Application of Time-Frequency Analysis to Intraoperative Myogenic Motor Evoked Potentials during Spinal Cord Decompression Surgery

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Abstract— **Intraoperative Neurophysiological Monitoring (IONM) during spine surgery has dramatically evolved over the past decade. Transcranial electrical Motor-Evoked Potential (TceMEP) technique has been proved capable of providing information about the integrity of the motor pathways. However, to date, quantitative criteria for interpretation of results of muscle-recorded TceMEP monitoring have not been established. The purpose of this study is the time-frequency analysis of the myogenic motor evoked potentials (mMEPs) during spinal cord decompression surgery in order 1) to examine the changes of the mMEP waveforms by using an adaptive approximation method based on the Matching Pursuit (MP) algorithm and 2) to evaluate other parameters than those that are commonly and conventionally used for neuromonitoring purposes. It appears that the time-frequency analysis based on the MP is an alternative method of evaluating the mMEPs during surgical procedures, and provides a new kind of neurophysiological markers that could be used in order to evaluate the neuronal functional integrity.**

I. INTRODUCTION

INTRAOPERATIVE Neurophysiological Monitoring (IONM) during spine surgery has dramatically evolved over the past decade. Operative procedures such as instrumentation for spine deformities (e.g. scoliosis, kyphosis), neurosurgical spinal cord procedures, and some cardiothoracic procedures constitute a risk of injury to the spinal cord. Patients at greatest risk are those with kyphosis, scoliosis, or pre-existing neurological impairment. Damage may occur due to excessive stretching of the spinal cord, compression during fitting of instrumentation and spinal cord/nerve decompression, trauma from passing wires near the spinal cord, or interference with spinal cord blood flow [1]. The consequences of the neurological complications can be devastating, including paraplegia, tetraplegia or even death [2], [3]. Because of the risks associated with spinal surgery, techniques by which spinal cord function can be continuously evaluated intraoperatively have been developed. The principal goal of such intraoperative neurophysiological monitoring is rapid identification of surgically induced neurophysiologal changes to allow for their prompt correction before irreversible neurological impairment occurs [1], [4].

Intraoperative monitoring using Somatosensory Evoked Potentials (SSEPs) consists of measuring neuronal integrity from the peripheral nerves through the dorsal columns of the spinal cord to the brain [3]. SSEPs have been used for more than 20 years and it is the most commonly used technique to monitor the integrity of the spinal cord [5]. However, multiple authors have recognized that the use of SSEPs, merely to monitor the dorsal columns of the spinal cord, is neither sufficient nor reliable enough to detect or prevent lesion of the motor tracts (corticospinal tracts) [6]-[9]. Another important limitation of SSEP monitoring is the delay produced by averaging procedures for waveforms, and in the operating theatre, SSEPs are usually accompanied by noise [10], [11].

During the past decade, Transcranial electrical Motor-Evoked Potential (TceMEP) monitoring has been proved capable of providing information about the integrity of the motor pathways that may not be shown by SSEP monitoring. Successful intraoperative use of TceMEP has been reported in several studies [12]-[17]. During surgery, TceMEPs are elicited by transcranial electrical stimulation of the motor cortex. The induced waves travel the corticospinal tract fibers and through the alpha motor neurons, the peripheral nerve axons. The resulting electromyographic responses (myogenic TceMEPs) are recorded at peripheral muscles, which are innervated by the spinal roots located below and at the level of the surgery. Various limb muscles can be used simultaneously for recording.

The sensitivity of myogenic TceMEPs to spinal cord manipulation during surgery suggests that postoperative neurological deficits may be predicted by the results of intraoperative monitoring. However response criteria that should warn the surgeon of impending neurologic damage

Manuscript received June 30, 2006.

