Vision Testing in the Evaluation of Concussion

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ABSTRACT

Traumatic brain injury results from an acute impact to the head causing brain dysfunction. Concussion is a form of mild traumatic brain injury. There are significant short- and long-term sequelae of concussion, and early diagnosis and management are key to recovery. Visual system symptoms and signs are common following concussion and have been shown to be a useful feature of concussion testing. Neuro-ophthalmic findings include abnormalities in the pupillary light reflex, accommodation, convergence, extraocular motility, stereoacuity, as well as pursuit and saccades. Concussion generally occurs out of the medical setting, and access to a trained examiner or equipment to assist in diagnosis is limited. For this reason, much research is focused on developing a concussion test that is practical and reliable, and technology is likely to play an important role in this. Ultimately, no single test is a substitute for clinical judgment and multifaceted testing.

Keywords: Brain, injury, neurology, neuro-ophthalmology, technology, traumatic

TRAUMATIC BRAIN INJURY (TBI)

Traumatic brain injury (TBI) resulting from an acute impact to the head, causing brain dysfunction, is commonly described as mild, moderate, or severe. Mild TBI involves brief loss of consciousness (less than 30 minutes), brief posttraumatic amnesia (less than 24 hours), Glasgow Coma Scale (GCS) between 13 and 15, and normal brain imaging results. Moderate TBI is classified as loss of consciousness for 30 minutes to 24 hours, posttraumatic amnesia for 1–7 days, GCS 9–12, and abnormal brain imaging. Severe TBI is defined as loss of consciousness over 24 hours, posttraumatic amnesia over seven days, and abnormal brain imaging.

Concussion falls under the category of mild TBI, is a frequent topic of discussion in the media, and is the focus of much current research. Although the signs of moderate or severe TBI are often evident on initial examination, concussion can be easily missed. Patients who suffer an initial impact to the head are at risk for recurrent head trauma, as well as a variety of short- and long-term sequelae. This risk of having a second concussion before complete recovery from the initial concussion is referred to as second impact syndrome and may lead to cerebral edema that, in many cases, results in permanent disability or death. Repeated mild TBI has been associated with long-term cognitive impairment in the setting of neurodegenerative disease. It is, therefore, imperative to screen patients appropriately who present after a recent blow to the head. Early identification of concussion allows for appropriate limitation of activity in the post-concussion period, thereby improving the patient’s chances for recovery.

Sports-related concussion accounts for over three million emergency room visits annually in the United States, and it is known that concussion in this setting is often underreported. This number does not account for the unknown number of emergency department presentations of concussion that occurred in the non-sports setting, such as motor vehicle accidents, assaults, and other traumatic events. If one also considers initial presentations to primary care providers or other specialists, it is likely that this number is significantly higher.

VISUAL SYSTEM SYMPTOMS AND SIGNS IN CONCUSSION

Mild TBI can lead to physical, cognitive, and psychological symptoms. Here, we will focus on concussion symptoms and signs that are specific to the visual system. Visual symptoms commonly reported in concussion include blurring or loss of vision, double vision, photophobia, and difficulty with focusing.
reading, and tracking objects. Patients also commonly report headaches and symptoms suggestive of higher-order dysfunction such as impaired attention, concentration, and memory. The presence of such symptoms often leads to challenges for the patient at school or in the workplace, and referral for further management is warranted.

The evaluation of concussion has historically been highly variable. Although it would be ideal to have a medical specialist available to diagnose mild TBI, this is not always practical. Because of the importance of early detection of mild TBI and the high number of concussions in athletes, many sports organizations now utilize a variety of concussion tests. These tests are based on a variety of common features and findings in concussion, and current research has shown that examination of the visual system plays a key role in diagnosis, as vision is often impacted in trauma (Table 1).

