to have a high degree of sensitivity (81.9%) and specificity (89.4%) in detecting neurocognitive effects of sports concussion and has also been show to be reliable and valid in the measurement of sports concussion.[19,24-27] After referral to the university's sports concussion program, athletes continued to be evaluated using the ImPACT test battery throughout their recovery. Both preinjury baselines and all postconcussion evaluations were collected using the same version of the ImPACT test battery.

Statistical Analysis

SPSS version 18.0 (SPSS, Inc, Chicago, Illinois) software was used in this study. To examine possible differences between the short and protracted groups for factors such as preconcussion history of migraine, headache, presence/absence of attention-deficit hyperactivity disorder, presence/absence of learning disability, and presence/absence of previous concussions, we used χ^2 tests. A *P* value <.05 was considered significant.

Statistical analysis was performed using ROC curves for each of the 4 neurocognitive (verbal, visual, processing speed, and reaction time) and

TABLE 1. Post-Concussion Symptom Scale: 4 Clusters[a]

Migraine	Cognitive	Sleep	Neuropsychiatric
Headaches	Fatigue	Difficulty sleeping	More emotional
Visual problems	Fogginess	Sleeping less than usual	Sadness
Dizziness	Drowsiness	Sleeping more than usual	Nervousness
Noise/light sensitivity	Difficulty concentrating/remembering		Irritability
Nausea/vomiting	Cognitive slowing		
Balance problems			
Numbness/tingling			

[a]Symptom Clusters first described by Pardini et al.[13]

4 symptom cluster (migraine, cognitive, sleep, and neuropsychiatric) scores. The sensitivity, specificity, and cutoff values of the 8 variables were evaluated by ROC curve analysis.

Generally, sensitivity measures the proportion of actual positives that are correctly identified as positive by test parameters. Specificity measures the proportion of actual negatives that are correctly identified by test parameters. In this analysis, sensitivity refers to the ability of the given cutoff score to correctly identify an athlete who has a protracted recovery when he actually has a protracted recovery. In contrast, specificity in this study is how reliable a given cutoff accurately demonstrates that an athlete does not have a protracted recovery and will become asymptomatic in 14 days, ie, short recovery (not protracted recovery = short recovery).

ROC curve analyses allow an investigator to determine possible numerical cutoff values to determine a positive test result (protracted recovery) or negative test result (short recovery).[28,29] An ROC curve is composed of false-positive rate (1-specificity) along the *x* axis and true-positive rate (sensitivity) along the *y* axis. The best possible cutoff, 100% sensitivity and 100% specificity, is represented by a point in the upper left corner (0,1), whereas a completely random cutoff would be represented on a point along the diagonal line from left bottom to top right corners. As such, points above and below the diagonal represent good and poor classification results, respectively. Similarly, as the area under the ROC curve comes to 1, the sensitivity and specificity for the corresponding cutoff improves. To maintain this convention, in this study, 2 separate ROC curves were used because poorer performance is represented in neurocognitive testing differently in 2 subsets of variables. Increasing scores represent poorer performance in reaction time and the 4 separate symptom clusters. In contrast, lower scores represent poorer performance in verbal memory, visual memory, and processing speed. It is common in ROC curve analyses that as a result of ties between the positive actual state group and the negative actual state group, the ROC curve underestimates the diagnostic accuracy of variables. An 80% sensitivity indicates that the corresponding cutoff will correctly identify 80% of concussed athletes who will require protracted recovery.

RESULTS

Of the 108 high school athletes eventually cleared to return to play based on international clinical criteria, 58 (53.7%) were classified as short recovery ($\leq$14 days) and 50 (46.3%) were classified as protracted recovery ($>$14 days). The average times between injury and initial post-injury evaluation were 1.91 days for the short recovery group (range, 0-5) and 2.6 days (range, 0-12) for the protracted recovery group and were not significantly significant as determined by independent *t* test (F = 12.2, P = .06). Regardless of eventual classification into protracted or short recovery, the median time to first evaluation was identical for both groups (2 days). Athletes who were classified in the short recovery group returned to play in an average of 6.90 days, whereas the protracted recovery group took an average 33.04 days. There was no significant difference noted between short or protracted recovery regarding demographic variables such as age (F = 0.88, P = .35) or education (F = 3.71, P = .061).

