Spatiotemporal Analysis of Brain Activity Response Using Near Infrared Spectroscopy

Raul Fernandez Rojas and Xu Huang
University of Canberra, Canberra, Australia
Email: raul.fernandezrojas@canberra.edu.au, xu.huang@canberra.edu.au

Keng Liang Ou
College of Oral Medicine, Taipei Medical University, Taipei, Taiwan
Email: klou@tmu.edu.tw

***Abstract*—Near infrared spectroscopy (NIRS) is an optical imaging tool that provides cerebral hemodynamics in response to changes in neural activity. Analysis of hemodynamic response to evoked stimulation is a research topic that tries to understand the mechanism of stimulation perception. In that context, cross correlation and optical flow were used to identify spatiotemporal features of brain activity after acupuncture stimulation in NIRS data. The results presented bilateral activations in the primary somatosensory cortex which were consistent with similar studies. The time dependent cross correlation analysis exhibited dominant channels and delays among channels that can be seen as relationships between cortical areas. The optical flow computation showed the origin of cortical activity and the spatial distribution of the evoked response in the brain cortex. This study contributes to the research field to investigate hemodynamic response in the cerebral cortex after evoked stimulation using near infrared spectroscopy.**

***Index Terms*—hemodynamic response, evoked stimulation, fNIRS, optical flow, cortical activity**

I. Introduction

Near-infrared spectroscopy (NIRS) is a non-invasive optical imaging technique that can be used to measure changes in oxygen saturation and hemoglobin concentration in response to changes in neural activity. NIRS is a technology that permits the design of portable equipment, low cost, wearable imaging caps, and real-time processing; which makes NIRS ideal for different neuroscience applications [1]. For instance, functional NIRS (fNIRS) has been successfully applied in both research and medical settings to assess cerebral functioning such as tasks on motor skills [2], face processing [3], [4] and language development [5], [6] in infants, pain research [7], [8], brain-computer interfaces [9], or brain activity in active and resting states [10]. However, there are still some limitations in fNIRS applications that have prevented the technique to become more popular.

Manuscript received November 13, 2015; revised January 13, 2016.

The effective detection of cortical activity is a difficult task and diverse methods have been proposed. In the literature the detection of cortical activity has previously done through the study of cortical regions where the hemodynamic response is significant after a given task or stimulation. Some of these studies have made use of methods such as contrast-to-noise ratio (CNR) [11], probabilistic analysis [12], or principal component analysis (PCA) [6]. However, these studies not only give no evidence of the relationship between active and inactive regions after evoked stimulation but also about the transition of the cortical activity in time.

The objective of this study is to present the use of two algorithms to obtain spatiotemporal characteristics of brain activation in near infrared spectroscopy. The computer algorithms used in this research are the time dependent cross correlation and optical flow. Both algorithms showed specific features within the hemodynamic response after acupuncture stimulation. The relevance of this study is that it shows spatiotemporal features that can help to understand the activation patterns and origin of the brain activity after evoked stimulation. In the present work, we report the specific spatiotemporal features discovered after evoked activation in the cerebral cortex using near infrared spectroscopy (NIRS) by applying the cross correlation and optical flow algorithms.

II. Methods

A. Subjects and Signal Acquisition

Six healthy right-handed individuals (2 females, 4 males) participated in the experiments, aged 25 to 35 years old. Written consent was obtained from all participants prior to initiation of the experiments. Subjects with a history of a significant medical disorder, a current unstable medical condition or currently taking any medication, were excluded.

Data was obtained using the Hitachi ETG-4000 (Hitachi Medical Corporation) to investigate cerebral hemodynamics by NIRS. Since Oxy-hemoglobin (HbO) and Deoxy-hemoglobin (HbR) absorb NIR light differently, two wavelengths of light (695 and 830 nm)

doi: 10.18178/ijpmbs.5.1.1-6

are used, while total hemoglobin (HbT) is calculated as the difference between HbO and HbR. The sample frequency used in this experiment was of 10Hz. The configuration for this experiment was using two probes of 12 channels to measure neurologic activity and it is showed in Fig. 1. The area examined was the bilateral motor cortex area, as we expected to obtain hemodynamic response in the somatosensory cortex area (S1) [13], [14]. According to the international EEG 10-20 system [15], the probes were centered on the C3 and C4 position.

