

Continuous Quantitative Motor Evoked Potentials for Spinal Cord Injury Detection

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Abstract - Motor evoked potential (MEP) monitoring is a complementary approach to directly monitor the integrity of the motor pathway and is another modality designed to ensure the integrity of the spinal cord during surgery. However, conventional interpretation of MEP signal based on amplitude and latency tracking is subjective and not always accurate, and usually a significant learning curve has been demonstrated. Hence, we proposed a quantitative time frequency analysis method, Window Energy Index, for monitoring spinal cord surgery. The preliminary results suggest the proposed analysis has better sensitivity than conventional amplitude analysis.

I. Introduction

Intraoperative neuromonitoring has been shown to improve outcome in high-risk spinal surgeries [1]. Traditionally, this has involved monitoring somatosensory evoked potentials (SEPs). Motor evoked potential (MEP) monitoring is another modality designed to ensure the integrity of the spinal cord during surgery. MEPs elicited by electrical stimulation have been used to provide rapid feedback about motor pathway function in spinal surgeries [2]. The waveform of motor evoked potentials (MEP) is the compound electrical action potentials from the nerve. Standard MEP evaluation and interpretation are limited to well trained and experienced clinicians and technicians. Langeloo et al. [3] have successfully monitored transcranial electric MEPs in 142 out of 145 patients undergoing corrective spinal surgery. A criterion of 80% or greater decrease in signal amplitude in any one of six muscular recording sites was used to indicate potential spinal cord compromise and predict postoperative neurological deficit.

However, the learning curve remains steep and the problem compounded by subjective interpretation during MEP monitoring. Additionally, conventional MEP monitoring employs time domain analysis for injury detection, such as amplitude and latency (e.g. N20) which would be potentially distorted by noise and artifacts and result in high error detections of False Positives (FP) and False Negatives (FN). In this paper, based on Hu's work which is focusing on somatosensory evoked potential analysis [4], we utilize time frequency joint analysis to monitor MEP signal and extract the injury information during the course of spinal cord surgery. The quantitative MEP monitoring & analysis may provide objective, automated feedback and improve application of the technology.

II. Methods

To produce time-frequency distributions (TFD) under spinal cord surgery we utilized the continuous wavelet transform (CWT), proposed by Grossmann and Morlet [5]. The CWT is able to detect MEP signal components of relatively higher spectral content and lower amplitude. We employed wavelets of Morlet which guarantee a minimum time-bandwidth product and provide for maximum concentration in both time and frequency domains. The joint time-frequency representations map is a one-dimensional signal in the time-frequency plane, giving an indication of distribution of spectral component in time.

Joint time frequency analysis is a new application in quantitative MEP signal analysis and monitoring. There are several approaches in time-frequency analysis, such as short-time Fourier transform, Wigner Ville distribution, etc [4]. Among them, the wavelet transform represents a signal in a 'lattice of building blocks', which have good frequency as well as time localization. It decomposes the signal on a set of basis functions, obtained by dilations, contractions and shifts of a unique function called the mother wavelet. The mother wavelet is analogous to a bandpass filter and the set of basis functions consists of modulated versions of this prototype. Therefore, the notion of scale is introduced as an alternative to frequency, leading to a time-scale representation.

The Continuous Wavelet Transform is defined for a continuous signal $x(t)$ as

$$CWT(t, a) = \sqrt{a} \int x(a\tau) * g^* \left(\frac{t-\tau}{a} \right) e^{j\omega\tau} d\tau \quad (1)$$

Where $g(t)$ is the *mother or basic wavelet* basis function, * denotes the complex conjugate, a is a scale factor, and τ is a time shift. The function $g(t)$ is a bandpass function centered around some center frequency, f_0 . Scale a allows the compression or expansion of $g(t)$. A larger scale factor generates the same function compressed in time whereas a smaller scale factor generates the opposite ($1/a$ is proportional to signal frequency, f). Equation 1 can also be formulated in the frequency domain:

$$CWT(t, a) = \sqrt{a} \int X(\omega) * G(a\omega) e^{j\omega t} d\omega \quad (2)$$

Where X and G are the Fourier representation of x and g , respectively.