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similar to those available for SSEPs (decrease in amplitude of 50% and an increase of latency of 10% [18]), have not been defined. Some centers have adopted an′′all or none′′ MEP response criterion [12], [19], [20]. Unfortunately, by the time the MEP response is no longer evocable, irreversible neurological compromise may have already occurred [21]. To date, explicit quantitative criteria for interpretation of results of muscle-recorded TceMEP monitoring have not yet been established. For this reason, several studies have been performed in order to define parameters that could provide quantitative information about the impending neurologic damage. These studies were mainly focused on 1) amplitude criteria [16], 2) changes in the morphology and duration of the distal muscle-MEP waveforms [22], 3) measurement of the minimum stimulus energy needed to elicit MEP responses [23] and 4) latency response criteria and waveform disturbances [24].

The purpose of this study is the time-frequency analysis of the myogenic motor evoked potentials (mMEPs) at the decompression stage of spinal stenosis (stage at which spinal cord or cauda equina are mechanically irritated/compressed, impending neurologic damage) and to examine the changes of the mMEP waveforms by using an adaptive approximation method based on the Matching Pursuit (MP) algorithm.

II. METHODOLOGY

A. Data Collection

Data were collected from 6 patients undergoing spinal cord decompression surgery. Two data sets of mMEP waveforms were studied. The first dataset consisted of 18 mMEPs during the decompression stage (3 per patient on the side of the mechanical irritation), and the second one consisted of 12 waveforms (2 per patient of the same side) after the decompression stage (post-decompression stage). For each patient a baseline (reference) mMEP waveform was retrieved before the beginning of the decompression. Both anaesthetic regime and systemic factors were unchanged during the two stages of the surgery. No muscle relaxants were given after induction and intubation, because these would influence the muscle responses.

After the surgery none of the patients had postoperative neurological impairment.

B. TceMEP monitoring

Multipulse transcranial electrical stimulation was produced by a constant-voltage stimulator (Axon Systems, Inc). Stimuli were delivered via two needle electrodes inserted subcutaneously at standardized 10 to 20 electrode position of C3 and C4 (position overlying the primary motor cortex). Trains of 7 pulses 500 μs in duration were delivered with a voltage range of 150 ± 50 volts and an inerstimulus interval of 2msec. These parameters kept constant throughout the two surgery stages. Evoked electromyographic activity was recorded using intramuscular needle electrodes placed 2-4 cm apart in the abductor hallucis muscles bilaterally. Recording and filtering parameters were typically 100 to 1000 Hz, amplified to 50 - 500 μV per division, at a time base of 100 msec. Frequency sampling was 10 KHz.

C. Matching Pursuit Algorithm

A nonstationary signal can be expanded into waveforms (called atoms) whose time-frequency properties can be adapted to its local structures. These waveforms are contained into a complete redundant dictionary. A general family of time-frequency atoms can be generated by scaling, translating and modulating a single window function $g(t)$ [25],[26]. For any scale $s > 0$, frequency modulation ω and translation u, we denote $\gamma = (s, u, \omega)$ and define the atom as:

$$g_\gamma(t) = \frac{1}{\sqrt{s}} g\left(\frac{t-u}{s}\right) e^{i\omega t} \qquad (1)$$

The factor $1/\sqrt{s}$ normalizes to 1 the norm of $g_\gamma(t)$. The window function $g(t)$ is usually even and its energy is mostly concentrated in a neighborhood of u, whose size is proportional to s. In frequency domain, the energy is mostly concentrated around ω with a spread proportional to $1/s$. The minimum of the time-frequency variance is obtained when $g(t)$ is Gaussian (Gabor atom). The dictionaries of windowed Fourier transform and wavelet transform can be derived as subsets of this dictionary, defined by certain restrictions on the choice of parameters. In the case of the windowed Fourier transform, the scale s is constant – equal to the window length – and the parameters ω and u are uniformly sampled. In the case of the wavelet transform, the frequency modulation is limited by the restriction on the frequency parameter $\omega = \omega_0/s$, ω_0 = constant. Thus, the Gabor atom used in the matching pursuit method is more flexible in that its scale, location and internal frequency may all be varied independently.

