JOURNAL OF NEUROTRAUMA 30:653–656 (April 15, 2013)

DOI: 10.1089/neu.2012.2585

Electroencephalography and Quantitative Electroencephalography in Mild Traumatic Brain Injury

Zulfi Haneef,[1,2] Harvey S. Levin,[3] James D. Frost, Jr,[1] and Eli M. Mizrahi[1]

Abstract

Mild traumatic brain injury (mTBI) causes brain injury resulting in electrophysiologic abnormalities visible in electroencephalography (EEG) recordings. Quantitative EEG (qEEG) makes use of quantitative techniques to analyze EEG characteristics such as frequency, amplitude, coherence, power, phase, and symmetry over time independently or in combination. QEEG has been evaluated for its use in making a diagnosis of mTBI and assessing prognosis, including the likelihood of progressing to the postconcussive syndrome (PCS) phase. We review the EEG and qEEG changes of mTBI described in the literature. An attempt is made to separate the findings seen during the acute, subacute, and chronic phases after mTBI. Brief mention is also made of the neurobiological correlates of qEEG using neuroimaging techniques or in histopathology. Although the literature indicates the promise of qEEG in making a diagnosis and indicating prognosis of mTBI, further study is needed to corroborate and refine these methods.

Key words: EEG; mild traumatic brain injury; postconcussive syndrome; quantitative EEG; TBI

Introduction

Quantitative electroencephalography (qEEG) has been claimed to be helpful in the diagnosis and measurement of mild traumatic brain injury (mTBI) and the postconcussion syndrome (PCS). PCS refers to a constellation of somatic and psychological symptoms after mild head injury.[1] The *Diagnostic and Statistical Manual of Mental Disorders-IV* for PCS includes (A) history of TBI causing ''significant cerebral concussion''; (B) cognitive impairment in attention or memory; (C) at least three of eight symptoms (fatigue, sleep disturbance, headache, dizziness, irritability, affective disturbance, personality change, apathy) appearing shortly after injury and persisting for at least 3 months; (D) symptoms beginning after injury or representing a significant worsening of pre-existing symptoms; (E) interference with social and/or occupational functioning; and (F) exclusion of dementia from head trauma and other disorders that better account for the symptoms. The diagnosis is made if the patient satisfies criteria C (symptoms), D (symptom threshold), and E (clinical significance) and if at least one of the patient's neuropsychological test scores suggested impairment.[2]

EEG changes in mTBI

EEG may be more sensitive than the clinical neurological examination in detecting brain injury. After mTBI, most patients (86%) with an abnormal neurological examination had an abnormal EEG. On the contrary, only 23% of abnormal EEGs were accompanied by an abnormal neurological examination.[3] EEG changes are not uniformly seen across all persons, and some of them have a clinically normal EEG as early as 15 minutes after concussion.[4] This is likely because of the difference in the severity of head injury and its likelihood of causing brain trauma.

Post-traumatic amnesia lasting more than 8 hours was invariably associated with an abnormal EEG.[5] EEG abnormalities are also more commonly seen in patients with durations of unconsciousness lasting more than 2 minutes (56%) than in patients with briefer periods of unconsciousness (17%).[6]

EEG recordings generate a large quantity of data that can be analyzed differently by aggregating the data and performing quantitative analysis of various components such as frequency and amplitude characteristics. This technique, called qEEG analysis, has been claimed to be of use in the diagnosis of mTBI and the PCS. It should be noted, however, that intermittent activity such as paroxysmal electrophysiologic changes are more likely to be noted in routine EEG than in qEEG, which is better for determining more persistent background activity.[7] As such, it would be useful to review the EEG based on conventional visual analysis in mTBI as a prelude to discussing the qEEG findings.

To facilitate review, the EEG and qEEG changes after mTBI were organized into the acute (hours to weeks after mTBI), subacute (weeks to months), and chronic (>6 months) phases after mTBI.

[1]Department of Neurology, Baylor College of Medicine, Houston, Texas.
[2]Department of Neurology, Michael E. Debakey VA Medical Center, Houston, Texas.
[3]Department of Physical Medicine and Rehabilitation, Baylor College of Medicine, Houston, Texas.

