QUANTITATIVE EEG ANALYSIS AND REHABILITATION ISSUES IN MILD TRAUMATIC BRAIN INJURY

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Introduction

There is an acute need to use an objective, non-invasive, and reliable technique to quantify the neurological consequences of mild head injury so that better patient management can be offered, and long-term treatment and rehabilitation can be properly established and evaluated, as well as in family counseling. For example, of the approximately 8 million individuals that suffer head injuries of all types each year in the U.S.,[1] approximately 80% involve mild head injuries, with more than 200,000 patients with mild head injury admitted to U.S. hospitals each year.[2,3] * The public health consequence of these injuries is emphasized by the fact that many of these individuals are unable to return to work, complain of headache and memory problems, and exhibit a variety of neuropsychological dysfunctions.[4,5,6]

Abrupt acceleration and/or deceleration of the brain can cause cerebral contusions and diffuse axonal injuries. It is precisely these neurological injuries that are believed to be the cause of both short- and long-term disability following mild head injury. Unfortunately, conventional CT and MRI scans are unable to detect structural damage at the microscopic level in mild head injured patients. This appears to be especially true in the case of reduced fidelity of axonal transmission in non-degenerated but myelin-damaged axons.

Computerized EEG analyses of coherence and phase provide an inexpensive and non-invasive technique to detect and quantify diffuse axonal injury and cerebral contusions in mild head-injured people.[8,9] For example, recent clinical analyses of 608 mild head-injured patients and 108 age-matched normal subjects provided greater than 95% accuracy in the detection and neurological classification of mild head injury.[9]

The purpose of this article is to describe the computerized EEG technique for the evaluation of mild head injury and to suggest some of the possible uses of this technique in the acute and long-term management and rehabilitation of individuals with mild head injuries.

qEEG

The application of quantitative EEG analysis (qEEG) has made it possible to detect and monitor diseases that are subtle in nature, such as transient ischemia,[10] and to detect abnormalities early in the course of a disease, such as degenerative dementia.[11] qEEG is quite complementary to the skill of the experienced clinical electroencephalographer, and is geared to extend clinical judgment rather than replace or automate it. The most often used technique involves recording EEG using paste-on electrodes and powerful multichannel amplifier systems, and digitizing the EEG signal using specialized analog-to-digital converters. The digitized signal may then be stored on disk for subsequent analysis. These analyses require several assumptions. Perhaps most importantly, the data is assumed to be "artifact free," that is, all signals recorded from the scalp are due to brain function per se. However, interposed between the recording electrode and the brain are scalp, skull, muscles, blood, membranes, cerebrospinal fluid, etc. Some of these factors, such as the skull and scalp, significantly attenuate and "smear" the brain electrical signal. Other factors such as muscles generate their own electrical signals, which obscure the EEG. Therefore, the EEG must be extensively reviewed and artifacts removed or reduced prior to quantitative EEG analysis. This is a labor-intensive and technically demanding task.

The analysis most often used to date has been frequency or spectral analysis. This method provides an estimate of the frequency composition of the complex EEG signal. It is used to decompose the EEG waveform into frequency components, typically from 1-32 cycles per second (called Hertz, "Hz."). The results of this type of analysis may produce many pages of computer printout, listing each scalp electrode and the amplitude of the signal at each frequency for each condition studied measured at regular time intervals. For example, a printout may include the amount of delta (1-3 Hz.), theta (4-7 Hz.), alpha (8-13 Hz.), and beta (14-32 Hz.) activity for each

* Because of misconceptions and misuses of the term "post- concussion syndrome," the American Congress of Physical Medicine and Rehabilitation proposed use of the term "mild traumatic brain injury (MTBI)" in June 1990.[7] A patient with MTBI is one who has experienced a traumatically induced disruption of cerebral function, as manifested by at least one of the following: 1. loss of consciousness of 30 minutes or less and a Glasgow Coma score not less than 13; 2. any loss of memory not greater than 24 hours for events immediately before or after the accident (retrograde or anterograde amnesia); 3. any alteration in mental state at the time of the accident, e.g., confusion, disorientation, even in the absence of loss of consciousness or amnesia; 4. physical symptoms that are potentially brain related, e.g., nausea, headache, tinnitus, sensory loss, fatigue, lethargy; 5. development of post-traumatic cognitive deficits (e.g., attention, concentration, memory, language, percetion) that cannot be completely accounted for by emotional state.

