DETECTION OF CONSCIOUSLY CONTROLLED MOTOR CORTICAL ACTIVATION BY NEAR INFRARED SPECTROSCOPY (NIRS)

Jennifer Kohlenberg[1,2] & Tom Chau[1,2]
1 Institute of Biomaterials and Biomedical Engineering, University of Toronto, Toronto, ON, Canada
2 Bloorview Research Institute, Toronto, ON, Canada

ABSTRACT

Custom headgear was developed and fabricated for the purposes of detecting the hemodynamic response in the motor cortex of the human brain by near infrared spectroscopy (NIRS). We present here, results from this NIRS study. Light in the NIR region was incident upon the human motor cortex in anticipation of observing differences in the absorption curves for recordings of periodic motor activation with respect to periods of rest. Frequency domain NIRS was used to obtain the properties of the NIR signal after the light waves had traversed the brain tissue. Analysis of the intensity of the signal reveals that the absorptive properties of the tissue are altered during periods of activation. Ten neurologically healthy individuals each performed both a resting and a motor cortical activation task. We examined the shape of the average time domain curve for each of the two tasks and observe distinct differences; therefore, we anticipate that feature differences between these two curves will consistently discriminate between activation task and baseline responses. In particular, we examined the distribution of the peak-to-peak ranges, inter-peak times, the slopes of the average curves, and the magnitude of the extrema with respect to the mean value. These feature differences may be harnessed to discern a binary signal, thereby demonstrating the hemodynamic signal's potential as an access pathway enabling individuals with severe motor disability.

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]. Recently, several research groups have begun to recognize its potential as an alternative to the conventional electroencephalography (EEG) brain computer interface (BCI) [10], [11], whereby signals from the brain are harnessed to control external devices such as communication aids or a computer mouse. 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 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 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.

EXPERIMENTAL PROCEDURE

NIRS System

We use a frequency domain NIRS instrument (Imagent, ISS Inc., Champaign, IL) to observe the changes in brain activation resulting from the execution of a motor task. Incident light, intensity modulated at a frequency of 110 MHz, was delivered to the head via eight 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 custom designed headgear along the circumference of a 4 cm - diameter circle surrounding the optical detector. 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 62.5 Hz (data acquisition period of 0.016 s).

Experimental Protocol

The study was approved by both the Bloorview Research Institute Research Ethics Board and the University of Toronto Research Ethics Board. All participants gave informed consent. Ten neurologically healthy individuals (7 female) over the age of 19 without a history of diabetes or epilepsy participated. Each participant 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 left motor cortex on the side contralateral to the tapping hand as depicted in Figure 1. The correct region of interest was determined by locating C3 as referred to by the International 10-20 system, which is the convention for electroencephalogram (EEG) [15]. Participants performed two tasks, each consisting of five trials. The first was a baseline recording during which the individuals refrained from outward movement as well as thinking about moving. The second was a tapping task. The participants alternately performed periods of finger tapping and resting. Finger tapping involved repetitive contact between a finger (or fingers) of the right hand with the thumb of the same hand. The tapping frequency was self-paced. The experimenter verbally directed the commencement and cessation of tapping. Tapping periods were selected at randomized time intervals ranging from 5 s to 30 s, all separated by more than 20 s of rest. Each trial lasted for 200 s.

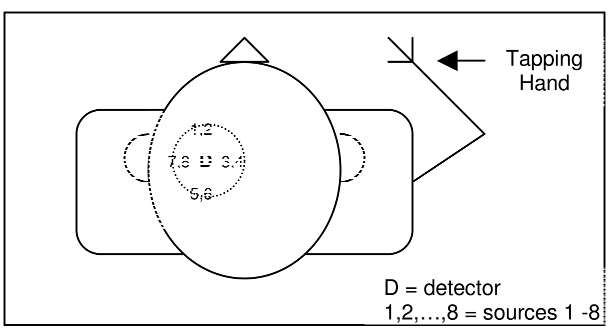

Figure 1: Optical probe positioning scheme viewed in the transverse plane. The eight sources are positioned on the circumference of a 4 cm - diameter circle surrounding the detector, D. The probe is centred over the left motor cortex, contralateral to the tapping hand.

ANALYSIS

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:

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

where DC(0) is taken to be the average intensity over all 5 trials of rest, DC(*t*) is the intensity measured at time *t*, and r is the source-detector distance [16]. 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.