Acute EEG changes after mTBI (first few hours–weeks)

Animal studies suggest that immediately after mTBI, there is epileptiform activity described as high amplitude sharp waves or high frequency discharges, followed by diffuse suppression of cortical activity usually lasting 1–2 min, and subsequently followed by diffuse slowing of the EEG, which returns to the normal baseline over 10 min to 1 h.[8–10] A case report of a patient undergoing ambulatory EEG recording during a motor vehicle accident and 2–3 minutes of post-traumatic amnesia revealed diffuse theta and delta slowing for 15–20 min immediately after the mTBI.[11] About half of 31 patients with minor head injury tested within 24 hours had evidence of EEG changes.[12] In the hours after mTBI, there is attenuation of the posterior alpha accompanied by generalized and/or focal slowing, in particular theta waves over the temporal regions.[13] The low voltage of the EEG has been suggested to be related to patient anxiety.[14]

Subacute EEG changes in mTBI (weeks to months)

An interesting finding that has been reported during the weeks to months after mTBI is a 1–2 Hz increase in the frequency of the posterior alpha rhythm, which has been posited to be a return to the original baseline from the post-traumatic slowing.[3,14] The majority of the acute EEG abnormalities described above resolve by 3 months, and 90% resolve by 1 year following the head trauma.[14]

Chronic EEG changes in mTBI (more than 6 months)

As noted above, diffuse EEG slowing can persist up to a year after mTBI.[14] In a group of 30 patients with persistent (>1 year) psychiatric, somatic, or cognitive complaints developing within the first few weeks of mTBI, magnetoencephalography (MEG) revealed epileptiform abnormalities in 16% and slow-wave abnormalities in 63%. A lack of sensitivity of MEG to radially oriented electrical dipoles may have caused underdetection of electrophysiologic abnormalities.[15]

qEEG changes after mTBI

Quantitative EEG refers to software-assisted interpretation of EEG recordings that can be used to demonstrate quantitative trends in EEG not visualized by routine EEG measurements. Among the various qEEG techniques described below, spectral analysis and coherence are of particular interest in mTBI. (1) ''Spectral analysis'' is used to demonstrate the frequency composition of EEG over a given period. (2) ''Coherence measurements'' correlate the EEG frequency between two channels to assess how similar or ''coherent'' the underlying brain activity is, which has been proposed to be a measure of neural network connectivity. (3) ''Phase'' refers to the temporal lead or lag of waveforms between two brain regions.

A discussion of qEEG changes in mTBI should be prefaced by noting some of the controversies surrounding the use of this technique. Some of the criticisms regarding the use of qEEG in mTBI include: (1) predisposition to be contaminated by artifacts such as drowsiness, eye movements, muscle activity, medications, and technical issues. In particular, the trend of qEEG interpretation by personnel not formally trained in EEG could lead to misinterpretation of these artifactual signals as abnormal leading to misdiagnosis; (2) likelihood of normal variation of EEG between persons, or even over time within the same person to be marked as abnormal by qEEG panels; (3) lack of a sufficiently large normative database for proper comparisons of the test population; (4) lack of confirmatory studies by outside groups for the field's many exploratory published studies; and (5) lack of openness of proprietary paradigms to scientific scrutiny by academic researchers.[14]

Acute qEEG changes in mTBI (first few hours–weeks)

After mTBI, qEEG has most commonly shown immediate reduction in mean alpha frequency[7,16] with increased theta,[1,17] increased delta,[16] or increased theta:alpha ratio.[18,19] QEEG during and immediately after a motor vehicle accident with mTBI showed an increase in the delta power over posterior head regions that persisted for 15–20 min, and subtle brief (1–3 min) episodes of reduced alpha:delta ratio with slight reduction in beta power over anterior head regions. An increase in alpha power noted was thought to be because of increased episodes of eye closure.[11] At 3–10 days after mTBI (average 6.2 days), qEEG shows an increase in the power of slow alpha (8–10 cps), and a reduction of fast alpha (10.5–13.5 cps), with a mean reduction of alpha frequencies, and a reduction of fast beta (20–35 cps) compared with normal controls. No consistent effects were seen in the theta band.[7]