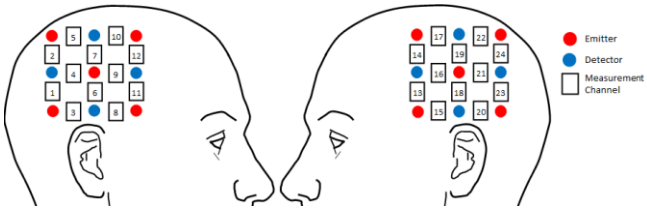

Figure 1. Location of the probes and the measurement channels. The measuring probes were placed on the C3 and C4 of the international 10-20 system; right hemisphere (channels 1-12) and left hemisphere (channels 13-24).

B. Experimental Procedure

The experiments were designed by the School of Oral Medicine of Taipei Medical University (TMU, Taiwan) in collaboration with the University Of Canberra (UC, Australia). The study and methods were carried out in accordance with the guidelines of the Declaration of Helsinki (DoH) and approved by full-board review process of the TMU-Joint Institutional Review Board under contract number 201307010. All experiments were carried out at TMU in a quiet, temperature (22-24^{o}) and humidity (40-50%) controlled laboratory room. The experiments were done in the morning (10:00am-12:00pm) and each experiment lasted around 30 minutes.

In order to obtain stimulation-related activation in the cerebral cortex, acupuncture was used to induce pain stimulation in a safe manner. Traditional Chinese acupuncture techniques were performed by an acupuncturist of TMU Hospital. Fig. 2 show the puncture point used for stimulation was the "Hegu Point", located on top of the hand, between the thumb and forefinger. This point was used because it is an area of easy access and the hand can be set aside while the patient is relaxed on the chair. The acupuncture procedure (Fig. 2) consisted of three types of acupuncture stimulations (tasks) [16]: the first stimulation is needle insertion (T1), the three following stimulations are needle twirl to increase Qi (T2), and the last stimulation is needle removal (T3). Pre-time and resting time (Rt) between acupuncture stimulations was 30 seconds, post-time was 10 seconds. The complete data set was used as primary source of our study.

C. Cross Correlation Analysis

Cross correlation is a mathematical method to measure the extent to which two signals are correlated. In other words, the cross correlation refers to the relationship between two signals, where one signal is shifted in time relative to the second signal. Cross correlation can provide evidence of a delayed response on one of the signals and the existence of a stimulus affecting (in time) both signals.

In our study, cross correlation is used to calculate the temporal similarity between channels and identify the dominant channels on both hemispheres. This time-dependent analysis provides evidence of the presence of regions where the cortical activity can be associated with increased localized cerebral blood flow. The cross correlation function was computed between channels 1-12 in the right probe and 13-24 in the left probe. This measure of temporal similarity of two signals can be done by computing a time-shifting along one of the input signals. The cross correlation between two waveforms *x(t)* and *y(t)* can be defined as

$$r_{xy}(\tau) = \sum_{-\infty}^{\infty} x(t)y(t-\tau)$$

Where τ is the time-lag between *x(t)* and *y(t)*, the value of Υ_{xy} denotes the difference (lag/lead) between channel signal *y(t)* and channel signal *x(t)*. The cross correlation value between two channels in the same probe is done after each stimulation from -40 sec to +40 sec at a rate of 10 samples per second.

For example, to find the dominant channel in the right hemisphere (Ch1-Ch12) we evaluate those channels with strong activations after noxious stimulation against the remaining channels in that particular hemisphere. Therefore, the channel with the fastest response is the dominant channel [16].