Firstly, as we were looking to detect the slowly evolving hemodynamic signal, the high frequency noise was eliminated from the raw DC data for each of the 8 sources for 10 trials. This was done using Daubechies wavelet filters [17],[18], keeping only the average and first detail signal of a maximum of 10 levels of decomposition. For each trial, the curves for the 8 sources were averaged, resulting in five trial-averaged signals for each of the baseline and the periodic motor activation task. Curve registration was then performed on the five trial-averaged signals in order to align the hemodynamic features. Lastly, the overall average curve was computed for the two respective tasks, resulting in one average baseline and one average periodic motor activation curve for each of the 10 participants. We then calculated the relative absorption based on equation (1) and removed the linear trend from the signal by detrending the data.

We then computed the peak-to-peak ranges, inter-peak times, the slopes between consecutive extrema, and the magnitude of the extrema with respect to the mean value for the two curves for each subject. Finally, we amalgamated the data for all subjects and performed three tests to determine if there existed a statistically significant difference between the distributions of the features for each of the two tasks. The tests used were the Kolmogorov-Smirnov test, the non-parametric ranksum test and the Fisz-Cramer-von Mises test.

RESULTS

Examination of the plots for each of the 10 subjects reveals clear differences between the relative absorption curves for the two tasks. We observe distinct peaks following the periods of finger tapping for the task involving alternating between motor activation and rest; however, the peaks in the baseline curves do not follow the same regular pattern. The plots of the curve during which the participant alternated between tapping and rest and the baseline curve follow below in Figures 2 and 3 respectively.

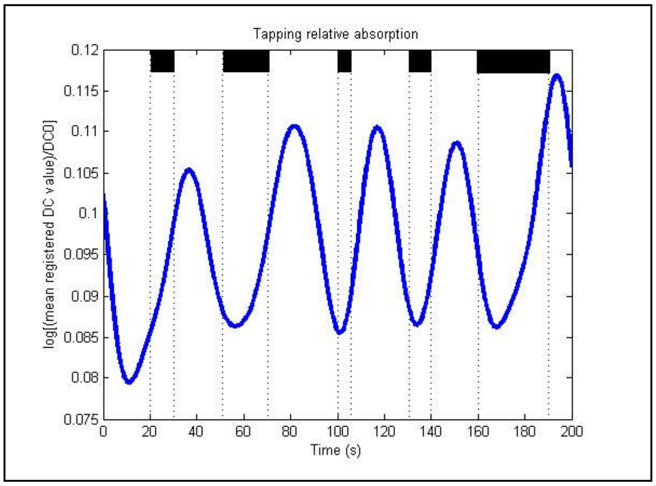

Figure 3: Motor activation relative absorption curve for subject A1. The periods of finger tapping are marked by the solid black bars along the top of the figure.

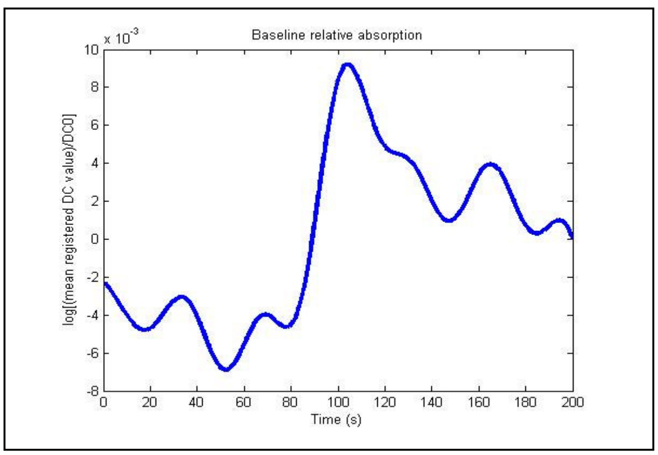

Figure 2: Baseline curve for subject A1

For some participants, peaks in motor cortical activity do not exist for each of the five periods of tapping. However, visual comparison with the baseline curve for the same subject (plots not shown) reveals that marked differences exist, even in the case where individual tapping periods are not distinct in the motor activation relative absorption curve.