The so-called ''Belfast studies'' examined EEG spectra from the temporal and parietal regions within 24 h and at 6 weeks follow-up, in addition to brainstem auditory evoked potentials (BAEP) in a total of 73 patients. Diffuse slowing was a universal finding in these patients.[1,20] In this group of patients, post-traumatic amnesia did not correlate with EEG, but with BAEP changes suggesting that amnesia was more likely to be because of brainstem, rather than cortical, dysfunction. In addition, the cortical changes were mostly found to be transient, while the BAEP changes persisted at 6 weeks follow-up.[1]

Subacute qEEG changes in mTBI (weeks to months)

Reduced alpha and increased delta frequency after mTBI noted above[16] can persist for weeks to months. In the Belfast studies,[1,20] most patients had subsidence of diffuse EEG slowing by 6 weeks of injury, although the left temporal regions showed more persistent slowing. This left temporal slowing was also associated with chronicity of PCS symptoms at 6–12 month follow-up.[1]

Chronic qEEG changes in mTBI (more than 6 months)

In a study of PCS (International Classification of Diseases-10 criteria), a higher power in the delta band (1.5–5 Hz) and a lower power in the alpha band (8.5–12 Hz) were seen compared with matched controls. Of the 17 patients included, EEG was performed after 6 months of injury in 11, at 1 month in four, and at less than 1 month in two patients.[21] The investigators also found that both the qEEG and blood–brain barrier (BBB) abnormalities could last for years in persistent PCS, or be reversible in transient PCS.

Time-independent qEEG changes in mTBI

''Discriminant functions'' in qEEG refers to a combination of qEEG characteristics such as coherence, phase, and power, which are appropriately weighted and summed to discriminate between two or more groups being classified.[22] In one of the seminal mTBI studies of qEEG discriminant functions, Thatcher and associates established discriminant criteria in 608 patients that included a composite of three measures to differentiate mTBI from normal controls.[23] These included: (1) increased frontal and temporal coherence and decreased phase, (2) increased anteroposterior amplitude difference, and (3) reduced posterior power. The criteria were accurate by 80.0%, 89.2%, 92.3%, and 77.8% when the EEG

was repeated at varying mean post-injury intervals of 17.2, 26.5, 43.3, and 223.6 days, and could thus represent a time-independent measure of identifying mTBI.

The discriminant developed, however, has been largely based on characteristics of alpha power and amplitude (12 of 20 items). Because alpha in EEG is known to be affected by conditions such as drowsiness or sedative medications, the basis of this discriminant has been questioned, especially given that there was no effect of sleep or medications on the discriminant function.[14,23] Further, the technique has not been independently replicated using this discriminant by other groups since its publication in 1989.

In a group of combat veterans with post-traumatic stress disorder, the discriminant scores described by Thatcher were found to reliably identify blast-positive (88%) and blast-negative (75%) victims.[24] Interestingly, however, although the discriminant scores could differentiate between a history of self-recollected blast injury, it could not reliably detect those with a history of other TBI or mTBI. This study also suffered from small sample sizes and was self-described as ''exploratory.'' Co-morbid attention deficit disorder and a recall bias of previous head injury could have impacted the study results.[24] Outcome or disability was not correlated to coherence measurements.

In a later study by Thatcher and colleagues, discriminant criteria were identified that could classify between mild and severe TBI with an accuracy of 96.4% (sensitivity 95.5%, specificity 97.4%) in EEGs performed between 15 days and 4 years after injury.[25] The stability of the findings over time was demonstrated by a lack of change when the test was repeated at 6–12 months after the initial baseline EEG. These criteria could also retrospectively predict injury-related Glasgow Coma Scale score, duration of post-traumatic coma, and post-TBI performance on neuropsychological tests. The discriminant criteria used in this study differed from the earlier criteria developed in 1989 quoted above.