A series of χ^2 tests evaluated the potential significance of factors such as preconcussion history of migraine, headache, presence/absence of attention-deficit disorder, presence/absence of a learning disability, and presence/absence of a previous concussion between short and protracted recovery groups. There was no statistical difference between group participants in preinjury history of migraine (χ^2 = 0.01, P = .94), headache (χ^2 = 0.04, P = .85), attention-deficit/hyperactivity disorder (χ^2 = 1.43, P = .85), learning disability (χ^2 = 0.15, P = .90), and at least 1 previous concussion (χ^2 = 0.10, P = .75).

To ensure that there were no differences between patients followed until recovery (n = 108) and those lost-to-follow-up (n = 69), a series of *t* tests and χ^2 tests were performed in these 2 groups. The *t* tests showed no significant differences in days to first evaluation (F = 5.61, P = .08), age (F = 0.34, P = .80), education (F = 0.085, P = .89), verbal memory (F = 0.30, P = .64), visual memory (F = 0.14, P = .24), processing speed (F = 0.14, P = .06), reaction time (F = 0.14, P = .80), migraine cluster (F = 0.35, P = .58), cognitive cluster (F = 1.4, P = .62), sleep cluster (F = 0.35, P = .28), or neuropsychiatric cluster (F = 0.37, P = .46). Chi-square tests in patients who were followed until recovery and those lost to follow-up also showed no statistically significant differences between patients followed until recovery and those lost to follow-up with a preinjury history of migraine (χ^2 = 1.22, P = .27), headache (χ^2 = 0.30, P = .582), attention-deficit/hyperactivity disorder (χ^2 = 0.08, P = .78), learning disability (χ^2 = 2.02, P = .155), and at least 1 previous concussion (χ^2 = 0.11, P = .74).

Full patient demographics are displayed in Table 2.

ROC curve analysis revealed that 4 of the 8t variables were significant: migraine (P = .01), cognitive (P = .04), visual (P = .01), and processing speed (P = .02) (Figures 1 and 2, and Table 3).

Possible cutoff values of all 8 potential predictors were determined at 80% sensitivity for detecting a protracted recovery. The rationale of 80% was chosen because the ability of ImPACT neurocognitive testing to detect the presence or lack of neurocognitive effects after a concussion has been documented at approximately the same sensitivity (81.9%).[24] This level of sensitivity has provided clinicians marked improvement in diagnosing concussions.[19,21,24,26,27,30] Likewise, 80% sensitivity in determining which athletes require protracted recovery may improve concussion management decisions. Cutoffs at 75% and 85% are also provided to offer clinicians the ability to balance sensitivity and specificity during the management of individual cases with their own personal experience and comfort. The cutoff value of each variable is listed in Table 4.

DISCUSSION/CONCLUSION

This study lends further support that specific neurocognitive and symptom cluster scores may differentiate between short and protracted recoveries. In this study, short and protracted groups had significantly different outcomes, a mean of 7 days and 33 days to recovery, respectively. Areas under the curve indicate that migraine symptom cluster, cognitive symptom cluster, ImPACT visual memory, and ImPACT processing speed

TABLE 2. Subject Demographics[a]

	Short Recovery (≤14 d, n = 58)	Protracted Recovery (>14 d, n = 50)	Did Not Recover or Lost to Follow-up (n = 69)
Days to recover, mean (SD)[b]	6.90 (3.30)	33.04 (47.22)	N/A
No. of days to first evaluation, mean (SD)	1.91 (1.2)	2.6 (2.5)	2.87 (2.69)
Median no. of days to first evaluation	2	2	2
Baseline testing, % (ratio)	82.75 (48/58)	72 (36/50)	76.81 (53/69)
Age, y, mean (SD)	16.12 (1.2)	15.9 (1.2)	15.94 (1.2)
Education, mean (SD)[c]	9.81 (0.85)	9.47 (1.14)	9.63 (0.99)
History of concussion, no.	11	14	20
History of headaches, no.	8	7	8
History of migraines, no.	6	5	4
History of ADHD, no.	2	2	2
History of learning disability, no.	1	1	4

[a]SD, standard deviation; N/A, not available; ADHD, attention-deficit/hyperactivity disorder.
[b]Indicates that there is a statistically significant difference between short and protracted recovery groups.
[c]An education level of 9 represents schooling up to ninth grade.