**Symptoms**

Several studies have employed symptom checklists as either the sole indicator of concussion or as part of a series of tests. Athletes, for example, may be asked to complete the checklist in the pre-season so that their baseline is known. The new score after head impact is then compared to the baseline score. There are a variety of symptom questionnaires available, and most include questions about visual symptoms, psychological symptoms, cognitive impairment, as well as physical complaints such as headache, dizziness, sleep changes, and vomiting. The advantages of these are that they can be readily available in any setting and do not require a skilled assessor or specialized equipment.

Information on symptoms alone is limited in that it relies on the subject’s willingness and ability to report. Several studies have shown that athletes often deny or delay reporting symptoms in order to continue in play. Additionally, there may be reporting differences between male and female athletes, thereby raising the possibility of missing the diagnosis of concussion. It is unclear if females have a higher rate of symptom reporting or whether they are at increased risk of concussion. An additional limitation of symptom scales or checklists is that most were subjectively, rather than scientifically, developed and analyzed. Although checklists can be useful as part of the evaluation of a patient, it is important to also take note of impairments in executive function or other findings that the subject may be unaware of in the acute setting.

**Visual Acuity and Fields**

Difficulty seeing is a common complaint in concussion and is variously described. Visual acuity is generally preserved in mild TBI, but testing may be limited due to other complaints. Patients sometimes report photophobia, and this may represent impaired dark adaptation. Being disturbed by glare is also a frequent complaint, but more commonly studied and reported in patients with cataracts. Research is ongoing in regards to assessing glare acuity as a parameter in the decision-making process for cataract extraction. It remains unknown if measuring glare acuity would be useful in the assessment of mild TBI.

Vision loss is more commonly a feature of moderate or severe TBI, rather than concussion, and may occur if there is trauma to the optic nerve or chiasm. Confrontation testing can be performed easily in non-clinical settings, but may only detect large field cuts. In the clinical setting, automated perimetry can be performed to evaluate the visual field in more detail, depending on the patient’s reliability parameters. This technology may be available in the field in the future as a variety of portable visual field systems are in development, including one that utilizes virtual-reality goggles. Preliminary data suggest that this method may be comparable to Humphrey automated static perimetry, but further studies are needed to verify the reliability and reproducibility of this type of testing.

**Pupils**

The pupillary light reflex is traditionally assessed using a penlight, and the interpretation is observer dependent. In cases of severe TBI, the pupillary response may be obviously notable for slowed constriction and dilation, as well as anisocoria, however, pupil abnormalities in mild TBI are likely to be subtle and not always recognized. Infrared pupillometry, a portable device that objectively characterizes the pupil’s response to light stimulus, can be used to detect subtle changes. Research using this device shows that patients with concussion had a variety of changes, including slowed constriction and slowed dilation, but unchanged minimum and maximum pupil size when compared to baseline. Another study suggested that patients with mild TBI may have reduced baseline pupil diameter. Pupillometry

<table>
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<tr>
<th>Symptoms</th>
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<td>Difficulty reading</td>
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<td>Loss of vision</td>
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also revealed differences in measurements between controls and subjects who were evaluated 2–4 weeks after sustaining mild TBI; however, this study did not show differences between controls and subjects who were evaluated within one week of injury. Therefore, this technology may be more useful for monitoring rather than evaluation in the acute setting.\textsuperscript{27,28}

**Accommodation and Convergence**

Accommodation and convergence abnormalities are also commonly present after concussion and, like the changes in the papillary light reflex, may be difficult to detect on clinical examination. Convergence has been studied in the laboratory and peak convergence velocity—the amplitude of the convergence response at the initiation of vergence—has been measured using computer and video technology. Measurements in controls and adults with mild TBI showed that the peak convergence velocity was significantly reduced, as much as 50\%, in the mild TBI group. It has also been shown that peak convergence velocity increases after vision therapy in this patient population. Importantly, this measurement cannot be volitionally altered by the subject.\textsuperscript{29,30} Limited studies also showed that accommodative peak velocity was reduced in patients with mild TBI, and improved with vision therapy.\textsuperscript{31,32}