D. Optical Flow Analysis

In computer vision, optical flow is defined as the "flow" of pixel values at the image plane in time varying images. Optical flow is an algorithm that performs at pixel level and estimates local displacement or velocity between two temporally-consecutive images. Optical flow refers to the perceived motion of an object in a field of view by an image sensor or human eye. The mathematical theory behind optical flow is well-established and the interested reader is referred to read two texts in the subject (Horn and Schunck [17] and Robot Vision[18]).

Figure 2. Experimental setup. Left image shows a subject wearing the 24-channel probe. Right picture exhibits the "Hegu Point", position used for the acupuncture stimulation.

Optical flow algorithms have been applied in different fields with different purposes. For instance, applications in the medicine field to map tumor contours [19], or to measure the impact of organ motion during radiation delivery using computed tomography (CT) scans [20],

and to study cardiac motion in magnetic resonance (MR) images [21]; in neural engineering and neuroscience, it has been used in rehabilitation of persons with stroke [22] and sensory perception [23]. In our case, we applied an optical flow algorithm to evaluate the time and spatial relationship between channels; to the best of our knowledge this is the first study where OF is used as analysis method of activation of NIRS signals.

III. Results and Discussions

A. Preliminary Visual Analysis

As a preliminary signal analysis, we observed the responses of Oxyhemoglobin (HbO) in different channels on both hemispheres after the external stimulation. The purpose of this optical analysis was to look for significant activation areas and patters in the NIRS data. The analysis showed dominant areas where the concentration of HbO was higher and also showed propagation delays from more-active areas to less-active areas. Fig. 3 presents three images from subject 4 and subject 5 as examples; these subjects and hemispheres were selected for illustration purposes, all subjects presented similar activations. The images were taken every five seconds after acupuncture stimulation.

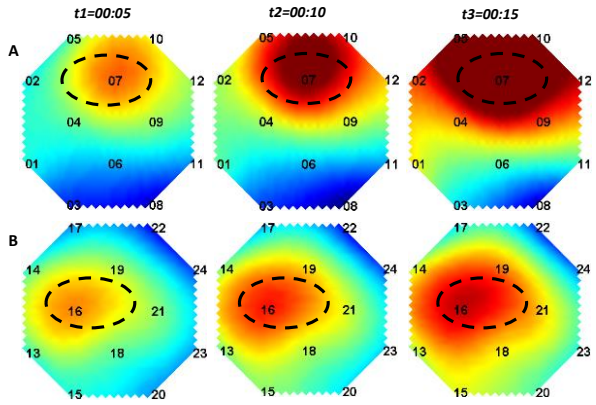

Figure 3. Activated areas existent in the NIRS data. A) Dominant region around Ch7 on right hemisphere in subject 4. B) Dominant region around Ch16 on left hemisphere in subject 5.

Firstly, these two examples showed the regions with higher activation after the stimulation. The NIRS data exhibited these areas in all subjects and on both hemispheres. These patterns reflect the activation area on the cerebral cortex. In our case, it was expected to obtain activation in functional areas where the cortical representation of pain is involved. We can see in Fig. 3, that the brain response increased around channel 7 (Ch7 in subject 4) on the right hemisphere and the area around channel 19 (Ch19 in subject 5) on the left hemisphere. These two areas are part of the postcentral gyrus in the parietal lobe. The postcentral gyrus is the location of the primary somatosensory cortex (s1), area that is involved with the perception and modulation of painful somatosensory sensations [24]. It is important to note that the cortical activity presented a bilateral S1 activation after the acupuncture stimulation. These results are consistent with other similar studies [24], [25]. Nevertheless, other experiments have reported that pain activation can also be detected in the secondary somatosensory cortex (S2), the anterior cingulate cortex (ACC), and the insular cortex (IC) [13], [26], [27]. These results proved the validity of our acupuncture stimulation to activate cortical areas linked with painful sensations.

