Proceedings of the 28th IEEE
EMBS Annual International Conference
New York City, USA, Aug 30-Sept 3, 2006

Detecting Controlled Signals in the Human Brain by Near Infrared Spectroscopy

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***Abstract*—We present here results from a preliminary trial of brain activation data collection by near infrared spectroscopy (NIRS). Light in the NIR region was incident upon the human motor cortex in anticipation of observing a detectable change during periods of motor activation with respect to periods of rest. Frequency domain near infrared spectroscopy (NIRS) was used to obtain the amplitude (AC) and intensity (DC) of the NIR signal after it passed through the brain tissue. Analysis of the DC component indicates that the absorptive properties of the tissue are altered during periods of activation. Spectral estimation reveals some frequency components in both amplitude and intensity signals that may serve to discriminate between the periods of activation and the periods of rest. These characteristic differences may be harnessed to control a brain computer interface (BCI).**

I. Introduction

NIRS is a monitoring and imaging technique that allows for the detection of changes in biological tissue. Common applications of NIRS include monitoring the neonate brain for complications and brain injury [1], [2]; constructing topographic brain maps [3], [4]; determining the level of regional oxygenation and deoxygenation in the hemoglobin [5], [6]; and studying the brain's physiological function [7], [8], and [9]. A few research groups have begun to recognize its potential as an alternative to the conventional electroencephalography (EEG) brain computer interface (BCI) [10], [11]. The appeal of NIRS in this application is that, while, for the user to generate signals detectable by EEG, training and focused effort are required [12], the brain activity signals detected by NIRS may be controlled by a more natural and intuitive means. It has been demonstrated that NIRS detects two types of brain responses: a slow (or hemodynamic) signal resulting from the changes in the levels of oxygenated and deoxygenated hemoglobin [5], [6], and [7], and a fast signal suspected to be a result of structural changes of the neurons [13], [14]. This fast signal has a response time of approximately 300 ms [13], [14] and, due to its low magnitude, is difficult to detect. Whereas, the hemodynamic signal has a response time between 5 and 8 s and its magnitude is larger than that of the fast signal [13]. Bearing this in mind, we have investigated the slowly evolving hemodynamic signal in the brain as a result of a finger-tapping task.

This work was supported in part by the Natural Sciences and Engineering Research Council, Canada and in part by the Canada Research Chairs Program.

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II. Experimental Procedure

A. NIRS System

We use a frequency domain NIRS instrument (Imagent, ISS Inc., Champaign, IL) to observe the changes in brain activation. Incident light, intensity modulated at a frequency of 110 MHz, was delivered to the head via eight (8) 400 μm-diameter optical fibres and collected by a 3 mm-diameter optical fibre. Four source pairs, each consisting of one 690 nm and one 830 nm wavelength source, were configured within the optical probe at distances 1.5, 2.0, 2.5, and 3.0 cm from the detector fibre, as per the multi-distance NIRS method. A multiplexer controlled the sequencing of sources 1 to 8, ensuring that no two sources were on simultaneously.

The instrument used Fast-Fourier-Transform (FFT) acquisition to measure the magnitude (DC), amplitude (AC) and phase (ϕ) of the transmitted light at its photomultiplier tube detector. Eight acquisition periods were used to construct the waveform in the FFT. The effective sampling rate for one complete sequence through the 8 sources was 2.003 Hz (data acquisition period of 0.4992 s).

B. Experimental Protocol

In the following procedure, the subject studied was a healthy, right-handed female, aged 22 years. She was seated comfortably throughout the trial. The experimental procedure was performed in a dimly lit environment so as to avoid noise introduced by the ambient light.

The optical probe was placed over the subject's right motor cortex on the side contralateral to the tapping hand. After a 30 s period during which the subject was encouraged to relax, the subject alternately performed finger tapping with all 4 fingers of the left hand for 30 s and subsequently rested for 30 s. The full recording procedure lasted approximately 5 minutes.

III. Results

Initial visual inspection of the AC and DC outputs indicate differences in the signal during the periods of tapping with respect to the periods of rest. The first of these differences

relates to the changes in the absorption of the brain tissue. The second is found in the frequency components of both the AC and the DC signal.