If a subject reports difficulty seeing in the distance after mild TBI, it is important to consider whether there is impaired accommodation.\textsuperscript{33} What is called *pseudomyopia* can be measured using a portable autorefractor; however, these devices are not widely available outside of the eye clinic. Alternatively, patients may report difficulty with reading, which suggests the possibility of convergence insufficiency. This can be measured with prisms by a trained examiner, but is not a practical for examination in the field. There are tablet-based orthoptics programs being used for the diagnosis and management of convergence insufficiency; however, the reliability of this technology is unknown. Accurate examination may also be difficulty if the patient’s mental status is altered as a result of head injury.\textsuperscript{34}

**Extraocular Motility**

Extraocular motility disturbances are common after TBI, and the severity varies.\textsuperscript{35} The presentation can range from latent strabismus that is not symptomatic to more significant misalignment with complaints of diplopia. Patients who report blurry vision may have a slight misalignment giving the appearance of blurred overlapping images rather than two discernible images, so careful history and examination are warranted. It is crucial to examine oculomotor nerve function as well as other cranial nerves. The presence of more than one cranial nerve abnormality may suggest the need for imaging to evaluate for structural abnormalities from trauma or another underlying etiology, such as an aneurysm or mass.\textsuperscript{36} Gross extraocular motor abnormalities can be assessed by a trained first responder; however, more subtle defects may be missed. Automated devices are available to assess ocular misalignment, but are not generally available outside the clinical setting.\textsuperscript{37,38}

**Stereoaucity**

Stereoaucity is dependent on alignment of the images from both eyes as well as visual processing in the brain. Extraocular motility abnormalities, as well as injury to the superior colliculus of the midbrain in more severe TBI, may lead to impaired stereopsis.\textsuperscript{39} This is a common finding in mild TBI, and testing can be easily performed in the clinic or the field; however, assessment does require a cooperative subject.\textsuperscript{40}

**Nystagmus**

Nystagmus is a repetitive and rhythmic involuntary movement of the eyes that may be horizontal, vertical, or torsional. Research has been conducted on nystagmus in a variety of medical conditions using video nystagmography, a technique that utilizes infrared goggles to monitor eye movements. This has documented the presence of vertical nystagmus in TBI, although additional studies to further characterize this area are warranted.\textsuperscript{41,42} Nystagmus in mild TBI may also be related to peripheral or central vertigo resulting from TBI. It can be challenging for even a trained examiner to classify nystagmus so, although this is an important feature of the clinical exam, it can go unnoticed and may not be a reliable component of testing in the field. Additionally, patients may have preexisting congenital or physiologic nystagmus that can be difficult for an untrained examiner to distinguish from pathologic nystagmus.

**Pursuit**

Smooth pursuit is a reflex tracking movement of the eyes that keeps the stimulus focused on the fovea. This requires awareness of not only where the stimulus is, but also the anticipated future location of a moving stimulus. Successful tracking may require both pursuit and saccades, governed by cerebellar and cortical input.\textsuperscript{43,44} Patients with concussion often describe difficulty with tracking objects, sometimes described as blurring or doubling, and studies have confirmed that patients with mild TBI have increased eye position errors when compared with controls. This has also
been correlated with impaired attention and memory.\textsuperscript{45,46} There are a variety of eye tracking devices, some of which are portable, used in research to detect such abnormalities. One study showed that there was an increase in horizontal disconjugate eye movements in patients with TBI relative to controls and that these improved as subjects recovered from injury.\textsuperscript{47} Gross abnormalities in pursuit can be detected in the field by a trained assessor, but subtle deficits may require more detailed neuro-ophthalmic examination.\textsuperscript{48,49}

**Saccades**

Saccades are rapid ballistic movements of the eyes that change the point of fixation and may be voluntary or involuntary. Saccades are described as ballistic because, once movement is initiated, the system cannot account for a change in position of the target. Therefore, if the target changes direction after initiation of the saccade, a subsequent saccade would be needed to maintain gaze on the target. The amplitude of these movements can be small, as in the case of reading, or larger when scanning scenery outdoors.