The Morlet Wavelet was introduced by Morlet *et al.* in 1984 originally for seismic analysis. The Morlet wavelet, $g_m(t)$, is simply a complex oscillating signal contained in a Gaussian envelope given by:

$$g_m(t) = \frac{1}{\sqrt{2\pi}} e^{j\omega_0 t} e^{-\frac{t^2}{2}} \quad (3)$$

For this study, the CWT was calculated in the frequency domain, as it provided a significant advantage in computational time as it avoids costly time domain convolution (1). To calculate the CWT in the frequency domain, the signal $x(t)$ is converted to the frequency domain $X(\omega)$ by the Fast-Fourier Transform (FFT). A vector of analyzing frequencies ω_k is created (for $k=1, 2, 3 \dots, n$), and similarly, a vector of scaling factors a_l is created (for $l=1, 2, 3, \dots, m$). A two-dimensional vector of size (n, m) is calculated with each element representing $G_m(\omega, a)$, the

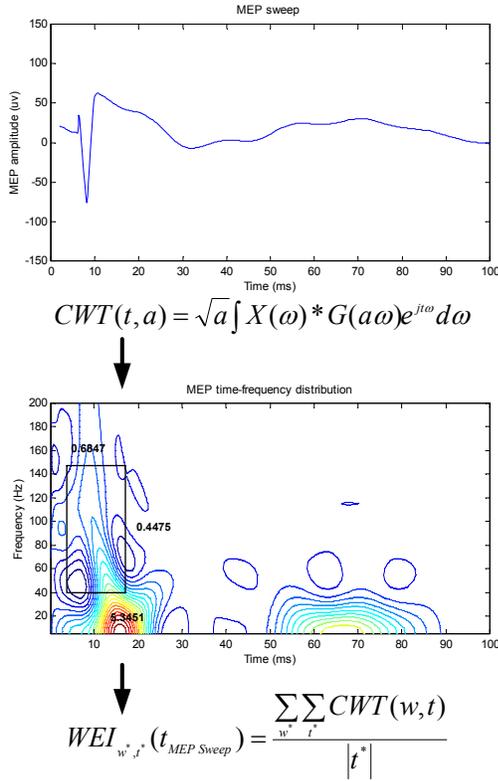


Figure 1: Continuous Wavelet Transform (CWT) based analysis of MEP signal $x(t)$. $G(w)$ and $X(w)$ are Fourier Transforms of the respective time domain waveforms. CWT is a two-dimensional function describing the original MEP signal in a time-frequency plane and is represented as a contour plot. Contour represents points of equivalent signal energy. Window Energy Index (WEI) is the measure index for spinal cord injury detection and is equal to the summation of MEP mid-frequency signal energy.

frequency representation of the scalable Morlet wavelet. The analyzing signal is then windowed in the frequency domain, creating a two-dimensional product $Y(\omega, a)$:

$$Y(\omega, a) = X(\omega)G_m(\omega, a) \quad (4)$$

The CWT is then recovered with use of the inverse FFT.

Window Energy Index (WEI) and analysis

To quantify the spinal cord injury changes in the time-frequency plane, window energy index is computed from the interesting time-frequency window selected from the joint distribution plane. MEP signal energy is summed up in the selected window (e.g. time range: 5 – 20 ms and frequency range: 40-150 Hz which can envision the main part of the signal changes during the course of spinal cord injury. See figure 1.). This mid-frequency region has been found to be the most sensitive to spinal cord injury related motor evoked potential signal changes during the preliminary rodent studies.

$$WEI_{w, t^*} (t_{MEP Sweep}) = \frac{\sum_w \sum_{t^*} CWT(w, t)}{|t^*|} \quad (5)$$

III. Experiments and data collection

The spinal cord injury (SCI) experimental studies were carried out at Johns Hopkins University School of Medicine facilities in anesthetized rats in which spinal cord compression were performed on a randomly selected basis. Adult Wistar male rats (300-350 g) were used in the study. Rats were used for this model because of, 1) suitability for carrying out electrophysiological investigations, 2) considerable prior knowledge of the neuroanatomy and physiology of rats, 3) recordings can be done in both anesthetized and awake animals and 4) our previous experience with this species.