In order to decompose a signal $x(t)$ into a set of atoms which can best describe the time-frequency structure of the signal, an iterative orthogonal projection of $x(t)$ onto the dictionary is necessary. In the first step of the iterative procedure we choose the vector $g_{\gamma 0}(t)$ which gives the largest product with the signal $x(t)$:

$$x(t) = \langle x(t), g_{\gamma 0}(t) \rangle g_{\gamma 0}(t) + R^1 x(t) \qquad (2)$$

where the first term in the right-hand side of the above equation is the projection of $x(t)$ onto the atom $g_{\gamma 0}(t)$ and the second term $R^1 x(t)$ is the residual vector after approximating $x(t)$ in the direction of $g_{\gamma 0}(t)$. After this first step, the iterative procedure is repeated on the following obtained residues:

$$R^i x(t) = \langle R^i x(t), g_{\gamma i}(t) \rangle g_{\gamma i}(t) + R^{i+1} x(t) \qquad (3)$$

In this way the signal $x(t)$ is decomposed into a sum of time-frequency atoms chosen to match optimally the signal's residues, and if this procedure is repeated until the signal is decomposed into m components, $x(t)$ is represented as:

$$x(t) = \sum_{i=0}^{m-1} \left\langle R^i x(t), g_{\gamma i}(t) \right\rangle g_{\gamma i}(t) + R^m x(t) \qquad (4)$$

and its energy is given by:

$$\|x(t)\|^2 = \sum_{i=0}^{m-1} \left| \left\langle R^i x(t), g_{\gamma i}(t) \right\rangle \right|^2 + \left\| R^m x(t) \right\|^2 \qquad (5)$$

where $R^i x(t)$ is the signal residue for the ith iteration and $R^0 x(t)=x(t)$.

It can be shown [25] that as m → ∞, the signal can be represented as an infinite series of time-frequency atoms from the dictionary without any distortion:

$$x(t) = \sum_{i=0}^{\infty} \left\langle R^i x(t), g_{\gamma i}(t) \right\rangle g_{\gamma i}(t)$$

$$\lim_{m \to \infty} R^m x(t) = 0 \qquad (6)$$

and the energy of the signal is:

$$\|x(t)\|^2 = \sum_{i=0}^{\infty} \left| \left\langle R^i x(t), g_{\gamma i}(t) \right\rangle \right|^2 \qquad (7)$$

Although this decomposition is nonlinear, we have energy conservation as if it was a linear orthogonal decomposition. The matching pursuit method finds the time-frequency atoms in a decreasing energy order and the higher energy components of the signal are always extracted first. These higher energy components are regarded as the coherent part of the signal due to the similarity between their waveforms and the signal.

To illustrate decomposition into time-frequency atoms, we compute its energy density defined by:

$$\varepsilon_{MP}(t,\omega) = \sum_{i=0}^{m-1} \left| \left\langle R^i x(t), g_{\gamma i}(t) \right\rangle \right|^2 W g_{\gamma i}(t,\omega) \qquad (8)$$

where $Wg_{\gamma i}$ is the Wigner distribution of atom $g_{\gamma i}(t,\omega)$.

III. DATA PROCESSING

In order to get a decomposition of the mMEP waveforms with real expansion coefficients and real residuals, real-only atoms are used of the form:

$$g_{\gamma i}(t) = K_i \frac{2^{1/4}}{\sqrt{s_i}} e^{-\pi[(t-u_i)/s_i]^2} \cos(\omega_i t + \phi_i) \qquad (9)$$

where s_i and u_i are the scale and location factors for the Gaussian envelope, ω_i and φ_i are respectively the frequency and phase of the real sinusoid within the Gaussian envelope and K_i is a normalization factor used to maintain unit energy for $g_{\gamma i}(t)$. We used a dictionary composed of discrete Gabor functions supplemented with canonical basis of discrete Dirac functions and discrete Fourier basis. In this case we denote $\gamma=(s,u,2\pi k/N)$, where N is the number of the samples of the signal, u and k are integers between 0 and N and $\varphi \in [0,2\pi]$. In order to reduce the computation, the scale s is also limited to an exponential relation $s = 2^j$ where j is the octave of the scale s which varies between zero and $\log_2 N$. Therefore, the signal duration was always zero-padded to a power of two in our case, resulting to 1024 signal points. The number of the atoms that has been taken into account in order to decompose each waveform was $m_{0.95}$:

