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Spinal cord integrity monitoring by adaptive coherence measurement

D.L. Sherman[a,*], V. Wuyyuru[a], M. Jason Brooke[b], H.X. Zhang[a], J.P. Sepkuty[c], N.V. Thakor[b], A. Natarajan[a], A.H. All[b]

[a] *Infinite Biomedical Technologies, Baltimore, MD, United States*
[b] *Department of Biomedical Engineering, United States*
[c] *Seattle Neuroscience Institute at Swedish Medical Center, United States*

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ABSTRACT

Objective: Injury during routine spinal cord procedures could result in devastating consequences for the surgical patient. Spinal cord monitoring through somatosensory evoked potentials (SEPs) remains a viable method for prevention of serious injury.
Methods: The adaptive coherence estimation (ACE) is a method to iteratively calculate signal match quality through successive filter entrainment. Here we compare the speed of detection with ACE to conventional amplitude measurements. Both absolute magnitude of ACE and amplitude as well as slope change detector algorithm (Farley–Hinich) was run as well to determine the earliest time when a significant change occurred.
Results: The standard error for the ACE algorithm is close to one tenth of the amplitude measure, Since the ACE algorithm achieved low variance during baseline measurement, we were able to achieve rapid detection of injury. For absolute magnitude detection ACE was faster than amplitude for the 20 g injury weight class. It took an average of 10 epochs to detect the injury with adaptive coherence and nearly 19 with standard amplitude metrics using absolute magnitude changes. Abrupt change detection methods using slope change show that ACE provides more favorable detection capabilities comparable to amplitude. Additionally, there was a significant increase in the ROC curve between ACE and amplitude alone ($p < 0.05$).
Conclusions: Because of its excellent detection capabilities, the adaptive coherence method provides an excellent supplement to traditional amplitude for capturing injury-related changes in SEPs.
Significance: Adaptive coherence remains a viable method for rapidly and accurately detecting spinal injury.

1. Introduction

Intraoperative neuromonitoring applies to a variety of tests used during surgery to evaluate the nervous system (Minahan, 2002). In the case of spinal cord surgery, EP evaluation was first used in animal studies in 1972 and was applied to patients by McCallum and Bennett in 1975 (McCallum and Bennett, 1975; Croft et al., 1972). The primary goal was to serve as an early warning system for a compromise in the somatosensory pathways. Such injury could lead to sensory loss, or worse, to paraplegia. In the past 25 years, the benefits and goals of monitoring have evolved significantly. Now, surgeons look to monitoring for reassurance of the integrity of the spinal cord. Finally, patients and families can be assured that the surgery is not being done "blind" to the potential for paraplegia, and that precautions have been taken (Brown and Nash, 1988; Cracco and Bodis-Wollner, 1986; Grundy, 1983; McPherson, 1993; Nuwer, 1986).

Current intra-operative monitoring techniques measure only the EP signal latency and amplitude while ignoring the fact that the EP signal consists of polyphasic wave forms that reflect different activation and conduction velocities within the spinal cord and corresponding part of the nervous system. Apart from the EP latency and amplitude analysis, some research has utilized spectrum and adaptive analysis (like the adaptive Fourier Linear Combiner) to extract spinal cord injury information (Barros and Ohnishi, 1997; Riviere et al., 1997, 1998; Vaz and Thakor, 1989). Signal modeling has also been used in EP monitoring in order to augment the signal quality (Davila and Srebro, 2000).

Adaptive signal processing can also be an effective means of detecting spinal cord injury. It uses past signal information and constructs a stable filter to convert one signal to another. Because of its reliance on using the entire signal and past information, consistent estimates of signal integrity are maintained. In this study we propose to utilize the adaptive coherence estimator (ACE) to

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[*] Corresponding author. Tel.: +1 410 889 8011; fax: +1 410 889 8012.
E-mail address: dvdsherman@gmail.com (D.L. Sherman).

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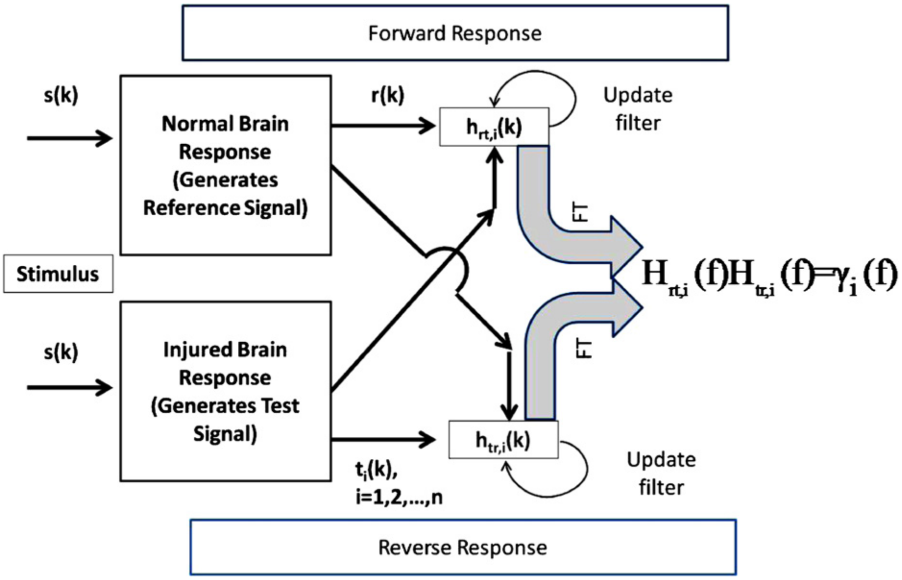