scalp electrode. In addition, rather than combining frequencies into arbitrary frequency bands, each frequency from 1-32 Hz. can be examined individually. Further, it may be desirable to look at the pattern of amplitudes and frequencies over only several seconds at a time. It is clear that a great deal of quantitative information may be extracted from the EEG signal. This creates the problem of how to interpret such a bulk of data. One solution has been to display the results in topographic form. Graphic representation of the results are often displayed as "topographic maps" in which data from multiple electrode sites can be reviewed in convenient color-coded displays. Figure 1 shows an example of topographic mapping for a patient with abnormal focal slow activity over the left medial frontal scalp.

Figure 1

Quantitative EEG Frequency Analysis with Topographic Mapping

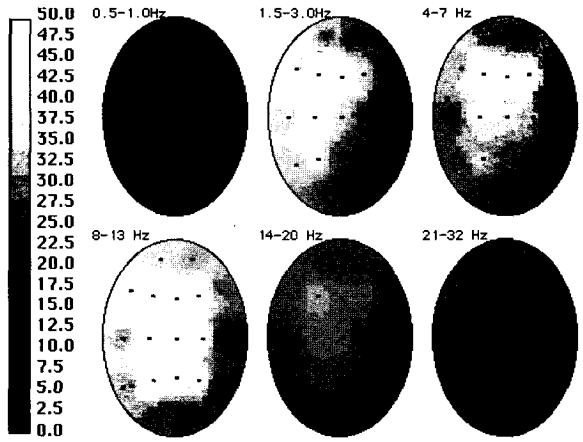


Figure 1: Example of brain electrical activity mapping. A segment of EEG selected for absence of artifact was submitted to EEG frequency analysis with results displayed as topographic maps. Significant focal slow activity is present, primarily over the left frontal region in the delta frequency band.

Neurometrics

Even given the convenience of representing large amounts of data in graphic format, there may still be difficulties in interpretation. Since clinical EEG readers often have little experience with assessing the proper amount of energy in each frequency from each electrode, additional guidance is needed to assess the bounds of normal variation. The concept of "neurometrics" was introduced in the late 1970s are a means of providing such guidance.[12] The idea of neurometrics was adapted from studies in psychology, termed "psychometrics." Scores on specific psychological tests were compared to normative measures obtained by administering the test to large populations of normal individuals, such as in typical IQ testing. The degree of deviation from "norms," usually represented as a "Z-Score," indicate how divergent a score is from the average of a large population. This method is used routinely in clinical psychological evaluation. In work on quantitative EEG, the degree of deviation is available for each EEG measure and may be represented graphically as Z-score "maps." Figure 2 shows Z-score mapping for the EEG data displayed in Figure 1. Note deviation exceeding 3 standard deviations over the left medial frontal region in the delta frequency range. This type of map allows a clinician to discern at a glance the extent and location of maximum statistical deviation from a reference population. It is not, however, diagnostic of specific diseases. For example, the interpreter may determine that an excess of slow activity may be present, but this excess may be due to stroke, tumor, infection, etc. The results of quantitative analysis therefore must be considered part of an overall clinical evaluation and related to other diagnostic tests and aspects of the clinical examination and patient history.