Secondly, the visual analysis also showed a propagation effect in activated areas. For instance, in Fig. 3 we can we can see that at time *t1* the activation starts around Ch7, in the following sample at *t2*, the activation has increased and reached Ch5 and Ch10, while in the last sample *t3*, the activation has spread to Ch2, Ch4, Ch9, and Ch12. Similarly in samples taken from subject 5, the activation starts in a small region (Ch16) and spreads to other channels (Ch18, Ch19, and Ch21) after 10 seconds. These two examples exhibit the intensity of the activation area and the movement pattern through time.

B. Cross Correlation Analysis

Based on the hypothesis that there is a dominant area and a relationship among the channels, we decided to evaluate these ideas by computing the cross correlation between channels. Fig. 4 shows the results of two cross correlation comparisons of two channels, Ch7 and Ch16 on the right and the left cerebral hemispheres from subject 4 and subject 5 respectively.

This analysis helped us to identify the dominant channel in both cerebral hemispheres. The analysis was carried out by comparing potential dominant channels and surrounding channels. In Fig. 4, we can see that the cross correlation confirmed that the regions around Ch7 and Ch16 were the dominant channels. For instance, results from subject 4, showed that Ch7 was the channel with the fastest hemodynamic response after the stimulation. It was also found that Ch5, and Ch10 have no time delay (τ=0.0 sec) with Ch7, which suggests that these three channels are positioned over a region of interest due to the strong activation in this area after the stimulation. Similarly, results from subject 5 revealed that Ch16 was the fastest channel to be activated; while delays with Ch18 (τ=3.5 sec), Ch19 (τ=0.5 sec), and Ch21 (τ=1.7 sec) reflect a progressive movement to other cortical areas.

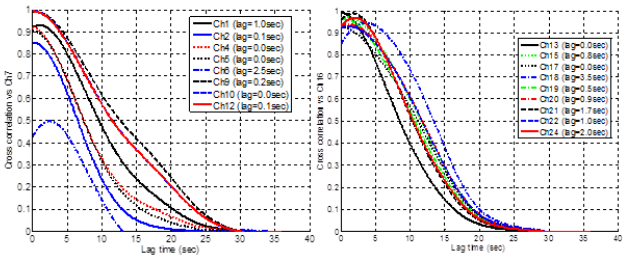

Figure 4. Cross correlation analysis of two dominant regions. A) Analysis between dominant channel Ch7 and surrounding channels; data from subject 4, right hemisphere. B) Results showing Ch16 as leading channel on left cerebral hemisphere for subject 5.

These results are in line with similar studies where cross correlation was used to evaluate lags/leads between

NIRS signals. For instance, Kurata *et al*. [28] used cross correlation to analyze the similarity between the reference and transmitted NIRS light in their experiments. Similarly, Sasai *et al*. [29] used cross correlation to investigate the regional signal relationship between NIRS and fMRI, where it was found that NIRS signals correlate with fMRI signals nor only within adjacent brain regions to NIRS channels but also with remote regions.

C. Optical Flow Analysis

After the computation of the optical flow algorithm, the origin of the activation area was more evident. Fig. 5 shows three examples of this feature, the examples show the OF results from two input frames (t1 and t2). The OF results displayed the origin of the cortical activity as the centre of the motion field vectors. For example, results from subject 4 presented the origin of the activated area in the brain cortex around Ch7; while for subject 5, the OF results displayed the origin of cortical activity around Ch16. This origin (or centre) of the motion filed vectors can be directly associated with the increase of localized cerebral flow in that particular area. Based on these results, we can tell that the OF results are in line with the visual and cross correlation analyses presenting dominant areas around Ch7 and Ch16 for subject 4 and subject 5 respectively. Therefore, by using the optical flow we can identify the dominant channel in that particular hemisphere.