In patients with mild TBI, complaints of difficulty reading or being overwhelmed by visual stimulation can often be due to impaired saccadic function. Studies have shown that such patients generate hypometric saccades that undershoot fixation on the object of interest. They may also be less able to balance the generation of volitional saccades with inhibition of involuntary saccades.\textsuperscript{50-52} Patients who have difficulty reading often describe that they have a hard time moving from one line of text to the next line, lose their place, or skip words.\textsuperscript{53}

Saccades have been studied in concussion with the use of video-oculography, and abnormalities have been noted in a variety of tests, including antisaccades, memory-guided saccades, gap saccade test, and visually cued saccades. This suggests that impairment in attention, memory, and higher executive functions plays a role in saccadic disturbances.\textsuperscript{54-57} Abnormal saccadic function, like many visual complications of mTBI, does improve over time.\textsuperscript{58,59}

**Neurologic Dysfunction and Visual System Findings**

All of the features of the ophthalmic examination discussed previously require adequate functioning of the central nervous system. Concussion can cause impairment in executive function and this can often be evident during neuro-ophthalmic examination.

- Memory impairment can be associated with mild TBI and has been studied using both visual and auditory tests. Such evaluation is simple to do and can be performed with minimal training or the use of tablet memory games.\textsuperscript{60,61}
- Confusion and impaired orientation to time, place, and person occur after concussion. This can easily be assessed via direct questioning or be incorporated into a variety of other testing into a tablet program.\textsuperscript{62,63}
- Slowed reaction time is also indicative of neurologic dysfunction. Research using a tablet program to capture reaction time in a variety of visually oriented tasks showed that this is impaired in TBI.\textsuperscript{64} Reading difficulty can be the result of impairment in saccades, but is also attributable to higher-order deficits relating to slowed processing and fatigue after TBI.\textsuperscript{65}
- Difficulty with visuospatial attention is also a feature of concussion. Patients having difficulty shifting attention from a given object of focus to a new one. This suggests impairment in executive control of visual discrimination, as well as orientation and attention.\textsuperscript{66-69} Another consequence of disturbance to visuo-spatial function is Visual Midline Shift Syndrome. Here, the patient perceives that his/her environment is compressed on one side of the body and expanded on the other. This can lead to changes in the patient’s posture as well as balance. Visual evoked potentials may be abnormal in the presence of such symptoms; however, this testing is not readily available outside of clinical centers, and additional research is still needed to determine if this is a reliable marker in concussion.\textsuperscript{70-72}

**CURRENT FIELD TESTS IN CONCUSSION**

The use of vision testing in concussion is dependent on the skill of the examiner and the setting. In the clinical setting (medical office, emergency department, or hospital), it is possible to perform a more detailed physical examination and advanced testing, including imaging. The challenge lies in the initial screening or assessment of concussion in the sports setting or by EMS first responders, where the quality of the assessment may be limited by the examiner’s training, equipment availability, and time. The initial evaluation often proves to be the most crucial, in that detecting signs of mild TBI early on is the first step to referral to a medical provider for management. There are a variety of concussion screening tools available, some of which utilize tablets or other portable devices.

**Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT)**

Immediate Post-concussion Assessment and Cognitive Testing (ImPACT) is a computerized test composed of
demographic data, six neuropsychological tests, and the Post-Concussion Symptom Scale (PCSS).\textsuperscript{73,74} ImPACT has been shown to correlate with traditional neuropsychological testing and addresses verbal memory, visual memory, reaction time, visual motor processing speed, impulse control, and reported symptoms.\textsuperscript{75}

