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A wearable time domain near infrared spectroscopy system

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ABSTRACT

We present a lightweight TD-NIRS system, two-wavelength, one detection channel that can be battery operated and worn as a backpack for freely-moving cerebral and muscle hemodynamic monitoring. Oxy- and deoxy-genated hemoglobin absolute concentration can be retrieved in real time even in outdoor measurements thanks to the rugged feature of the device.

Keywords: wearable, compact, wireless, td-nirs, brain, muscle, freely-moving, outdoor.

1. INTRODUCTION

Time Domain Near-Infrared Spectroscopy (TD-NIRS) technique is gaining interest in the world of health and medicine. Better accuracy and depth selectivity in determining tissue optical properties make TD-instruments interesting compared to continuous wave and frequency domain ones [1],[2]. Nevertheless the complexity in the hardware design, the bulkiness, and the difficult usage of this system are strongly limiting the spread of this technique [3,4]. In this work, we are presenting a system developed to overcome those limitations making TD-NIRS more accessible to non-experts and easier to be implemented even in outdoor conditions. The system here presented is wearable, light weight and can be wireless controlled. Nearly all components have been custom made to be able to match optimal TD-instrument features with a compact design. We validated the system performances by standardized characterization protocols on calibrated tissue phantoms recently developed in European collaborative efforts (e.g. BIP, MEDPHOT, nEUROPt) [3,4,6]. The system also shows low sensitivity to motion artifacts under challenging measurements conditions such as muscle oxygenation monitoring during outdoor bike riding.

2. INSTRUMENT DESCRIPTION AND CHARACTERIZATION

2.1 Hardware Description

Two custom-made laser diodes emit light pulses (830nm and 670nm) in gain switching mode, at a frequency of 50 MHz, and with a full-width at half maximum (FWHM) lower than 250ps. Single-photon detection is achieved thanks to a Silicon Photomultiplier with 1.3x1.3mm^2 active area combined with custom-made timing electronics devised to maximize the

Figure 1 Single channel compact TD-NIRS device worn as a backpack for freely moving brain and muscle hemodynamic monitoring.

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timing performance[5] and a custom-made 10ps resolution Time-to-digital converter. Further details and technical specifications can be seen in [6],[7]. The system can be wirelessly controlled via Wi-Fi connection thanks to a built-in single board PC (LattePanda 4G/64G), with Windows10TM OS and it can be battery operated for a maximum measuring time of 6 hours. For the measurements presented in this work, a customized backpack holder was designed and built (Fig.1) in order to make the system wearable by the enrolled subjects.

2.2 Characterization on Phantoms

BIP, MEDPHOT and nEUROPt protocols [3],[4] have been followed to characterize the wearable TD-instrument. From MEDPHOT protocol, the reproducibility for the estimate of optical properties (absorption and reduced scattering coefficients) on tissue mimicking phantom measurements showed a coefficient of variation of less than 2%. High stability in total counts and temporal position of the collected photon distribution of time of flight (DTOF) and in optical properties have been verified over a total of 15 hours making the developed system perfectly suited for long term monitoring applications. From nEUROPt protocols the depth sensitivity measurement shows that the system is able to distinguish a 7mm diameter cylindrical inclusion at 2.7mm depth into a tissue mimicking homogeneous phantom, paving also the way to functional studies of the brain cortex response.

3. IN-VIVO MEASUREMENTS

We performed a series of in-vivo measurements, to verify the system capabilities in monitoring oxy- and deoxy-genated hemoglobin (O_2Hb and HHb, respectively) dynamics in cortical tissue during functional studies and in muscles under exercise. Data concerning brain cortical activations were analyzed with TD-gating analysis of the DTOF [8]. This analysis is meant to better estimate the variation in hemoglobin concentrations in deep layers, lowering the contribution of superficial systemic changes. In the case of muscle monitoring, the presence of a thin (< 3 mm) fat layer overlying the muscle, allowed us to use the homogeneous sample approximation to analyze the data. The fit of the DTOF curve to retrieve absorption and reduced scattering coefficient was done considering the sample with homogeneous optical properties.

3.1 Finger Tapping

The finger tapping experiment was chosen as standard protocol to elicit a functional response from the cortical area and to be able to compare results with other well-known studies from TD-NIRS literature [8],[9]. We measured three right hand subjects placing the probe in the C3 position of the 10/20 EEG system with 3cm inter fiber distance. The task consisted in touching the fingers of one hand with the thumb of the same hand in a determined sequence: 1-3-2-4 (fingers have been enumerated as following: thumb:0, index:1, middle finger:2, ring finger:3 little finger:4.) at a frequency of approximately 3Hz. the protocol consisted in 20s baseline, 20s task (with audio start and stop signals) and 20s recovery (no movement), repeated 5 times for a total of 5 minutes. The subjects were asked to follow the protocol first with the right hand (contralateral exercise) secondly with the left hand (ipsilateral exercise) and eventually not making any movement (control measurement). Task related activations of the brain cortex are usually related to an increase of O_2Hb and decrease of HHb concentration and this is what we see in the contralateral measurement of the finger tapping exercise in Fig.2. Each one of the five repetitions shows a significant brain cortex activation compared to the baseline values. In the ipsilateral measure, where the TD-system is probing the motor cortex area opposite to the one that is performing the task, we don't see any significant activation. Only some task related like activation are seen probably due to crosstalk between the two hemispheres. In the control measure, where no movement was performed, data always vary around baseline values.