The relevance of finding stimulation-related activation pattern in the data is that channels with low activation can be discarded. For instance, we can see in Fig. 5 that Ch1, Ch3, Ch6, Ch8, and Ch11 in subject 4 presented limited activation after the stimulation; therefore we can say that these channels could be dropped from the analysis. Equally in subject 5, Ch15, Ch17, Ch20, and Ch22-Ch24, present small reaction to the stimulation, and these channels could be excluded from further analysis. The advantage of discarding channels from the data is that it helps to reduce the complexity and time of analysis, and computational resources needed for further analysis.

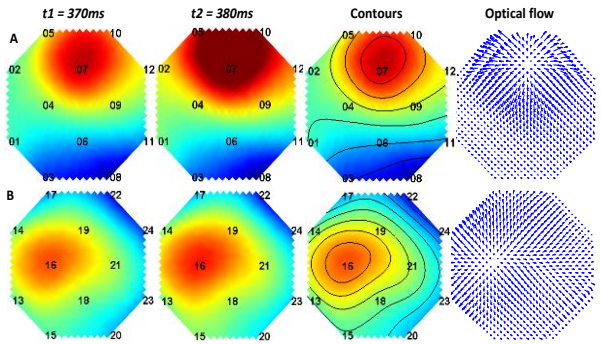

Figure 5. Optical flow results from three sample subjects A) subject 4 and B) subject 5. First two columns present the colour representation of images (at time t1 and t2) used to compute the optical flow. The images were recorded after the needle insertion (task 1), which presented the strongest evoked activation during the whole experiment. The third column shows the application of the contour tool in Matlab, this application exhibits the different activation levels and presents the dominant region as the "peak" of the activation levels. The last column presents the computation of the optical flow showing the stimulation-related activation area as the "flow" to outer channels.

Optical flow can also provide an indication of pattern activation areas in the brain cortex associated with the evoked stimulation. In Fig. 6, two examples of how optical flow predicts the progression of activated areas in time are presented. In the top panel of Fig. 6, two image frames (t1 and t2) show a constant increase (expansion) of cortical activity in the dominant region, while the weak regions shrink (dotted circle). This phenomenon is more evident using the motion vectors of the optical flow result. In Fig. 6A we can see the expansion (outer movement) of OF vectors from dominant channel Ch16 and the contraction (inner movement) of OF vectors to Ch18. However, the contraction to Ch18 is not evident in the coloured images (t1 and t2); but if we take another sample four seconds (t3) later, we can clearly see the contraction effect in Ch18. This behaviour is also observable in subject 6 (bottom panel, Fig. 6), we can see the expansion of region around Ch4 and contraction around Ch10 and Ch12. In this case, we have chosen region around Ch6 to show that in frames t1 and t2 the flow towards Ch9 is not very clear, but in a posterior frame four seconds later (t3) the increase in the concentration in Ch6 is much more evident; this can be clearly observed in the flow of motion vectors from Ch3, Ch4, and Ch8. Therefore, these results show that by using the optical flow field it could be possible to predict the direction of the cortical activity.

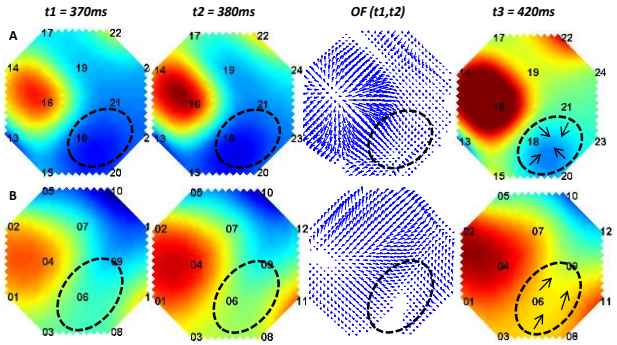

Figure 6. The use of optical flow for movement prediction of cortical activity. A) The top panel belongs to images taken on the left hemisphere (Ch13-Ch24) from subject 3. B) The bottom panel refers to frames taken on the right hemisphere (Ch1-Ch12) from subject 6.