$$0.95 \le \sum_{i=0}^{m_{0.95}-1} \frac{\|c_i\|^2}{\|x\|^2} \quad \text{and} \quad 0.95 > \sum_{i=0}^{m_{0.95}-2} \frac{\|c_i\|^2}{\|x\|^2} \qquad (10)$$

where $c_i = \langle R^i x, g_{\gamma i} \rangle$ and the square of c_i represents the part of the signal energy associated with atom $g_{\gamma i}$. Each mMEP waveform was decomposed by $m_{0.95}$ atoms, explained 95% of the signal energy. This number is not necessarily the same for the waveform, since it depends on the amount of information contained in the signal and the coherence with the chosen dictionary.

The Last Wave software package [27] was used for applying the MP algorithm.

The parameters of main interest were the energy and the weighted latency (in order to evaluate the shift of the waveforms) of the decomposed mMEPs. The energy (E_{MP}) was determined as the summation of the square of the c_i coefficients:

$$E_{MP} = \sum_{i=0}^{m_{0.95}-1} \|c_i\|^2 \qquad (11)$$

and the weighted latency (wL_{MP}) as:

$$wL_{MP} = \sum_{i=0}^{m_{0.95}-1} w_i * u_i \qquad (12)$$

where $w_i = \|c_i\|^2 / E_{MP}$ and u_i the time location of each atom.

For each mMEP we calculated the percentage of the difference of the above parameters in relation to the corresponding baseline waveforms for each patient.

IV. RESULTS

In order to evaluate the difference between the two datasets (decompression vs post-decompression stage), we used the Students' t-test. As a criterion of significance, the 95% confidence level ($p < 0.05$) was chosen. For each dataset we estimated the mean value and the standard error

(S.E.).

The examples of results of the decomposition of individual mMEP by means of MP are shown in the form of energy distributions in time-frequency (t-f) space in figure 1 for a patient during the decompression and the post-decompression stage of the surgery respectively. This figure serves as an illustration of the main trends of the mMEP changes during the two stages. One can observe the decrease of the response and the shift in latencies during the decompression. After the decompression procedure these parameters almost converged to the values of the baseline mMEP waveform.

The quantification of the described behavior of the mMEPs is given in table I. During the decompression stage the mean value of the decrease of the energy E_{MP} is 57% and the weighted latency is increased by 12%, in relation to the individual baseline waveforms. This means that not only the response of the muscles is reduced, but also the conduction time (time between the transcranial stimulus and the muscle response) is increased, due to the irritation of the neuronal structures of the spinal canal. The corresponding values for the post-compression stage are 4% and 3% respectively, indicating that mMEPs converged to the baseline waveform of each patient after the decompression stage, since none of the patients had a postoperatively neurological impairment.

V. DISCUSSION

Transcranial motor evoked potentials are used increasingly for intraoperative neuromonitoring during spinal surgery. In contrast to SSEP, this technique monitors the more vulnerable and clinically more relevant motor pathways, and averaging procedures are not required. However, monitoring guidelines are available only for SSEP. A decrease in amplitude of 50% and an increased latency of more than 10% is considered a warning criterion. For TceMEP, the threshold values that warn of imminent neurologic damage have not yet been established. Methodologically, it is difficult to determine warning criteria because it is ethically unacceptable to ignore neuromonitoring outcomes while waiting for postoperative evaluation to determine whether these signal changes were indeed true-positives or false-positives.

In our study we applied the time-frequency analysis of the myogenic motor evoked potentials in order to examine other parameters than those that are usually and conventionally used.

The analysis was based on the MP method which exhibits high time-frequency resolution, provides time-frequency representations of the signal's energy without cross-terms and gives a priori the exact values of time and frequency centers, widths, amplitudes and phases of the components of the analyzed signal [28], [29].

Our data demonstrate that when spinal cord or cauda equina (depending on the level of stenosis) are mechanically compressed, the mMEPs of the distal limb muscles show a decrease of the energy of above 50% and an increase of the conduction time above 10%.