In one study, controls and athletes with concussion underwent ImPACT, and the results showed that the sensitivity in detecting concussion was 81.9%, with a specificity of 89.4%. This study is, however, limited in that it was retrospective, and there was a male predominance in the study group.\textsuperscript{76} The PCSS can be regarded as a subjective assessment in that it relies on an athlete’s honesty in reporting symptoms. One study suggested that intentional underperformance can be detected in the PCSS and, therefore, accounted for in return to play decisions.\textsuperscript{77} The reliability of such computerized neuropsychological testing is thought to be variable, so this should be used in conjunction with more thorough assessment of the subject.\textsuperscript{78,79} Another study showed continued abnormalities post-concussion after the ImPACT score returned to baseline.\textsuperscript{80} ImPACT is also thought to have limited utility in the evaluation of pediatric concussion patients in an emergency department.\textsuperscript{81} Current research also shows that neuropsychological testing may be less sensitive in detecting concussion than tests of the visual system.

**Sports Concussion Assessment Tool (SCAT3)**

The Sports Concussion Assessment Tool, Third Edition (SCAT3), was developed by experts at the 2012 International Consensus meeting on Concussion in Sport and is frequently used as a field test during sporting events. The test is designed to be administered in 15–20 minutes by a trained medical professional. Return to play is not recommended if a subject sustains loss of consciousness, has signs of incoordination or confusion, memory loss, or facial injury with other impairment.\textsuperscript{82,83}

- The test begins with a Sideline Assessment to assess whether the subject should be urgently transported to the hospital for reasons such as a Glasgow Coma score under 15, declining mental status, suspected spine injury, or any other signs of deterioration. After assessing the subject’s level of consciousness with the Glasgow Coma Scale, the examiner moves on to the Maddocks Questions to check orientation. Relevant history, including prior concussions and cognitive/psychiatric comorbidities, is also obtained.
- The subject is then asked about the presence of 22 concussion symptoms, followed by the Standard Assessment of Concussion (SAC) to assess cognition. The SAC consists of questions regarding orientation as well as evaluation of memory through immediate and delayed recall, and digit span and months backward testing for concentration. In isolation, it is not a reliable detector of concussion, but it has been shown to detect some concussions that would otherwise be missed.\textsuperscript{84}
- A neck examination is performed as well as balance testing via the Modified Balance Error Scoring System (BESS), where the patient’s gait and posture are assessed. One downfall of the BESS is that there is intra- and inter-examiner variability in scoring. The SCAT3 also incorporates a timed tandem walking test that has been shown to be more reliable in detecting impairment.\textsuperscript{85,86} Research is also ongoing on the use of a Wii board to assess balance, and results are promising so far in the reliable detection of balance problems in subject with concussion.\textsuperscript{87}

Impairment in any section of the SCAT3 may be consistent with concussion, and in some cases the SCAT3 may be normal in the presence of concussion. It is important to compare the subject’s performance after injury to their baseline SCAT3, and ultimately, clinical judgment is the key factor in detecting concussion. Additionally, this test does not include an assessment of vision, and visual system dysfunction may, in some cases, be the only noticeable feature of concussion.\textsuperscript{88,89}

**The King-Devick Test**

The King-Devick Test (K-D Test) is a tablet-based evaluation of saccades where the subject is required to read a series of numbers on cards that become increasingly more challenging due to variable spacing between the numbers. This test assesses the visual system (saccades), as well as higher functions such as attention and language.\textsuperscript{90,91}

Advantages of this test are that it can be administered by non-medical professionals, is tablet-based and portable, takes only two minutes to administer, and can be used in young pediatric subjects who may struggle with more complex testing. A subject’s score, the total time it takes to read three number cards, is compared with their baseline prior to head injury. If reading is slowed or errors are made, this raises the concern for concussion and should be considered in making the decision to remove the athlete from play. An increase in total reading time of 5–7 seconds has been found in subjects with concussion.\textsuperscript{92,94} It is thought that neuropsychological testing is better suited for decisions relating to return to play. When the K-D Test is added to the SAC and BESS, a significantly higher proportion of concussions are detected when compared to only using the SAC and BESS. This was also true when the K-D Test was added to the SAC and timed tandem
al. It has also been shown that K-D Test scores correlate to visual motor processing time, visual memory, and reaction time in ImPACT.97,98