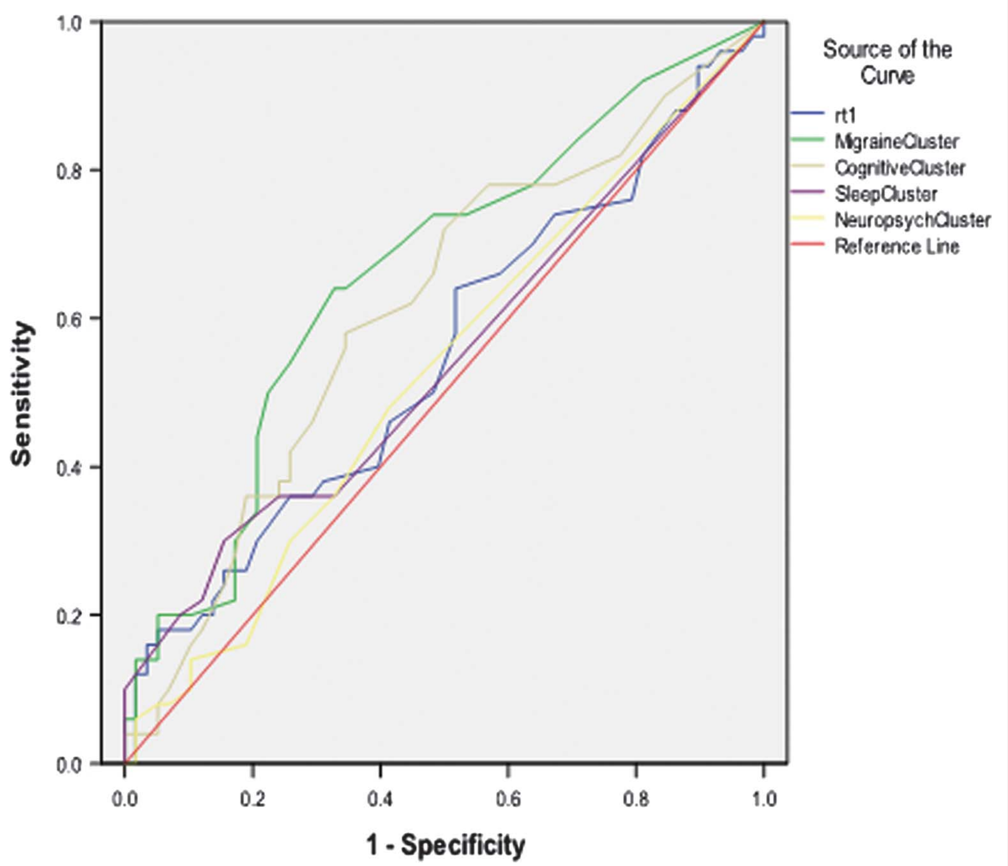

FIGURE 1. *Receiver-operating characteristic curve of 4 symptom clusters and reaction time: variables in which increasing value indicate worse performance. Rt1, Immediate Postconcussion Assessment and Cognitive Testing (ImPACT) reaction time composite score.*