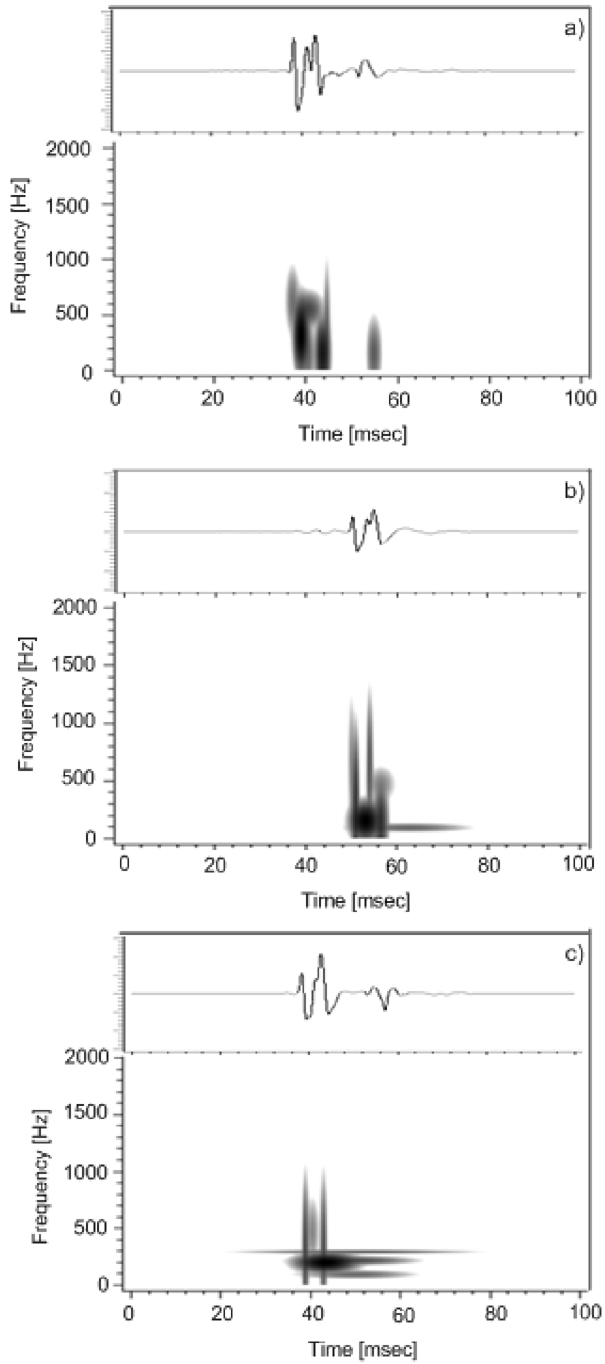

Fig. 1. The examples of energy distributions in time-frequency of mMEPs for a patient undergoing spinal cord decompression surgery a) baseline mMEP waveform, b) mMEP waveform during the decompression stage and c) during the post-decompression stage.

Of course the exact value of these changes depends on the intensity of the compression, and this kind of relationship, definitely could not be evaluated in our study, since it was impossible to measure the compression intensity during the

TABLE I
STATISTICAL ANALYSIS OF THE ESTIMATED PERCENTAGE OF DIFFERENCES BETWEEN THE DECOMPRESSION AND POST-DECOMPRESSION STAGE . GROUP MEAN VALUES AND STANDARD ERRORS ARE GIVEN

	Decompression (%)	Post-decompression (%)	p-value
E_{MP}	57 ± 15	4 ± 12	0.01
wL_{MP}	12 ± 2	3 ± 1	0.006

surgical procedure.

Comparing the standard errors of the two parameters, it is obvious that the energy E_{MP} showed a greater within-patient variability compared to the weighted latency wL_{MP}, making perhaps the latter a more reliable and adequate parameter.

Since the current study population is small, it is not possible to declare that these values of the estimated parameters E_{MP} and wL_{MP} could be used as the warning criteria of impending neurologic damage. However it appears that the time-frequency analysis based on the MP gives an alternative method of evaluating the mMEPs during surgical procedures, and provides a new kind of neurophysiological markers that could be used in order to evaluate the neuronal functional integrity.

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