Adult rats were anesthetized with halothane (induction 2.5%, maintenance 2%) until the onset of unconsciousness, and then intravenous propofol (10mg/kg over 15 min). Propofol sedation was maintained at infusion rate of 400-700 μ g/kg/min. The rate is variable as it is adjusted to suppress spontaneous hind-limb EMG activity. Following this, the animals were intubated and ventilated. Throughout the protocol, the temperature was maintained constant at $37 \pm 0.50^\circ\text{C}$ with the aid of a heating pad and rectal temperature probe. The MEP signal acquisition occurred while electrical stimulation was delivered, at the rate of 1/s, pulses of 200 μ s duration, at amplitudes of twice the motor threshold (typically 5 to 10 mA). EMG (electromyogram) and ECG were continuously recorded throughout the experiments. EMG was recorded bilaterally from the calf muscles (gastrocnemius). The amplifier bandpass was set at 5-1000 Hz, and the sampling rate was 5000 samples/sec. Before spine injury infliction, baseline normal MEP waveforms were recorded for 20 mins. After the spine was exposed and

the screw placed, continuous MEP monitoring was instituted for the acute injury and subsequent recovery until the end of the procedure. In our preliminary study, we employed a cervical screw model to introduce progressive injury to the spinal cord at T7 [4].

IV. Analysis results

Three rats were monitored, with SCI induced on one of which via the implanted screw. Based on wavelet analysis, we analyzed the injury events. Figure 2 shows the continuous monitoring of the SCI experiment. In the example, the experiment includes three epochs: baseline, injury and recovery. The window energy index shows decrease (injury) of the calculation value after 1000 second and gradual increase (recovery) after 1400 seconds. The normalized WEI calculation value for baseline vs. injury vs. recovery = 1: 0.13: 0.51 (Normalized mean value). As a comparison, we also calculated the amplitude value before, during and after injury. In figure 2, we also show the single MEP sweep signal. The normalized the amplitude values are baseline vs. injury vs. recovery = 1: 0.64: 0.76 (Normalized mean value). Comparing with conventional amplitude monitoring, the WEI calculation demonstrates better sensitivity in analysis and detection during SCI events: the injury change of WEI vs. Amplitude = 87% : 36%. At the same time, WEI calculation and analysis can greatly decrease the noise effects via selection of time and frequency range, such as body movement, electrical stimulation artifacts, etc. In conventional MEP monitoring and interpretation, it is difficult to characterize or estimate the noise proportion as well as signal distortion.

Figure 3 shows the 3-dimensional time frequency distribution of the signal changes in Injury vs. Baseline and Recovery vs. Baseline. The 3-dimensional WEI calculation shows the energy distribution in time and frequency domain (time:0-100ms; frequency: 0-200Hz) during SCI. The 3-dimensional mapping shows the differential signal changes caused by SCI are focusing on the region (time range: 5-40ms; frequency range: 0-100 Hz). The normalized WEI calculation comparison is:

$$WEI_{diff(Recovery-Baseline)}^{vs. WEI_{diff(Injury-Baseline)}} = 0.937:0.106.$$

The three dimension energy distributions in time-frequency domain are capable of accurately capturing and characterizing the SCI process and even the transition from injury to recovery. 3D energy mapping can provide more clear MEP signal changes during spinal cord surgery.

V. Discussion and Conclusions

In standard MEP recordings, amplitude and latency are the key components in monitoring and analysis. Unfortunately, there are some disadvantages:

- a. EP amplitude recognition requires significant experience for which trained technicians or clinicians are needed for visual monitoring.