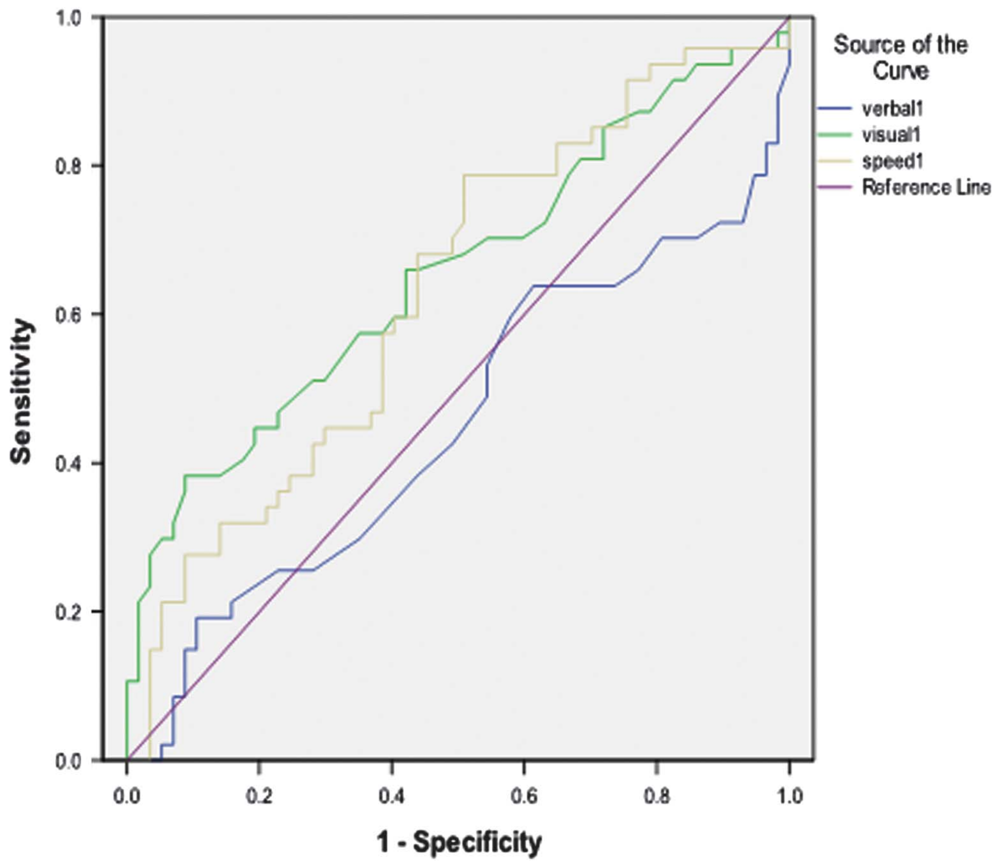

FIGURE 2. *Receiver-operating characteristic curve of Immediate Postconcussion Assessment and Cognitive Testing (ImPACT) verbal memory, visual memory, and processing speed: variables in which decreasing value indicates worse performance. Verbal1, ImPACT verbal memory composite score; Visual1, ImPACT visual memory composite score; Speed1, ImPACT processing speed composite score.*

TABLE 3. Area Under the ROC Curve and *P* Values for Symptom Clusters and Neurocognitive Scores[a]

Variable	Area Under Curve	*P* Value
Migraine symptom cluster[b]	0.66	.01
Cognitive symptom cluster[b]	0.61	.04
Sleep symptom cluster[b]	0.55	.41
Neuropsychiatric symptom cluster[b]	0.53	.61
Reaction time[b]	0.55	.37
Visual memory[c]	0.66	.01
Verbal memory[c]	0.45	.39
Processing speed[c]	0.63	.02

[a]ROC, receiver-operating characteristic.
[b]Variables in which increasing values indicate poorer performance.
[c]Variables in which decreasing values indicate poorer performance.

composite scores have cutoff scores with a statistical significance in discriminating short and protracted recoveries. Possible thresholds for these specific variables, defined from the ROC curve analysis, at 80% sensitivity for predicting protracted recovery are migraine symptom cluster total of 18 or greater (specificity = 6.9%, PPV = 42.6%), cognitive symptom cluster of 19 or greater (specificity = 15%, PPV = 44.8%), ImPACT visual of 46 or less (specificity = 1.8%, PPV = 41.3%), and ImPACT processing speed of 23.5 or less (specificity = 5.2%, PPV = 42.1%).