IV. Conclusions

In this study, we present the use of cross correlation and optical flow algorithms to obtain spatiotemporal features of brain activity response after evoked stimulation in near infrared spectroscopy. We used visual analysis to identify activation areas and patterns, we then used two techniques for the analysis, time dependent cross correlation and optical flow. Firstly, the visual inspection showed cortical activity in the primary somatosensory cortex, which was expected because this area is linked with painful sensations. Secondly, the cross correlation exhibit the dominant channel in each cerebral hemisphere and delays between dominant channels and surrounding channels. The dominant channel was identified as the channel with the fastest hemodynamic

response after the acupuncture stimulation, while the delays between channels can be seen as the transition of strong activated areas to less active areas. Thirdly, the application of the optical flow algorithm displayed: the origin of cortical activity after the evoked stimulation, the spatial distribution of the activated region, and also predict the movement of activated areas in the brain cortex. Finally, the results showed the effectiveness of using the cross correlation and optical flow methods to obtain spatiotemporal features within functional NIRS data.

ACKNOWLEDGMENT

The authors wish to thank Meta Tech (AP) Inc.

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Raul Fernandez Rojas received his B. Eng. (Electronics) at the Universidad Tecnologica de la Mixteca, Mexico and his M. Eng. (Hons) at The Australian National University, Australia. Raul's research interests are robotics, computer vision, medical imaging, and signal processing.
He is currently pursuing a PhD degree in Information Sciences and Engineering at the University of Canberra, Australia.

Xu Huang received his B.E. and M.E. degrees and first Ph.D. in Electrical Engineering and Optical Engineering prior to 1989 and his second Ph.D. in Experimental Physics in the University of New South Wales, Australia in 1992. He has earned the Graduate Certificate in Higher Education in 2004 at the University of Canberra, Australia. Prof Xu's fields of research includes: cybersecurity, network security, Internet of Things (IoT), wireless and optical communications, cloud computing, digital signal processing, bio signal

processing, brain computer interface (BCI), intelligent system, and smart networks.

He has worked at the Australia National University from 1988 to 1990, the University of New South Wales from 1990 to 1995, also University of New England from 1995 to 2001. He is currently the Head of the Engineering at the Faculty of Information Sciences and Engineering, at the University of Canberra, Australia. He has been the Chair, Co-Chair, and TCM at various high quality International Conferences, and Editor for various high quality Journals. He has edited seven books, nine Book Chapters, 45 Journal Articles, and more than two hundred papers in high level of the IEEE and other international conferences (within ERA ranking); he has been awarded 17 patents in Australia in 2010 and 2013.

Prof. Huang has been a senior member of IEEE in Electronics and Computer Society since 1989, a Fellow in the Institute of Engineering Australian (FIEAust), Chartered Professional Engineering (CPEng), a Member of Australian Institute of Physics. He has been a member of Committee of the Institution of Engineering Australia at Canberra Branch for last 10 years.

Keng-Liang Ou graduated from the Mechanical Engineering Ph.D. program at the National Chiao Tung University, Taiwan. Professor Ou focuses his research on Biomaterials, Bioengineering, Biomedical Devices and Nanotechnology.

He went to Taipei Medical University to work on biomaterials research and development, and he is the current elected Dean of College of Oral Medicine in Taipei Medical University, Taiwan. He is also in charge of the Graduate Institute of Biomedical Materials and Tissue Engineering, Research Center for Biomedical Implants and Microsurgery Devices and Research Center for Biomedical Devices and Prototyping Production.

Professor Ou is the President of Institute of Plasma Engineering Taiwan, the leader of The Taiwan society for metal heat treatment and the Head Taiwan Oral Biomedical Engineering Association. He is the leader and organizer for the biomedical product design, production, manufacturing, testing, legalization and market planning, with supports from team of scientists and researchers with different expertise. Professor Ou has extensive collaborations with industry and has played a major role in developing medical devices for health service professions in the world. Professor Ou was honorably awarded with the 49th Ten Outstanding Young Persons of Taiwan on 2011.