Validity of qEEG in mTBI

There has been intense, and even impassioned, debate in the literature about the validity of qEEG in mTBI.[14,26–30] These discussions have focused particularly on the ability of qEEG to differentiate mTBI from normal persons and patients with associated neuropsychiatric conditions, many of which may cause qEEG changes themselves. Some of the other concerns raised include questions about the subjects and data analytic methods. Issues have been raised regarding the validity of results and potential financial conflicts of interest for the qEEG diagnostic discriminant literature in mTBI.[14] As Arciniegas notes, qEEG may be supportive of the diagnosis of mTBI in a fashion analogous to the finding of interictal epileptiform discharges being supportive of the diagnosis of epilepsy.[30] At this time, qEEG findings cannot definitively rule in or rule out mTBI. This underscores the need for further urgent research on qEEG in mTBI.

qEEG correlation to the neurobiology of mTBI

There have been attempts to correlate the qEEG findings to neuropathological findings of mTBI, which are important in understanding the underlying pathophysiology and developing hypotheses for future work.

The localized frontal EEG coherence and phase abnormalities have been hypothesized to be related to the localized contusions and axonal injury to frontal regions and the posterior cortical diminished alpha activity with the ''contra-coup'' damage to posterior regions.[23]

In the study of PCS noted earlier, the generators of increased theta/reduced alpha suggested by low-resolution electromagnetic tomography were found to be closely related to the areas of abnormal BBB determined by Tc-99 single-photon emission computed tomography in 75% of patients suggesting focal, rather than diffuse, cortical dysfunction in conjunction with BBB disruption as the reason for the qEEG rhythm abnormalities.[21]

A significant correlation between histopathologic evidence of diffuse axonal injury and interhemispheric coherence or temporo-occipital alpha band was noted in patients with post-traumatic coma.[31] Although this study was performed in patients with more severe head injury, the findings suggest mechanisms that could be applied in mTBI.

Lengthened gray and white matter T2 relaxation times (T2RT) in MRI were found to negatively correlate with decreased coherence between short interelectrode distances (eg, adjacent electrode at 7 cm), and increased coherence between long interelectrode distance (eg, distant electrode at 28 cm) in mTBI. Lengthened T2RT was also associated with reduced cognitive function.[32] In a separate analysis, the same authors also reported correlation of white matter T2RT with increased delta amplitude and inverse correlation of gray matter T2RT with alpha and beta amplitude. Increased delta and reduced beta and alpha amplitudes were also associated with diminished cognitive function.[33]

Sleep EEG changes in mTBI

Power spectral analysis of EEG from frontotemporal and temporal electrodes after minor head injury in eight adolescent patients revealed increased delta, theta and alpha-1 within 72 hours of mTBI. During the 6 weeks post-injury, theta in the rapid eye movement (REM) sleep cycle 1 decreased significantly.[34] Over a 12-week period, decreases in mean log power of theta and alpha-1 in cycle 1 and decreases in delta, theta, and alpha-1 in cycle 2 from frontotemporal leads were seen. In addition, decreases in delta and theta during cycle 2 in temporal leads and intrusion of theta during the first REM cycle within 6 weeks followed by decrease within 6 weeks were also noticed.[34] A more recent study, however, failed to find differences in REM or NREM sleep in a group of 10 athletes with sport-related concussion compared with 11 non-concussed athletes in spite of the concussed group showing significantly more delta and less alpha activity in wakefulness in power spectral analysis of EEG.[16]

Conclusion

Much work has been done in describing the EEG and qEEG changes of mTBI. EEG findings prominent at different stages after mTBI are somewhat different. Discriminant analysis using a battery of different correlates has been proposed to diagnose mTBI independent of the time after injury, but remains controversial and unconfirmed. Further independent research and corroboration of these findings is needed. Although several findings have been reported in the acute, subacute and chronic phases of mTBI, a reliable test or battery of tests that is suited best for different post-injury phases has not been described. Further research in these areas could help in better diagnosis of mTBI, thus improving the identification for treatment, prognostic, or research purposes. EEG/qEEG findings in mTBI have been hypothesized to be related to the known pathophysiology of mTBI, and in some cases have also been corroborated with other investigations such as neuroimaging or histopathology. Further similar work would help improve our

understanding of the underlying pathophysiology in mTBI and of the associated neurophysiological correlates.

Acknowledgments

This research is supported by the Department of Defense (Contract # W81XWH-08-2-0149; Grant # PT74693P22); The Mission Connect Translational MTBI Translational Research Consortium: Neurophysiology Core (Eli M. Mizrahi, PI) and Neuropsychology Core (Harvey S. Levin, PI).

