Neurovascular Coupling and Cerebrovascular Reactivity Analysis through Near-Infrared Spectroscopy

A Thesis submitted in partial fulfilment of

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by

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DECLARATION BY THE RESEARCH SCHOLAR

I hereby declare that the entire work embodied in this Thesis is the result of investigations carried out by me in the School of Computing and Electrical Engineering, Indian Institute of Technology Mandi, under the supervision of Dr. Shubhajit Roy Chowdhury and that it has not been submitted elsewhere for any degree or diploma. In keeping with the general practice, due acknowledgements have been made wherever the work described is based on finding of other investigators.

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DECLARATION BY THE RESEARCH ADVISOR

I hereby certify that the entire work in this Thesis has been carried out by Yashika Arora under my supervision in the School of Computing & Electrical Engineering, Indian Institute of Technology Mandi, and that no part of it has been submitted elsewhere for any Degree or Diploma.

Signature:

Name of the Guide:

Date:

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ABSTRACT

Near-infrared spectroscopy (NIRS) is a portable non-invasive tool to analyze the organic composition of a sample by the application of near-infrared light. For instance, in a routine medical check-up, a small clip: pulse oximeter is placed on the index finger which employ NIRS technique to determine the oxygen in the blood. In brain imaging, NIRS detect the local hemodynamic response with reasonable spatial resolution, better temporal resolution and comfort compared to other brain imaging modalities like magnetic resonance imaging (MRI) and electroencephalogram (EEG). It is an optical imaging technique that is sensitive to light and skin optics parameters. The usage of optode (light emitter-detector pair) for detecting the NIRS signals to estimate the cerebral oxygenation levels is hindered considerably by surface roughness profile of skin, which necessitates the optodes to be positioned at certain angle with respect to the skin surface and not perpendicularly on the skin surface. In the present study, first an attempt has been made to optimize the placement of NIRS optodes in reflection photoplethysmographic sensor system by analyzing the roughness of surfaces of skin layers. Its implications on cerebral cortex imaging down the line have been presented to obtain accuracy in cerebral hemodynamic response.

The second part of the work focuses on cortical excitability through various electrode configurations of anodal transcranial direct current stimulation (tDCS). tDCS method involves application of weak direct current using non-invasive electrodes placed on the scalp. tDCS have shown to modulate both cortical neural activity and hemodynamics and is used in various neuro-rehabilitation strategies. However, the underlying mechanism of tDCS is not completely known and there is a huge inter-individual variedness in the responses to tDCS. This study evaluates the effect of various anodal tDCS designs with regard to electric field and voltage distribution using subject's specific anatomy in a computational framework. The study evaluates the effect of conventional and high definition transcranial direct current stimulation (HD-tDCS) by utilizing synthetic magnetic resonance image volumes for normal and lesioned brain.

The study next focuses on the application of NIRS to analyze the correlation between cerebrovascular reactivity (CVR) and neurovascular coupling (NVC). Cerebrovascular reactivity represents the responsiveness of cerebral blood vessels to vasoactive stimuli.

And, neurovascular coupling is a phenomenon through which neuronal activity elicits a local change in cerebral blood flow (CBF). This leads to the notion of neurovascular unit (NVU) consisting of the vascular smooth muscle, perivascular space, synaptic space and, astrocyte glial cell. Several neural disorders are associated with impaired NVC. The study postulates a correlation between neurovascular coupling and cerebrovascular reactivity under the effect of tDCS based on experimental NIRS data. The study presents a computational model to evaluate vessel volume response under anodal transcranial direct current stimulation considering a basic system of neurovascular unit. The proposed model based on neurovascular dynamics tracked vascular response elicited through neuronal activity via various signaling pathways during anodal tDCS. It was found that the stimulation can perturb the vessel response via both neuronal and non-neuronal pathways. The proposed model specifies the signaling pathways in a compartment model of neurovascular unit with respect to evoked hemodynamic responses in a computational framework which is otherwise extremely difficult to examine in wet lab environment. The computational modeling of neurovascular coupling and cerebrovascular reactivity measured through NIRS will possibly enable the understanding of underlying dynamics of non-invasive current stimulation.

PREFACE

Material presented in Chapters of this thesis have been either published or intended for publication in international, peer-reviewed journals and international conference proceedings.

Chapter 1:

S. Roy Chowdhury, G. Sharma, **Y. Arora**, "Cerebral oxygenation studies through near infrared spectroscopy: A review", Advanced Materials Letters, Vol. 11(3), 20031482 (1-10), 2020.

Chapter 3:

Y. Arora, S. Ramasahayam, S. Roy Chowdhury, "An Optimal Reflection Photoplethysmographic Sensor System based on Skin Optics", IEEE Sensors Journal, Vol. 18, No. 17, pp. 7233-7241, 2018.

G. Sharma*, **Y. Arora***, S. Roy Chowdhury "Studies on Rat Brain Phantoms for the Development of Near-Infrared Spectroscopy (NIRS) System" , In Proceedings of the 11th International Joint Conference on Biomedical Engineering Systems and Technologies (BIOSTEC 2018) - Volume 1: BIODEVICES, pages 157-163.***Equal Contribution***

Chapter 4:

Y. Arora and S. R. Chowdhury, "Cortical Excitability through Anodal Transcranial Direct Current Stimulation: a Computational Approach," Journal of Medical Systems, vol. 44, no. 2, pp. 1-13, 2020.

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Chapter 5:

Y. Arora, A. Dutta, S. Roy Chowdhury, "Pathways of hemodynamic response during anodal transcranial direct current stimulation: a computational approach" 5th International Conference on Neurorehabilitation (ICNR 2020), Vigo, Spain, October 13-15, 2020.

Chapter 6:

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Y. Arora, P. Walia, M. Hayashibe, M. Muthalib, S. R. Chowdhury, S. Perrey, and A. Dutta, "Grey-box linear modeling to analyze functional near-infrared spectroscopy-based cerebrovascular reactivity to anodal high-definition tDCS in healthy humans," 2020.

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