A. Changes in Absorption

Assuming that the scattering properties of the brain tissue remain relatively constant over the duration of the procedure and that the variations in the absorptive properties are not large, we base our calculation on the change in absorption coefficient ($\Delta\mu_a$) given by [15]:

$$\Delta\mu_a(t) = \frac{1}{rDPF}\ln\left(\frac{DC(0)}{DC(t)}\right), \quad (1)$$

where DC(0) is taken to be the average intensity over the first 30 s rest period, DC(t) is the intensity measured at time t, and r is the source-detector distance. The differential path length factor (DPF) was omitted in our calculations as this factor, most easily obtained from the literature, serves only to scale the result. The calculated change proportional to $\Delta\mu_a$ was averaged over the sources with a source detector distance less than 3.0 cm. Those measurements at 3.0 cm displayed little change which was likely due to the sources being too far from the detector. The result of these computations is graphed in Fig. 1, where the tapping periods are designated by darkly shaded bars.

We observe that for approximately the first 180 s of the trial, the tapping task causes an increase in the absorption, while when the subject is at rest, the value remains relatively constant. Over the last 120 s of the trial, the tapping task causes the absorption to remain constant while, when the subject is at rest, the absorption decreases.

B. Frequency Components

The second analysis that was performed resulted from the observation that fluctuation rate of the AC and DC signal components differed between the tapping and rest periods.

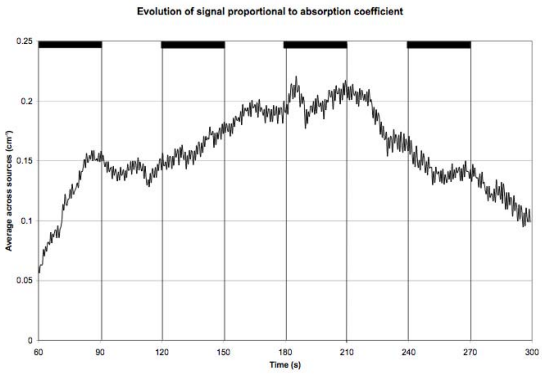

Fig. 1. Evolution of the term proportional to the absorption coefficient, $\Delta\mu_a$. indicating changes in the absorptive properties of the tissue. The dark bars at the top of the plot mark periods of tapping. The overall trends of the slopes for each interval are markedly different when comparing the tapping periods with the neighbouring rest periods.

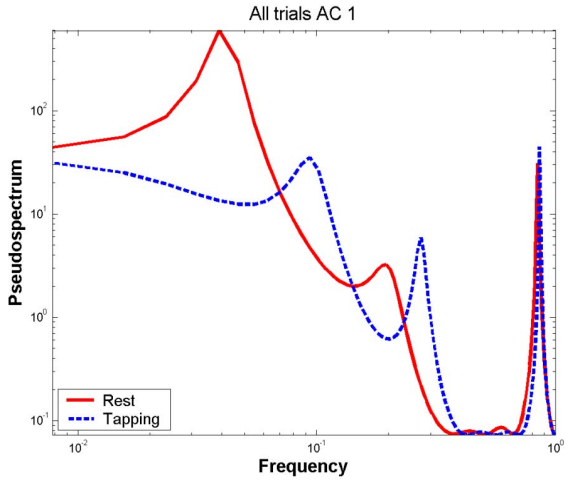

Fig. 2. Pseudospectrum of the frequency components of the AC (amplitude) signal for source 1 of 8. Peaks of the tapping signal and rest signal are located at distinct frequencies.

We assume that the critical data are contained in the higher frequency components of the signal; therefore, we perform a wavelet decomposition and set the approximation coefficients to zero, to remove the lower frequency trend. The justification here is demonstrated in the information revealed later on. Using a multiple signal classification (MUSIC) algorithm, we estimate the power spectral density of the rest and of the tapping signals for each of the 8 sources. We graph the resulting pseudospectrum for each of the sources independently. Graphs of the AC and the DC signal for source 1 are displayed here in Fig. 2 and Fig. 3 respectively.