The ability to better predict the length of recovery, prognosis, from a sports-related concussion would greatly improve their management. During the 1980s and 1990s, more than 20 different concussion management guidelines were published with the intent of providing a directive for safe return to play; however, these were not age specific and often had no clinical evidence to support their use. As such, child and adolescent concussion evaluation is often

TABLE 4. Cutoff Values of Neurocognitive and Symptom Clusters With Respect to Sensitivity and Specificity[a]

	75% Sensitivity			80% Sensitivity			85% Sensitivity		
Parameter	Cutoff	Specificity, %	PPV, %	Cutoff	Specificity, %	PPV, %	Cutoff	Specificity, %	PPV, %
Verbal memory[b]	66.5	22.8	45.6	64.5	15.8	45.03	60.5	10.5	45.0
Visual memory[b]	48	3.5	40.1	46	1.8	41.3	44.5	1.8	42.7
Processing speed[b]	24.5	8.6	41.4	23.5	5.2	42.1	22.5	5.2	43.6
Reaction time	0.72	15.5	43.4	0.78	13.8	44.5	0.86	5.2	43.6
Migraine cluster	15.0	17.2	43.9	18.0	6.9	42.6	20.0	5.2	43.6
Cognitive cluster	18.0	18.0	44.1	19.0	15.0	44.8	22.0	6.9	44.0
Sleep cluster	3.0	15.0	43.2	4.5	8.6	43.0	6.0	1.7	42.7
Neuropsychiatric cluster	2.5	25.9	46.6	3.0	22.5	47.1	3.5	19.0	47.5

[a]PPV, positive predictive value.

[b]For these variables, a lower score represented worse performance. For the remaining variables, a higher score represented poorer performance.

Sensitivity is defined as the ability of the cutoff to accurately identify a protracted recovery (>14 days) in an athlete. Specificity is defined as the ability of the cutoff to accurately identify a short recovery (not protracted recovery) (≤14 days) in an athlete.

limited to self-reported symptoms by the patient and observation by parents and physicians. Therefore, decisions regarding which athletes should be provided academic accommodations, including time away from class and more time to complete assignments and tests, often depend on the clinician's experience and clinical acumen. These cutoffs, despite a low specificity, may serve as an objective-based method in determining which athletes should receive academic accommodations, as well as more cautious return to sport-related activity. The cutoffs can also allow sports medicine professionals to more accurately set expectations for patients, parents, teachers, teammates, and coaches regarding return to normal activities and thus minimize external pressures on student athletes to expedite recovery.

Given the complexity and potential consequences of inappropriately treating concussions in high school athletes, it behooves clinicians to be more cautious when managing these athletes. Therefore, as we continue to refine our understanding of concussions, we believe that although proposed cutoffs have less specificity and PPV than desirable, they are clinically useful. Moreover, the sensitivity, specificities, and PPVs are listed for each variable if used in isolation. However, variables should be used together. A previous DFA[15] highlighted that when using variables together (particularly migraine cluster, reaction time, visual memory, and verbal memory), the PPV may be improved to 73.17%.[15] As such, listed individual specificities and PPVs for individual cutoffs likely underestimate that actual values when cutoffs are used as intended, which is in concert with one another and not in isolation.

When compared with the 4 variables defined in the previous DFA,[15] only migraine symptom cluster and ImPACT visual memory cutoffs were found to be significant in this study's ROC curve analysis. However, the cutoffs provided in this current study of the 4 variables from the previous DFA may be valuable clinical thresholds in determining prognosis when used together and warrant further investigation.

Moreover, the cutoffs from this study are consistent with documented age-matched (16- to 18-year-old males) data published on the ImPACT Web site reference page that show that the listed thresholds are worse than the defined cutoffs for impaired results (verbal ≤68, visual ≤51, processing speed ≤26.4, and reaction time ≥0.74).[31] In other words, athletes meeting the proposed cutoffs for protracted recovery are worse than those merely meeting thresholds for impaired neurocognitive function after a concussion.

The finding that migraine and cognitive symptom clusters are significant contributors is consistent with previous studies. Headaches (member of the migraine cluster) and fogginess (member of the cognitive cluster) have also been found to be symptoms that commonly persist in patients after a concussion.[12,15,30,32] Neuropsychiatric and sleep symptom clusters did not have any cutoffs that were statistically significant as determined by ROC curve analysis. However, the authors caution ignoring symptoms in these clusters because they are rare, and the presence of any of these symptoms clinically, unless present at baseline, warrants more attention.