**Technology in the Assessment of Concussion**

In addition to portable devices such as pupillometry, eye movement tracking devices, and the Wii board, there are many other devices under development. Tablets are readily available and portable, and much research focuses on the development of tablet-based programs to detect concussion via the visual system. Some applications incorporate established concussion tests, such as the Concussion Assessment and Response™: Sport Version (CARE-Sport Version).99

It is important to note that not all tablet and smartphone applications advertised for use in concussion have been validated, and such programs should not be a substitute for clinical evaluation.100 In addition to the previously discussed tablet applications, the Pro-point and Anti-point test is a novel visual test based on eye movements. The subject begins with a finger on a white dot in the center of the screen and, 480 ms later, one of the surrounding boxes turns white. For the Pro-point portion of the test, the subject is asked to move the finger from the circle in the center to the box that turned white. This maneuver is thought to be similar to prosaccade movements. During Anti-point assessment, the subject was told to move a finger from the circle to the box opposite the white box, and this is thought to correlate with antisaccade movements. This test has been studied in soccer players as well as emergency department patients where scores were compared to the SAC and K-D Test. Preliminary results suggest that this could prove to be a useful tool in concussion assessment.101,102

The Head Impact Telemetry System is a modified football helmet fitted with sensors that provide detailed data on head impacts during play. The magnitude of impact has been variably correlated with concussion, but is not a direct indicator of the presence of concussion. Thus, it is a useful research tool, but limited in practice.103

Another interesting example is the Display Enhanced Testing for Concussion and mTBI System (DETECT™). This device consists of a portable computer and headgear that provides audio-visual immersion. The subject undergoes a variety of tests to assess cognitive function. This device has been shown to allow for detailed neuropsychological testing in a controlled, quiet environment, regardless of the subject’s location.104 This technology could potentially be combined with portable video-oculography to expand testing parameters.

**CONCLUSIONS**

The visual system is commonly impacted in mild TBI, and appropriate assessment can assist in the early detection of concussion. This is of utmost importance considering the potential long- and short-term sequelae of concussion. Assessment of the subject is dependent on the location—field versus medical setting—as well as by the skill set of the examiner. It is important to detect concussion at the time and site of occurrence, often during sporting events. In other settings, first responders are unlikely to be trained in detailed examination techniques. If symptoms and signs are missed, the subject may not be appropriately referred for further management and is at risk for sustaining a second concussion that may complicate recovery. Therefore, much research has focused on developing tools to assess concussion in the field.

In addition to the development of improved testing, studies have shown variability in the knowledge and management decisions of coaches. This indicates the need for increased education.105 One study demonstrated that increasing public awareness and establishing a multidisciplinary concussion program led to a substantial increase in the number of athletes who presented for medical care.106 Another aspect of concussion detection is the importance of obtaining a baseline neuropsychological assessment in those who are at high risk of sustaining head trauma, such as athletes or police officers. Baseline evaluation is already performed on military personnel prior to deployment and is thought to minimize misdiagnosis.107 This may further assist in identifying the features of individuals who are at risk of delayed or complicated recovery.108

Although there are a variety of portable tools under development to assist the non-medically trained examiner, the availability of such devices in the field is limited. Tablet-based tools are currently the most readily available and user-friendly method. Another advantage of tablet-based approaches is that monitoring can be standardized and continued in a variety of settings, such as from home or a rehabilitation facility. Studies have demonstrated utility in combining tests of the visual system with motor assessment and neuropsychological evaluation. No single test has been shown to reliably detect all concussions and, therefore, it is important to use clinical judgment as well as multifaceted testing.109,110

**DECLARATION OF INTEREST**

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of this article.
REFERENCES


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