Following the generation of these averaged curves, we computed the peak-to-peak ranges, inter-peak times, slopes between consecutive extrema, and the magnitude of the extrema with respect to the mean. Table 1 below displays the mean and variance of these four features for each task. We observe large differences in the mean values between the resting and tapping tasks for the peak-to-peak ranges and the slopes. While the differences in the mean inter-peak times are minimal, the variance of the resting task is more than four times that of the tapping task. Neither the mean nor the variance of the extrema magnitudes appear to distinguish between the two tasks.

Table 1: Resulting p-values from statistical test of different distributions between motor activation and the baseline curves

	p-value		
	K-S test	**F-C-v M test**	**Ranksum test**
Peak-to-peak ranges	***0.01***	0.55	***0.05***
Interpeak times	***0.01***	0.61	0.23
Slopes	0.17	0.53	0.32
Extrema magnitudes	***0.001***	0.60	***0.004***

DISCUSSION

We observe that for the majority of the 10 participants, differences between the baseline curve and the curve showing alternating between tapping and rest are visually apparent. As the finger tapping stimulus was executed at randomized periods, we attribute the peaks to the brain's hemodynamic response to the task rather than to any other physiological source.

We do observe instances where the number of peaks in the motor activation task's relative absorption curve does not correspond to the number of periods of finger tapping. The potential explanation for this is that the length of time required to recover from executing the task may be greater for some individuals. However, once an individual becomes accustomed to the task, the recovery period decreases. This may be what we observe in the relative absorption curve for some subjects.

Perfomance of three tests for statistically significant distributions reveal differences between the two tasks. There exists potential to use these features to discriminate between resting and a motor task. In particular, the peak-to-peak ranges and of the magnitude of the extrema with respect to the mean value demonstrate signifact differences when either a K-S test or a ranksum test are used. P-values there were 0.01 and 0.05, and 0.001 and 0.004 respectively.

The distributions of the interpeak times have also been shown to be different when a K-S test in employed, yielding a p-value of 0.01. The slopes between consecutive extrema did not demonstrate significant differences in inter-task distributions.

We have demonstrated the ability to discriminate between the relative absorption curves for a baseline, resting task and a periodic motor activation task by visual inspection. This leads to the conclusion that feature differences exist between these two curves that we can use to quantify the differences. In particular, we examined characteristics of the distribution of peak-to-peak ranges, inter-peak times, the slopes of a piecewise function approximating the curve, and the magnitude of the extrema with respect to the mean value. Our findings show that the differences between the distributions of the peak-to-peak ranges and of the magnitude of the extrema with respect to the mean reveal the task distinction. These feature differences may be harnessed discern an active signal from a rest signal; hence, demonstrating the hemodynamic signal's potential as an access pathway enabling individuals with severe motor disability.

CONCLUSION AND FUTURE WORK

We have shown that it is possible to detect consciously controlled motor cortical activity by frequency domain NIRS using visual inspection. The signal produced by the subject did not require extensive user training; rather it was a result of a highly natural motor task. Finger tapping caused an increase, in the absorptive properties of the brain tissue as was evident in the relative absorption curves for periodic motor activation. 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 work will include quantification of feature differences between the relative absorption curves for resting and periodic motor activation. Secondly, we will repeat this testing procedure in order to verify the reliability of the headgear apparatus. In addition, investigation of motor imagery as a signal in place of motor tasks such that those who experience constrained motor control, such as those with sever motor disability may use this technology.

REFERENCES

[1] A. Bozkurt, A. Rosen, H. Rosen, and B. Onaral. "A portable near infrared spectroscopy system for bedside monitoring of newborn brain," *BioMedical Engineering OnLine*, vol. 4, April 2005.

[2] K. Isobe, T. Kusaka, Y. Fujikawa, M. Kondo, K. Kawada, S. Yasuda, S. Itoh, K. Hirao, and S. Onishi. "Changes in cerebral hemoglobin concentration and oxygen saturation immediately after birth in the human neonate using full-spectrum near infrared spectroscopy," *J. Biomed Optics*, vol. 5, pp. 283-286, July 2000.

[3] I. Nissila, K. Kotilahti, T. Noponen, M. Huotilainen, R. Naatanen, and T Katila. "Optical topographic studies of adults and neonates," in *Proc. SPIE Opt. Eng. Soc*. vol. 4955, 2003, pp. 134-144.