Figure 2

Z-Score Mapping

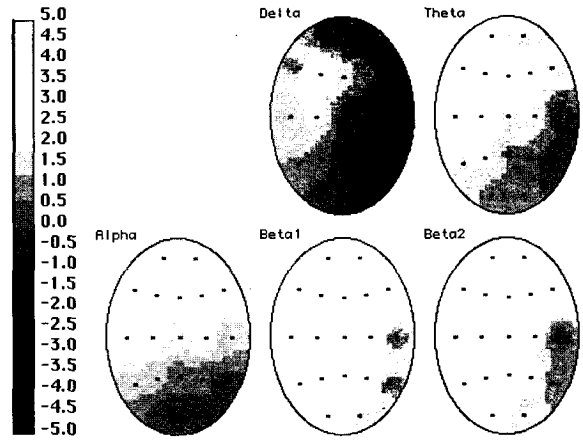


Figure 2: Z-score mapping for EEG data shown in Figure 1. Deviation from a reference database is apparent over the left medial frontal region in the delta and theta frequencies. Deviation in the beta frequency over frontal scalp is secondary to medication effects.

qEEG in Mild Traumatic Brain Injury

Given this background, we introduce the notion of using quantitative EEG features for identification of effects of mild traumatic brain injury. There is a distinct need to develop an objective, non-invasive, and readily available measure capable of identifying and classifying patterns of neurophysiological dysfunction in mild head injury patients. Studies by Thatcher et al. (1989)[9] were instrumental in specifying a set of EEG variables which appear to reliably discriminate MTBI patients from a normal age-matched control group. The main statistical technique used to separate the MTBI patients from the normal group is called discriminant analysis. This procedure is used to find a set of variables which when appropriately weighted and summed provides maximally different scores for the two or more groups being classified. Note that the groups are pre-classified. The computer analysis is intended to find those variables that most accurately place indi-

viduals in their designated group. When validated as a means of accurately and reliably categorizing patients into predesignated groups, the discriminant rule can be applied to a single individual with unknown group membership to determine how the individual is classified by the same rule.

The MBTI discrimination was based to a large extent on group differences in certain EEG measures termed "coherence" and "phase." The power of the qEEG method is immediately apparent, since these measures are not amenable to visual inspection. The clinical electroencephalographer is largely unaware of these measures when performing a visual interpretation of the routine chart recording. Coherence is essentially a correlational measure indexing the amount of shared activity between two scalp regions. Phase is a measure of the lead or lag of shared rhythms between two regions measured in milliseconds.

In functional terms, coherence reflects the integrity of connections between regions, largely due to white matter. It is manifest in a U-shaped function such that low coherence may reflect lack of connection between brain subsystems, e.g., due to penetrating wounds. Elevated coherence appears to reflect similarity of cortical processing, or lack of differentiation between regions. Low coherence conversely may also reflect differentiation of cortical regions due to regional cerebral specialization, which is likely a substrate for increased information processing capacity.

The phase relationships between channels may also be interpreted as reflecting the degree of functional differentiation between neuronal systems. Phase in a connected system such as the cerebral cortex is a function of EEG frequency, distance between sites, and conduction velocity. Basic studies of EEG coherence and phase suggest that phase measures are not linearly related to distance. There appear to be two systems of cortico-cortical connections responsible for coherence, a short axon system and a long axon system.[8] These two different systems can be identified and independently assessed. Appropriate use of measures of functional brain differentiation and information processing capacity such as EEG coherence and phase could have profound impact on our understanding of issues in development, education, and rehabilitation.

Thatcher et al. (1989)[9] studied a relatively large population of adult patients with MTBI. Full details of this study are available in published form and the study is summarized here. Of a grand total of 608 patients, 264 patients were used for the initial data analysis and three separate, independent populations of 130, 144, and 70 patients, respectively, were used to assure replicability of the initial results. Approximately 60% of the MTBI population were victims of a motor vehicle accident, 10% were pedestrians, and the remainder were victims of home or industrial accidents, or violent crime. All had Glasgow Coma Scores between 13-15. Patients were excluded if there was evidence of skull fracture, intracranial mass lesion, or need for intracranial surgical procedures. Based on patient and medical personnel interviews, patients suffered either no loss of consciousness or loss of consciousness was no longer than 20 minutes. Normals met the following criteria: 1) no history of head injury with cerebral symptoms; 2) no history of central nervous system disease; 3) no history of convulsions of emotional, febrile, or other nature; 4) no obvious mental diseases; and 5) no abnormal deviation with regard to mental and physical functioning.