Author Disclosure Statement

No competing financial interests exist.

References

1. McClelland, R.J., Fenton, G.W., and Rutherford, W. (1994). The postconcussional syndrome revisited. J. R. Soc. Med. 87, 508–510.
2. American Psychiatric Association: Task Force on DSM-IV. (2000). *Diagnostic and Statistical Manual of Mental Disorders: DSM-IV-TR*. American Psychiatric Publishing, Inc.: Arlington, VA.
3. Koufen, H., and Dichgans, J. (1978). [Frequency and course of post-traumatic EEG-abnormalities and their correlations with clinical symptoms: a systematic follow up study in 344 adults.] (Ger) Fortschr. Neurol. Psychiatr. Grenzgeb. 46, 165–177.
4. Dow, R.S., Ulett, G., and Raaf, J. (1944). Electroencephalographic studies immediately following head injury. Am. J. Psychiatry 101, 174–183.
5. Scherzer, E. (1966). Das flache EEG als bioelektrischer Ausdruck der Erwartungsspannung (psychogene Alphareduktion). Psychiatr. Neurol. (Basel) 152, 207–212.
6. Geets, W., and Louette, N. (1985). [Early EEG in 300 cerebral concussions.] (Fre) Rev. Electroencephalogr. Neurophysiol. Clin. 14, 333–338.
7. Tebano, M.T., Cameroni, M., Gallozzi, G., Loizzo, A., Palazzino, G., Pezzini, G., and Ricci, G.F. (1988). EEG spectral analysis after minor head injury in man. Electroencephalogr. Clin. Neurophysiol. 70, 185–189.
8. Walker, A.E., Kollros, J.J., and Case, T J. (1944). The physiological basis of cerebral concussion. J. Neurosurg. 1, 103–116.
9. Meyer, J.S., and Denny-Brown, D. (1955). Studies of cerebral circulation in brain injury. II. Cerebral concussion. Electroencephalogr. Clin. Neurophysiol. 7, 529–544.
10. Hayes, R.L., Katayama, Y., Young, H.F., and Dunbar, J.G. (1988). Coma associated with flaccidity produced by fluid-percussion concussion in the cat. I: Is it due to depression of activity within the brainstem reticular formation? Brain Inj. 2, 31–49.
11. Moeller, J.J., Tu, B., and Bazil, C.W. (2011). Quantitative and qualitative analysis of ambulatory electroencephalography during mild traumatic brain injury. Arch. Neurol. 68, 1595–1598.
12. von Bierbrauer, A., Weissenborn, K., Hinrichs, H., Scholz, M., and Kunkel, H. (1992). [Automatic (computer-assisted) EEG analysis in comparison with visual EEG analysis in patients following minor cranio-cerebral trauma (a follow-up study).] (Ger) EEG EMG Z Elektroenzephalogr. Elektromyogr. Verwandte Geb. 23, 151–157.
13. Geets, W., and de Zegher, F. (1985). EEG and brainstem abnormalities after cerebral concussion. Short term observations. Acta Neurol. Belg. 85, 277–283.
14. Nuwer, M.R., Hovda, D.A., Schrader, L.M., and Vespa, P.M. (2005). Routine and quantitative EEG in mild traumatic brain injury. Clin. Neurophysiol. 116, 2001–2025.
15. Lewine, J.D., Davis, J.T., Bigler, E.D., Thoma, R., Hill, D., Funke, M., Sloan, J.H., Hall, S., and Orrison, W.W. (2007). Objective documentation of traumatic brain injury subsequent to mild head trauma: multimodal brain imaging with MEG, SPECT, and MRI. J. Head Trauma Rehabil. 22, 141–155.
16. Gosselin, N., Lassonde, M., Petit, D., Leclerc, S., Mongrain, V., Collie, A., and Montplaisir, J. (2009). Sleep following sport-related concussions. Sleep Med. 10, 35–46.
17. Fenton, G. (1996). The postconcussional syndrome reappraised. Clin. Electroencephalogr. 27, 174–182.
18. Watson, M.R., Fenton, G.,W. McClelland, R.J., Lumsden, J., Headley, M., and Rutherford, W.H. (1995). The post-concussional state: neurophysiological aspects. Br. J. Psychiatry 167, 514–521.