Continuous WEI calculation during MEP monitoring

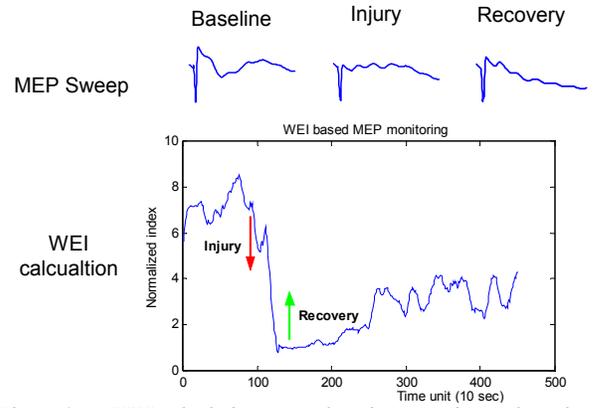


Figure 2: A WEI calculation example using experimental rat data illustrates how MEP signal spans from baseline to injury and then recovery. The aim of the Window Energy Index (WEI) algorithm is to quantify the time-frequency distribution alterations in a single measure of electrophysiological changes.

Energy difference (3D) in the time frequency distribution

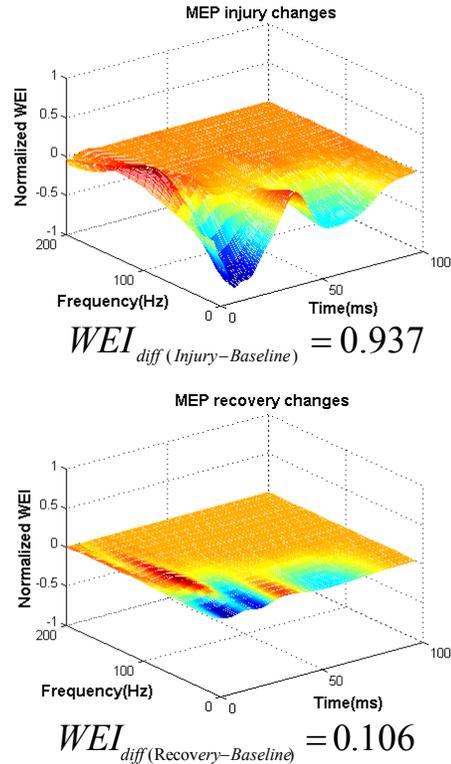


Figure 3: 3D illustration of WEI simulation using experimental rat data shows the energy difference of the time-frequency distribution during injury and recovery compared with MEP baseline signal. The changes of time-frequency energy distribution show the discrimination of the injury and recovery process: comparing with MEP baseline, the normalized WEI energy change of the injury is 0.937 while the WEI change of recovery is 0.106.

- b. EP amplitude (peaks, troughs in waveforms) in general are difficult to detect automatically and hence do not lend themselves well for implementation in automated instruments.
- c. In noisy environments, e.g. in the OR (Operating Room), the noise (environment, electrical or bio-noise) is repeated with each MEP trial; it increases the difficulty for clinical analysis and recognition.

Window Energy Index calculation and analysis provide an alternative approach to quantitative MEP monitoring and injury detection. Our goal was to develop a quantitative method for easy interpretation of neurophysiology, such as the pathway of the nerve system. WEI analysis combines both time and frequency information of MEP signal which we hope to demonstrate better performance in continuous MEP monitoring analysis. We hope to encourage implementation of this new technology in automated MEP monitoring and improved neuro-diagnostic equipments.

This paper lends support for a new approach in time-frequency distribution based MEP monitoring. This MEP analysis approach for neurological monitoring is a significant improvement over conventional analysis techniques, uniting the examination of signal alterations in both time domain and frequency domains. Additionally, the study provides a possibility to explore the real-time application of the Window Energy Index in monitoring electrophysiological changes for spinal cord surgery. In future research, we will seek to demonstrate the quantitative analysis ability and application of the Window Energy Index and to prove its utility in MEP monitoring during spinal cord surgery. At the same time, we also plan to develop the signal processing method further by 1) Studying the effects of different noise sources; 2) Contrasting inter-trial variability to the injury/recovery related physiological changes, and 3) Developing an empirical model of the baseline signal against which changes (better or worse) can be compared. It is our long-term goal that this sophisticated signal processing technique be further developed to improve the sensitivity and specificity of neuro-functional MEP monitoring for clinical application and its translation into intraoperative EP systems.

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