A composite of measures of frontal and temporal coherence and phase, anterior-posterior amplitude differences, and posterior relative power was successful in discriminating the initial population from normal with an overall classification accuracy of 94.8%. The first independent replication yielded a discrimination at 95.4%, with the second and third replications at 87.5% and 92.8%, respectively. Additional analyses were carried out to assess the stability of the discriminant analysis over time as well as the post-injury time course of the discriminant pattern. Similar results were obtained from four subgroups, ranging from a mean of 17 to 223 days post injury, although a non-significant trend toward normality was seen over time. The overall level of accuracy of discrimination and the replicability and stability of the discriminant rule suggest that this analysis may be applied to individual patients in a clinical setting.

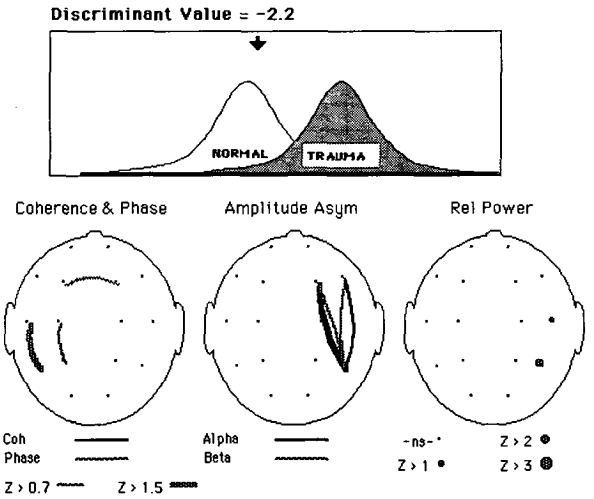
These results were interpreted given current information about the nature of acceleration-deceleration injuries. There were three classes of measures comprising the discriminant rule, frontal and temporal lobe coherence and phase, anterior-posterior amplitude gradients, and posterior relative power. Interestingly, measures of EEG slowing such as an increase in 1-3 Hz. (delta) activity, suggestive of frank structural pathology, were not entered into the discriminant. The results suggest a functional reorganization following MBTI. The localized frontal coherence and phase abnormalities are consistent with localized contusions and axonal injury to frontal regions. The phase relationships tend to decrease in the presence of increases in coherence. This pattern suggests reduced a lack functional differentiation or increased redundancy between neuronal systems. The abnormal anterior-posterior gradient of activity is likely related to changes in the long axonal systems, whereas diminished posterior activity is consistent with "coup-contra-coup" processes and reduced excitability of posterior cortex in general.

Overall, the pattern of discriminating variables suggests that the most consistent interpretation is the development of a new neurophysiologically stable state characterized by both local and global effects. Localized dysfunction may cause relatively specific neuropsychological deficits, due to damage to frontal and temporal regions. This sort of damage may be expected to result in problems with attention, planning and sequencing, short-term memory disturbance, and emotional lability. Global effects might be expected to produce a dedifferentiated state resulting in overall reduced information processing capacity. This type of effect may be more related to the ability to simultaneously operate on different information, rapidly shift attention, and process complex information.

Results from two clinical cases are shown in Figures 3 and 4. Figure 3 displays results for a patient reporting symptoms common in mild traumatic brain injury following a work-related injury. There is no elevation in frontal coherence measures and no reduction in phase relationships over frontal cortex. There are some minor findings, but overall a pattern showing little similarity with the head injury population. In

contrast, Figure 4 shows a patient with markedly positive findings following a motor vehicle accident. There is significant elevation of frontal theta coherence in the presence of lowered phase. Temporal coherence is also mildly elevated. However, there are no effects of posterior relative power, indicating well developed posterior rhythmic activity. Comparison of these figures indicates distinct differences in the pattern of coherence and phase between these two patients, particularly over frontal cortex.