Fig. 1. is a schematic of the operations involved in calculation the coherence using forward and reverse transfer functions and filters. In many respects this is a template matching method that is largely frequency dependent. The top and bottom panel shows the forward and reverse frequency response estimation and update procedure, respectively. The reference and the test signals are used as input and output for the forward response, respectively. Filters are adapted at each time point using both signals. A signal estimate is generated at every time point and that estimate is subtracted from actual signal to provide the adjustment to the filter weights.

characterize the transfer function of the neurological system and construct valid relations between the calculation of the neurological system transform function and the physical event of the EP in an intraoperative neurological monitoring paradigm. Coherence is a key component derived from multi-channel spectral estimation. It examines consistency of the linear transfer function estimate between probable input and output signals. If we take the viewpoint of the seminal article by Cadzow and Solomon (Cadzow and Solomon, 1987), we see that the coherence function only measures how well linear modeling captures the relationship between the two time series. To quote these authors "A perfect bidirectional relationship linear association requires that each of the time series be related to one another by means of a time-invariant linear operation (not necessarily causal)." Coherence estimation in our context is a method of template matching between signals. We examine the coherence between a signal taken at the beginning of an experiment (or critical surgery) and a test case during the same surgery. A mismatch between signals from the injured state and the normal state causes a decrease in coherence between the signals. In this study we will examine the baseline variability with conventional signal averaging vs. adaptive signal coherence. Specifically, we will investigate the speed of detection and the pre-injury baseline variability when using the conventional average vs. using the ACE. Traditionally, conventional average amplitude is highly variable and can have a high number of false positives. To avoid this, a high threshold is used in determining signal change, i.e. $\geq$50% change of signal amplitude from pre-injury baseline. We will investigate if the low baseline variability can turned around into faster detection through ACE.

2. Methods

2.1. Adaptive Coherence Estimation (ACE)

The *Adaptive Coherence Estimate* measures the level of correlation between two different signals (Thakor et al., 1995). In the interpretation of coherence, it is suggested that the SEP response under normal conditions can be thought of as a linear system, where injury to the spinal cord results in non-linear changes in the output response (Fig. 1). The reference signal is created by stimulating the normal brain during the immediate pre-surgical period after anesthesia has been administered. Once surgery begins, subsequent realizations of the signal are considered test signals. Two filter responses are simultaneously created and iteratively adapted. The first response (forward response) convolves the reference signal to test signal. The reverse filter convolves the test signal to the reference signal. This essentially provides a measure of coherence between the reference and test signals. Under normal conditions the test and reference signals would match. Thus the corresponding relationship between two normal SEP filter responses would be linear, while the relationship of a normal response to an injured response would be non-linear. Given this model, the coherence function is able to provide an indication of non-linear changes in the SEP due to injury. The coherence function is found from multiplying complementary transfer functions as seen in Fig. 1. The basic idea is to use the coherence estimate to determine whether the association between control and diseased states are linear which the coherence function can imply. Coherence function values close to one imply a linear association, while values close to zero imply a deviation from a linear association between two time series (Cadzow and Solomon, 1987).

Here is the summary of the ACE algorithm: We start by comparing the *pre-surgery* reference signal, $r_i(k)$, (*vector form* $\mathbf{r}$) and primary test signals $t_i(k)$ ($t_{i,k}$, $i = 1, 2, \ldots, n$; $k = 1, \ldots, K$) are the i^{th} successive test signals and K is the number of time points within a single SEP signal. To begin with, these equations are developed in the time domain so that signals and their respective filters are updated iteratively in time. Observations of coherence are done completely in the frequency domain. This update is done once per individual SEP average. This process of comparing frequency responses is shown in Fig. 1.

Here are the iterative equations that define the transfer response between the reference and test signals. The frequency domain rendering of these transfer functions yields the coherence function.

a. Transfer function representation of one signal in terms of the other:

$$t_i(k) = h_{rt,i}(k) \times r_i(k)$$
$$\mathbf{t}_i = \mathbf{h}_{rt,i}^T \mathbf{r}_i$$