It is apparent that there exist frequency components strictly attributable to tapping but absent during the rest period. Observation of the pseudospectra yields the possibility of a frequency shift of the tapping signal. The AC rest signal has peaks at approximate frequencies of 0.4 and 2 Hz. In contrast, the tapping signal has peaks at 1 and 3 Hz. Both display peaks around 8 Hz. Each of the DC rest signal and the

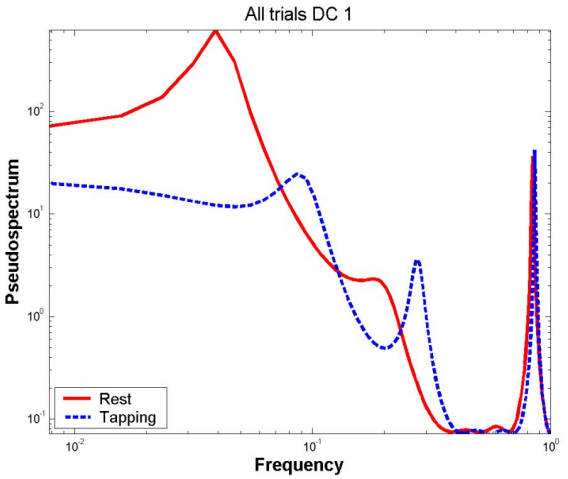

Fig. 3. Pseudospectrum of the frequency components of the DC (intensity) signal for source 1 of 8. Peaks of the tapping signal and rest signal are located at different frequencies.

tapping signal has peaks at or near the same locations as their AC counterpart.

IV. Discussion

Fig. 1 shows the evolution of the absorptive properties of the brain tissue during periods of tapping and periods of rest. We have observed that both periods exhibit varying trends between the first half of the trial and the second. There exist two potential explanations for this; a technical one and a physiological one. The technical one is an issue of proper coupling of the optical fibres to the subject's scalp. The presence of hair is an obstacle, as is maintaining a constant probe position throughout the trial without slipping. As the trial progresses, the signal degrades due to increasingly poor fibre-scalp contact. The physiological explanation is one of resource allocation and automaticity. Initially, the learning stage of the motor task is mentally demanding; however, with repetition, the subject becomes increasingly efficient in executing the motor task. Hence, automaticity takes over and she requires less mental activation to complete it as time progresses [16].

While the power spectral density (Figs 2 and 3) of the frequency components provide a definitive method of discriminating the tapping signal from the rest signal, its physiological source has yet to be determined.

The ability to discriminate between the tapping and rest signals that we have observed points toward NIRS as a promising method to harness inputs to a BCI.

V. Conclusion and Future Work

We have shown that it is possible to consciously control the signal detected by a frequency domain NIRS instrument. The signal produced by the subject did not require extensive user training rather it was a result of a highly natural motor task. The finger tapping either caused an increase, or prevented a decrease in the absorptive properties of the brain tissue as was evident in the analysis of the intensity of the signal. The pseudospectrum of the frequency components of the tapping and resting signal exhibits peaks at distinct frequencies for both AC and DC values. The peaks were near 0.4 and 2 Hz and near 1 and 3 Hz for the resting and tapping signals, respectively. The ability to differentiate the active signal produced consciously by in the brain by NIRS gives rise to its potential as a promising alternative to the conventional EEG BCI.

Future technical considerations include the development of a reliable apparatus to couple the optical fibres to the subject's head over extended periods of recording. In addition, sampling at a higher frequency to capture the information that was missed at the low acquisition rate of 2 Hz is essential to further investigate and characterize the changes in the signal.

Secondly, increasing our knowledge of the physiological source for the observed changes will be beneficial to obtaining a more informative signal. We will investigate motor imagery as a signal in place of motor tasks such that those who experience constrained motor control, such as those with Locked-in Syndrome, may use this technology. Employing both imagined and actual motor tasks, further trials must be done with a greater number of subjects to verify the reliability and repeatability of the results.

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