[4] T. Yamamoto, E. Okada, F. Kawaguchi, A. Maki, Y. Yamada, H. Koizumi. "Optical fiber arrangement of optical topography for spatial resolution improvement," in *Proc. SPIE Opt. Eng Soc*. vol 4955, 2003, pp. 487-496.

[5] D. Boas, G. Strangman, J. Culber, R. Hoge, G. Jasdzewski, R. Poldrack, B Rosen, and J. Mandeville. "Can the cerebral metabolic rate of oxygen be estimated with near infrared spectroscopy?" *Phys. Med. Bio.* vol 48, pp. 2405-2418, 2003.

[6] Y. Xie, K. Sakatani, W. Lichty, H. Zuo, Z. Xie, and J. Bai. "Near-infrared spectroscopy studies on cerebral blood oxygenation changes during brain activation: possible limitations of blood oxygenation level dependent functional magnetic resonance imaging," *Opt. Eng.*, vol 40, pp. 2302-2307, October 2001.

[7] A. Sassaroli, Y. Tong, B. Frederick, P. Renshaw, B Ehrenberg, and S. Fantini. "Studying brain function with concurrent near-infrared spectroscopy (NIRS) and functional magnetic resonance imaging (fMRI)," in *Proc SPIE Biomed. Opt. Imag.*, vol. 5693, 2005, pp. 161-165.

[8] Y. Tong, E. Rooney, P. Bergethon, J. Martin, A. Sassaroli, B. Ehrenberg, B. Toi, P. Aggarwal, N. Ambady, and S. Fantini. "Studying brain function with near-infrared spectroscopy concurrently with electroencephalography," in *Proc SPIE Biomed. Opt. Imag.*, vol 5693, 2005, pp. 444-449.

[9] V. Toronov, A. Webb, J Choi, M, Wolf, L. Safonova, U. Wolf, and E. Gratton. "Study of local cerebral hemodynamics by frequency-domain near-infrared spectroscopy and correlation with simultaneously acquired functional magnetic resonance imaging," *Optics Express*, vol 9, pp 417-427, October 2001.

[10] S. Coyle, T. Ward, C. Markham, and G. McDarby. "On the suitability of near-infrared (NIR) systems for next-generation brain-computer interfaces," *Physiol. Meas.*, vol 25, pp. 815-822, 2004.

[11] S. Ranganatha, Y. Hoshi, and C. Guan. "Near infrared spectroscopy based brain-computer interface," in *Proc. SPIE Exp. Mech*, vol. 5852, Bellingham, WA, 2005, pp. 434-442.

[12] J. Wolpaw, N. Birbaumer, D. McFarland, G. Pfurtscheller, and T. Baughan. "Brain-computer interfaces for communication and control," *Clin. Neurophysiol.*, vol 113, pp 767-791, 2002.

[13] M. Wolf, U. Wolf, J. Choi, R. Gupta, L. Safonova, L. Paunescu, A. Michalos, and E. Gratton. "Functional frequency domain near infrared spectroscopy detects fast neuronal signal in the motor cortex," *NeuroImage*, vol. 17, pp. 1868-1875, 2002.

[14] M. DeSoto, M. Fabiani, D. Geary, and G. Gratton. "When in doubt, do it both ways: brain evidence of the simultaneous activation of conflicting motor responses in a spatial stroop task," *J. Cognitive Neuroscience*, vol. 13, pp. 523-536, 2001.

[15] S. Fantini, D. Hueber, M. Franceschini, E. Gratton, W. Rosenfeld, P. Stubblefield, D. Maulik, and M. Stankovic. "Non-invasive optical monitoring of the newborn piglet brain using continuous-wave and frequency-domain spectroscopy," *Phys. Med. Bio.*, vol 44, pp. 1543-1563, 1999.

[16] H. Jasper, "Report of Committee on Methods of Chemical Examination in Electroencephalography," *Electroenceph. Clin. Neurophys.*, vol 10, pp. 370-375, 1958.

[17] Daubechies, I. "Ten lectures on wavelets," *CBMS-NSF conference series in applied mathematics. SIAM Ed*, 1992.

[18] Mallat, S. "A theory for multiresolution signal decomposition: the wavelet representation," *IEEE Pattern Anal. and Machine Intell.*, vol. 11, no. 7, pp. 674-693, 1989.