19. Chen, X.P., Tao, L.Y., and Chen, A.C. (2006). Electroencephalogram and evoked potential parameters examined in Chinese mild head injury patients for forensic medicine. Neurosci. Bull. 22, 165–170.
20. Fenton, G., McClelland, R., Montgomery, A., MacFlynn, G., and Rutherford, W. (1993). The postconcussional syndrome: social antecedents and psychological sequelae. Br. J. Psychiatry 162, 493–497.
21. Korn, A., Golan, H., Melamed, I., Pascual-Marqui, R., and Friedman, A. (2005). Focal cortical dysfunction and blood-brain barrier disruption in patients with Postconcussion syndrome. J. Clin. Neurophysiol. 22, 1–9.
22. Johnstone, J., and Thatcher, R.W. (1991). Quantitative EEG analysis and rehabilitation issues in mild traumatic brain injury. J. Insur. Med. 23, 228–232.
23. Thatcher, R.W., Walker, R.A., Gerson, I., and Geisler, F.H. (1989). EEG discriminant analyses of mild head trauma. Electroencephalogr. Clin. Neurophysiol. 73, 94–106.
24. Trudeau, D.L., Anderson, J., Hansen, L.M., Shagalov, D.N., Schmoller, J., Nugent, S., and Barton, S. (1998). Findings of mild traumatic brain injury in combat veterans with PTSD and a history of blast concussion. J. Neuropsychiatry Clin. Neurosci. 10, 308–313.
25. Thatcher, R.W., North, D.M., Curtin, R.T., Walker, R.A., Biver, C.J., Gomez, J.F., and Salazar, A.M. (2001). An EEG severity index of traumatic brain injury. J. Neuropsychiatry Clin. Neurosci. 13, 77–87.
26. Nuwer, M. (1997). Assessment of digital EEG, quantitative EEG, and EEG brain mapping: Report of the American Academy of Neurology and the American Clinical Neurophysiology Society. Neurology 49, 277–292.
27. Hoffman, D.A., Lubar, J.F., Thatcher, R.W., Sterman, M.B., Rosenfeld, P.J., Striefel, S., Trudeau, D., and Stockdale, S. (1999). Limitations of the American Academy of Neurology and American Clinical Neurophysiology Society paper on QEEG. J. Neuropsychiatry Clin. Neurosci. 11, 401–407.
28. Thatcher, R.W., Moore, N., John, E.R., Duffy, F., Hughes, J.R., and Krieger, M. (1999). QEEG and traumatic brain injury: Rebuttal of the American Academy of Neurology 1997 report by the EEG and Clinical Neuroscience Society. Clin. Electroencephalogr. 30, 94–98.
29. Gaetz, M., and Bernstein, D.M. (2001). The current status of electrophysiologic procedures for the assessment of mild traumatic brain injury. J. Head Trauma Rehabil. 16, 386–405.
30. Arciniegas, D.B. (2011). Clinical electrophysiologic assessments and mild traumatic brain injury: state-of-the-science and implications for clinical practice. Int. J. Psychophysiol. 82, 41–52.
31. Kane, N.M., Moss, T., Curry, S.H., and Butler, S.R. (1998). Quantitative electroencephalographic evaluation of non-fatal and fatal traumatic coma. Electroencephalogr. Clin. Neurophysiol. 106, 244–250.
32. Thatcher, R.W., Biver, C., McAlaster, R., and Salazar, A. (1998). Biophysical linkage between MRI and EEG coherence in closed head injury. Neuroimage 8, 307–326.
33. Thatcher, R.W., Biver, C., McAlaster, R., Camacho, M., and Salazar, A. (1998). Biophysical linkage between MRI and EEG amplitude in closed head injury. Neuroimage 7, 352–367.
34. Parsons, L.C., Crosby, L.J., Perlis, M., Britt, T., and Jones, P. (1997). Longitudinal sleep EEG power spectral analysis studies in adolescents with minor head injury. J. Neurotrauma 14, 549–559.

Address correspondence to:
Zulfi Haneef, MD
Department of Neurology
Baylor College of Medicine
One Baylor Plaza, MS NB302
Houston, TX 77030

E-mail: haneef@bcm.edu