It is important to note that ImPACT reaction time and ImPACT verbal memory, which were noted as significant contributors in a previous discriminant function analysis, were not found to have statistically significant cutoffs on ROC curve analysis. A possible explanation for this is that the changes in reaction time are in 1/100th of a second, and the difference between short and protracted recoveries may be too minute and more patients are needed to differentiate a distinct cutoff point. These findings also highlight that these cutoffs are likely a starting point for determining clinically objective data to predict protracted recovery in sports concussions and need to be refined further with larger, more diverse sample sizes.

This study is not without limitations. Although baseline data were available in the majority of athletes in this study (77%), the cutoffs determined in this study were based solely on the initial scores at presentation (2-3 days post-injury) and not in relation to any baseline data. It was the aim of the authors of this study to propose cutoffs that will assist in the management of as many athletes as possible when seen post-injury, including those that do not have an organized sports concussion program that record baseline testing. It should be noted that baseline data and age-normative data were used indirectly as part of the criteria to determine return-to-play status. Moreover, given the individualized nature of the international concussion clinical protocol that was used in this study to manage concussed athletes, precise assessment intervals and specific numbers of assessments varied between athletes. This clinical pathway, conclusion of data collection after the 2006 season, and graduation of students resulted in a natural attrition and a number of athletes lost to follow-up. Athletes did, however, require clearance for return to play by the same group of concussion specialists, resulting in relatively consistent clinical referral and management of all concussed athletes. The retrospective classification of athletes into short or protracted recovery groups in this study creates the possibility that athletes classified as protracted recovery had recovered in less than 14 days post-injury but were not cleared until after this time. If athletes who had short recovery were incorrectly categorized as prolonged recovery, it would result in fewer between-group differences. As a result, the cutoffs may be forced further to the extreme (ie, higher for reaction time and symptom clusters; lower for verbal memory, visual memory, and processing speed). Last, our subject pool consisted completely of injured high school football players; therefore, the findings cannot be generalized to athletes in other sports, collegiate/professional athletes, or female athletes.

Specific cutoffs in migraine symptom cluster and the ImPACT verbal memory, visual memory, and processing speed may be able to better predict prognosis when used together. These cutoffs set the stage for future studies to validate their clinical effectiveness.

Disclosure

Drs Lovell and Collins are part owners of ImPACT Applications, the company that distributes the ImPACT program. As such, they have a financial interest in the company. Brian Lau is not an employee, owner, or shareholder in ImPACT Applications and has no financial interest in ImPACT or ImPACT Applications. Riddell Inc, a football helmet manufacturing company provided a grant to the University of Pittsburgh Medical Center, where Drs Collins and Lovell are faculty.