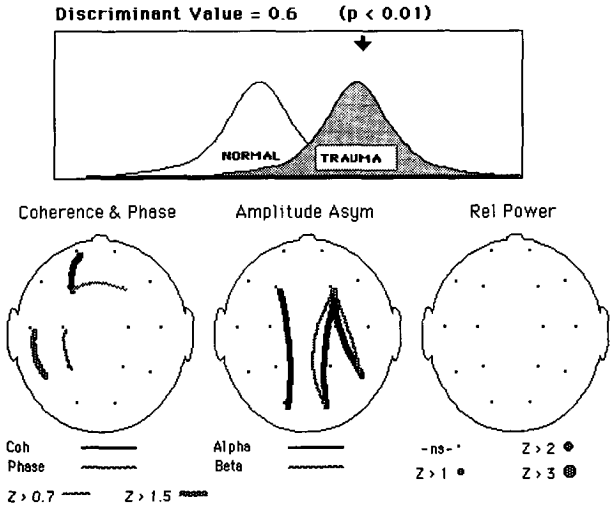
Figure 3
Patient with Negative Findings



Measure	Value	Z-Score	DB-Mean
Theta Coh FP1-F3	77.5	0.32	75.0
Beta Coh T3-T5	82.9	1.91	50.7
Beta Coh C3-P3	83.3	0.79	75.1
Beta Pha FP2-F4	1.2	0.06	1.1
Beta Pha F3-F4	-0.4	-1.26	0.7
Alpha ADif F4-T6	54.7	2.02	-47.9
Alpha ADif F8-T6	-44.7	1.33	-95.8
Beta ADif F4-T6	40.1	0.91	-5.3
Beta ADif F8-T6	-15.0	0.73	-46.0
Alpha ADif F3-O1	-153.4	-1.19	-93.1
Alpha ADif F4-O2	-170.2	-1.36	-100.5
Alpha ADif F7-O1	-173.3	-1.18	-126.8
Beta ADif F4-O2	-131.8	-1.51	-46.8
Alpha Rel Pow P3	48.1	-0.10	49.8
Alpha Rel Pow P4	53.9	0.29	48.7
Alpha Rel Pow O1	63.7	0.35	57.8
Alpha Rel Pow O2	71.9	0.77	59.4
Alpha Rel Pow T4	22.0	-0.92	33.8
Alpha Rel Pow T5	41.3	-0.51	48.9
Alpha Rel Pow T6	25.7	-1.63	52.0

Figure 3: Results of Mild Traumatic Brain Injury Discriminant Analysis for a patient with negative findings. The top part of the display shows a schematic representation of the two populations and the relative standing of this patient. The patient clearly falls within the range on the normal population with an overall score of -2.2. The three head diagrams represent the three classes of measures contributing to the discrimination described by Thatcher et al., 1989. There are few significant effects. The table of results at the bottom of the figure shows that the patients values fall quite close to the database mean, indicating a result within the limits of normal variation.

Figure 4
Patient with Positive Findings



Measure	Value	Z-Score	DB-Mean
Theta Coh FP1-F3	98.0	2.98	75.0
Beta Coh T3-T5	78.7	1.66	50.7
Beta Coh C3-P3	83.3	0.79	75.1
Beta Pha FP2-F4	0.7	-0.45	1.1
Beta Pha F3-F4	0.0	-0.76	0.7
Alpha ADif F4-T6	101.5	2.94	-47.9
Alpha ADif F8-T6	-70.6	0.66	-95.8
Beta ADif F4-T6	63.3	1.38	-5.3
Beta ADif F8-T6	-54.8	-0.21	-46.0
Alpha ADif F3-O1	45.4	2.72	-93.1
Alpha ADif F4-O2	59.0	3.10	-100.5
Alpha ADif F7-O1	-101.4	0.64	-126.8
Beta ADif F4-O2	17.7	1.14	-46.8
Alpha Rel Pow P3	52.7	0.18	49.8
Alpha Rel Pow P4	46.6	-0.12	48.7
Alpha Rel Pow O1	57.5	-0.02	57.8
Alpha Rel Pow O2	54.8	-0.28	59.4
Alpha Rel Pow T4	47.3	1.06	33.8
Alpha Rel Pow T5	55.6	0.44	48.9
Alpha Rel Pow T6	55.8	0.23	52.0