REFERENCES

1. Bakhos LL, Lackhart GR, Myers R, Linakis JG. Emergency department visits for concussion in young child athletes. *Pediatrics*. 2010;126(3):e550-e556.
2. Meehan WP, d'Hemecourt P, Comstock RD. High school concussion in the 2008-2009 academic year: mechanism, symptoms, and management. *Am J Sports Med*. 2010;38(12):2405-2409.
3. Gioia GA, Vaughan CG, Reesman J, et al. Characterizing post-concussion exertional effects in the child and adolescent [Abstract]. *J Int Neuropsychol Soc*. 2010;16(suppl 1):178.
4. Gioia GA, Gerst E, McGuire E, McGill C, Palacios M, Vaughan C. Standardized assessment of cognitive exertion effects in pediatric mild TBI: application of reliable change methodology [Abstract]. *J Int Neuropsychol Soc*. 2011;17(suppl 1):135.
5. Gerard Gioia. *Committee on Education and Labor: United States House of Representatives*. Washington, DC: The Impact of Concussions on High School Athletes; 2010.
6. Gerst EH, McGuire EL, Hunter SR, Vaughan CG, Gioia GA. Assessing cognitive and physical activities and their association with symptom exacerbation in children and adolescents with mTBI [Abstract]. *J Int Neuropsychol Soc*. 2011;17(suppl 1): 134-135.
7. Guskiewicz KM, McCrea M, Marshall SW, et al. Cumulative effects associated with recurrent concussion in collegiate football players: the NCAA Concussion Study. *JAMA*. 2003;290(19):2549-2555.
8. McCrory P. Does second impact syndrome exist? *Clin J Sport Med*. 2001;11(3): 144-149.
9. Aubry M, Cantu R, Dvorak J, et al. Summary and agreement statement of the First International Conference on Concussion in Sport, Vienna 2001. Recommendations for the improvement of safety and health of athletes who may suffer concussive injuries. *Br J Sports Med*. 2002;36(1):6-10.
10. Iverson G. Predicting slow recovery from sport-related concussion: the new simple-complex distinction. *Clin J Sport Med*. 2007;17(1):31-37.
11. Lovell MR, Iverson GL, Collins MW, et al. Measurement of symptoms following sports-related concussion: reliability and normative data for the post-concussion scale. *Appl Neuropsychol*. 2006;13(3):166-174.
12. Lau B, Lovell MR, Collins MW, Pardini J. Neurocognitive and symptom predictors of recovery in high school athletes. *Clin J Sports Med*. 2009;19(3):216-221.
13. Pardini J, Stump JE, Lovell MR, Collins MW, Moritiz K, Fu F. The post-concussion symptom scale (PCSS): a factor analysis. *Br J Sports Med*. 2004;38(5):661-662.
14. McCrory P, Meeuwisse W, Johnston K, et al. Consensus statement on concussion in sport—the Third International Conference on Concussion in Sport held in Zurich, November 2008. *Phys Sportsmed*. 2009;37(2):141-159.
15. Lau BC, Collins MW, Lovell MR. Sensitivity and specificity of subacute computerized neurocognitive testing and symptom evaluation in predicting outcomes after sports-related concussion. *Am J Sports Med*. 2011;39(6): 1209-1216.
16. Collins M, Lovell MR, Iverson GL, Ide T, Maroon J. Examining concussion rates and return to play in high school football players wearing newer helmet technology: a three-year prospective cohort study. *Neurosurgery*. 2006;58(2):275-286.
17. Erlanger D, Saliba E, Barth J, Almquist J, Webright W, Freeman J. Monitoring resolution of postconcussion symptoms in athletes: preliminary results of a web-based neuropsychological test protocol. *J Athl Train*. 2001;36(3):280-287.
18. Field M, Collins MW, Lovell MR, Maroon J. Does age play a role in recovery from sports-related concussion? A comparison of high school and collegiate athletes. *J Pediatr*. 2003;142(5):546-553.
19. Iverson GL, Brooks BL, Lovell MR, Collins MW, Lovell MR. Tracking neuropsychological recovery following concussion in sport. *Brain Inj*. 2006;20(3):245-252.
20. Makdissi M, Darby D, Maruff P, Ugoni A, Brukner P, McCrory PR. Natural history of concussion in sport: markers of severity and implications for management. *Am J Sports Med*. 2010;38(3):464-471.
21. Randolph C, McCrea M, Barr WB. Is neuropsychological testing useful in the management of sport-related concussion? *J Athl Train*. 2005;40(3):139-152.
22. McCrory P, Jonhson K, Meeuwise W, et al. Summary and agreement statement of the 2nd International Conference on Concussion in Sport, Prague 2004. *Clin J Sports Med*. 2005;15(2):49-55.
23. Iverson GL, Lovell MR, Collins MW. Interpreting change on ImPACT following sport concussion. *Clin Neuropsychol*. 2003;17(4):460-467.
24. Schatz P, Pardini JE, Lovell MR, Collins MW, Podell K. Sensitivity and specificity of the ImPACT Test Battery for concussion in athletes. *Arch Clin Neuropsychol*. 2006;21(1):91-99.
25. Iverson GL, Lovell MR, Collins MW. Validity of ImPACT for measuring processing speed following sports-related concussion. *J Clin Exp Neuropsychol*. 2005;27(6):683-689.
26. Van Kampen DA, Lovell MR, Pardini JE, Collins MW, Fu FH. The "value added" of neurocognitive testing after sports-related concussion. *Am J Sports Med*. 2006;34 (10):1630-1635.
27. Collins MW, Grindel SH, Lovell MR, et al. Relationship between concussion and neuropsychological performance in college football players. *JAMA*. 1999;282(10): 964-970.
28. Zweig MH, Campell G. Receiver-operating characteristic (ROC) plots: a fundamental evaluation tool in clinical medicine. *Clin Chem*. 1993;39(4):561-577.
29. Koch HJ, Hau P. ROC analysis as an additional method to characterize time to event data. *Pathol Oncol Res*. 2005;11(1):50-52.
30. Lovell MR, Collins MW, Iverson GL, et al. Recovery from mild concussion in high school athletes. *J Neurosurg*. 2003;98(2):296-301.