Figure 4: Results of Mild Traumatic Brain Injury Discriminant Analysis for a patient with positive findings. The format is as described for Figure 3. These results show both a marked increase in frontal theta coherence as well as decreased phase. Anterior/posterior gradients are aberrant, but no significant effects for relative posterior power are noted. Overall, the patient is identified as a member of the trauma population.

Rehabilitation and Case Management Issues

The most significant issue in management of individual cases is the cost-effectiveness of both diagnostic procedures and rehabilitative therapies. The quantitative EEG evaluation using the specialized MTBI discriminant analysis, including professional interpretation, typically costs less than a magnetic resonance imaging study. It appears to provide more benefit than MRI in the MBTI patient since it is a relatively direct dynamic measure of brain function rather than a static measure of brain structure. MRI is exceptionally useful in localizing lesions and identifying certain disease processes, but the technique is unable to detect whether a patient is dead or alive. The *combined* use of these modalities promises to provide the most useful clinical information. Technologies are currently in development to make direct, quantitative comparisons among imaging modalities such as qEEG, MRI, and Positron Emission Tomography (PET).

With regard to the cost of case management, the qEEG procedure when combined with MRI and neuropsychological evaluation can provide convincing evidence that negative results are meaningful. Expensive measures to rehabilitate patients with uniformly negative findings cannot be justified given such factors as secondary gain and the limited availability of funds for rehabilitation. The ability to predict outcome may help in determining the extent to which funds for rehabilitation should be encumbered.

Positive results suggests that aggressive rehabilitation efforts be undertaken quickly. Waiting for repeated expensive patient evaluations or simply waiting for symptoms to subside may be quite counterproductive in getting such patients back to work. The idea that a short series of cost-effective tests can significantly help to guide the rehabilitation effort is an attractive one. The specific results may also assist in developing particular rehabilitation regimes. A physician skilled in rehabilitation medicine or a clinical neuropsychologist may note the specific pattern of abnormality and recognize that particular compensation strategies may be most relevant or that certain remediation programs are likely to be relatively ineffective. For example, the patient with signs of localized frontal contusion, even in the absence of MRI findings, may be best served by support for planning activities or sequencing rather than emphasizing receptive language function, spatial relationships, etc. The patient with marked temporal lobe abnormality may have verbal memory or other memory deficits requiring a different rehabilitative approach. The precision of evaluation with qEEG, identifying regional cerebral dysfunction, allows for determination of the most rational treatment strategies. Using qEEG as a monitor of treatment effectiveness may also be useful. The method could be used in conjunction with behavioral assessment to gauge the need to change the course of therapy to achieve optimal outcome.

Conclusion

The quantitative EEG technique has been reviewed in regard to general assessment of cerebral function as well as with respect to evaluation of mild traumatic brain injury. The discriminant analysis as described by Thatcher et al. 1989[9] was shown to be an objective, non-invasive, and reliable technique for evaluation of diffuse axonal injury characteristic of MTBI. In contrast to other available imaging modalities, the qEEG technique is unique in providing high temporal resolution of cerebral function while being highly cost-effective. Use of the qEEG procedure requires considerable sophistication with technical aspects of the study such as artifact rejection, signal processing, and statistical analysis, as well as professional interpretation by an experienced clinician. When used appropriately by knowledgeable technicians and clinicians, the qEEG technique can provide unique information to identify and monitor the effects of mild traumatic brain injury.

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