31. ImPACT. ImPACT-Testing & Computerized Neurocognitive Assessment Tools: Baseline Normative Table—Quick Reference 2003. Available at: http://impact-test.com/publications/baseline_data/qrtables. Accessed November 3, 2010.
32. Iverson GL, Gaetz M, Lovell MR, Collins MW. Relation between subjective fogginess and neuropsychological testing following concussion. *J Int Neuropsychol Soc.* 2004;10(6):904-906.

COMMENTS

This study investigates a clinically important issue of predicting protracted recovery from concussive injuries. Among athletes, in particular, the question of when one will be able to return to play is of paramount importance, and research thus far has indicated that it is relatively difficult to predict recovery time at the time of diagnosis or initial evaluation. The current study builds on existing research by evaluating whether there are cutoff scores of post-injury symptom clusters or neurocognitive performance that may be prognostic of prolonged recovery. Using ROC curve analysis, the researchers compared early postinjury symptom reports and testing performance of short (≤14 days) and long recovery groups. Several clusters were found to have cutoff scores that could predict group membership significantly better than chance. Although these cutoff scores were calculated to result in a reasonably high level of sensitivity (thus correctly identifying a large percentage of true positives), the accompanying specificity and PPVs were significantly lower. These results indicate that, as clinical experience has shown, it is difficult to predict recovery time. The cutoffs provided will yield a high number of false positives, such that athletes may be incorrectly told to expect a long recovery. However, the cutoffs are also likely to correctly identify patients who will experience longer recoveries, allowing clinicians to provide more realistic expectations. It should be noted that the current sample consisted of high school football players; so future research should examine these issues in female players and with broader age ranges. Although additional research is needed to improve early prediction of recovery time, the current study provides preliminary evidence that certain symptoms (migraines, cognitive effects) and low test scores (visual memory, processing speed) may be predictive of longer recovery in some athletes.

Maegan D. Sady
Rockville, Maryland

This is an interesting and potentially important study in that there are currently no cutoffs available to clinicians and team physicians to identify neurocognitive performance indicative of more severe concussions with prolonged recoveries. These findings are, thus, a first step in this regard. Although data are presented to help identify scores representing prolonged concussions, readers are cautioned that the sensitivity of these cutoffs occurs at the expense of specificity. In other words, cutoffs that will identify 80% of athletes with prolonged recoveries will only identify 1% to 22% of athletes with less severe concussions/shorter recoveries. The authors address the relatively low specificity as a potential precautionary benefit of not returning youth athletes to the classroom or field prematurely. However, based on these cutoffs, nearly all athletes will be identified as having more severe concussions with prolonged recoveries. Although false positives may be acceptable for those with a more conservative return-to-play approach, both false positives and false negatives may have a significant expense for the individual athlete. Although data-driven, cutoff-based, actuarial decision making may be part of future heuristics, the current findings can only serve as a first step toward developing more balanced cutoffs with respect to sensitivity and specificity. Finally, the authors note that the study used a relatively small retrospective sample, and results are only representative of select high school football players who met inclusion criteria, without longitudinal data tracking. As such, findings cannot be generalized to female athletes or athletes competing at higher levels (eg, collegiate, professional).

Philip Schatz
Philadelphia, Pennsylvania