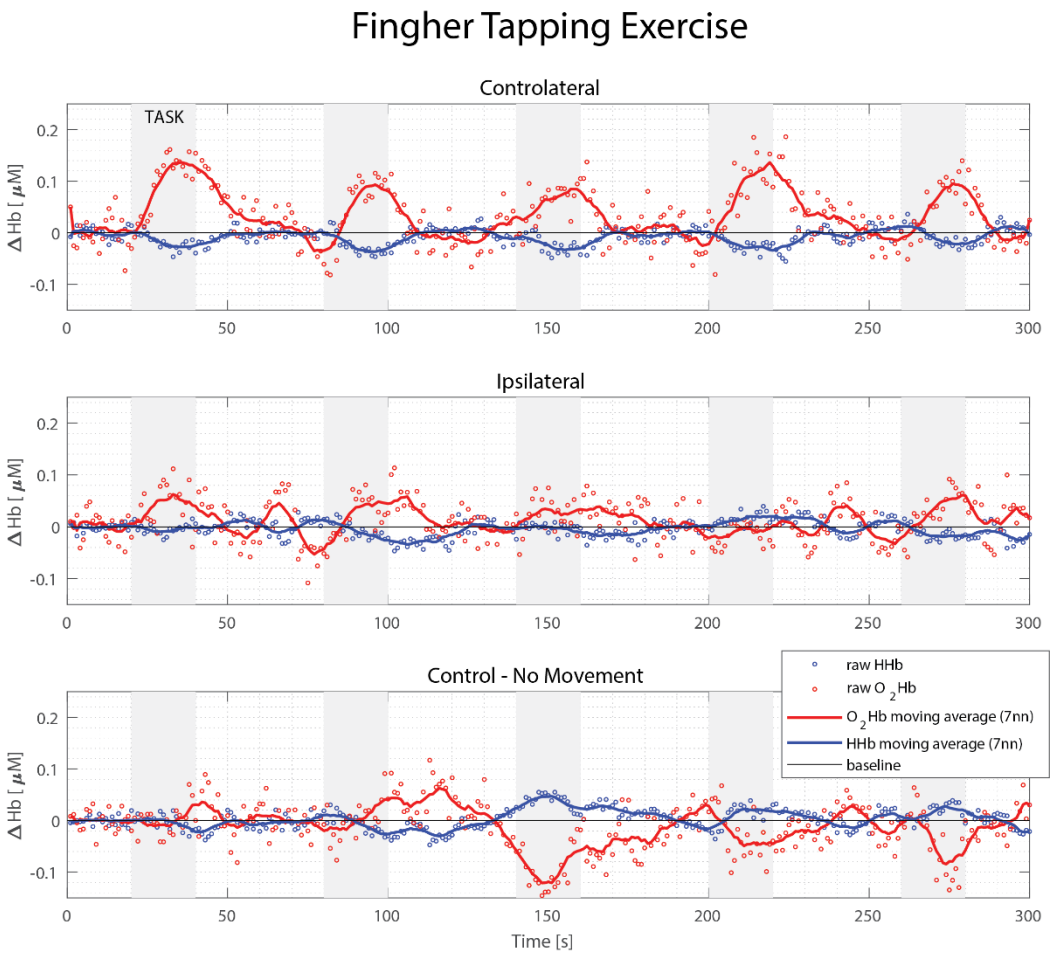

Figure 2. Results of the finger tapping experiment for one single subject. Task periods are highlighted in gray rectangles. On the three different rows are placed the three parts of the exercise: contralateral (top), ipsilateral (middle) and control (bottom) measure.

3.2 Outdoor bike riding experiment

The wearability and compactness of the device have been fully exploited in outdoor bike riding experiment where the system proved to be rugged and reliable even in outdoor measurement conditions. The experiment took place during a sunny (32°C) summer day and three male adults where measured during a bike riding task. The probe was placed on the right vastus lateralis muscle, in order to measure muscle's O_2Hb and HHb during the exercise. The protocol was designed as follows: 60s of initial baseline, subject standing still on both legs, 60s of task, pedaling at a frequency of 0.5Hz (15Km/h average speed) and 60s of rest, subject standing still on both legs. The protocol was repeated five times. The TD-device was worn as a backpack in battery mode by the subjects and it was controlled via Wi-Fi connection from a laptop. The maximum connection distance is 40m but even if the connection is lost, the system is programmed to work on stand-alone mode until the connection is restored. Measurements from one subject are shown in Fig.3, where we can see clear task related hemodynamic variations. The time behavior of the O_2Hb and HHb hemoglobin in the resting period is similar after each task and an overall increasing trend is appreciable along the all the time of the protocol. The abrupt variations of the O_2Hb and HHb at the beginning and at the end of the task are due to the muscle contraction. When the muscle is contracted, it's volume increases, its shape change and probably a vessel occlusion occurs.

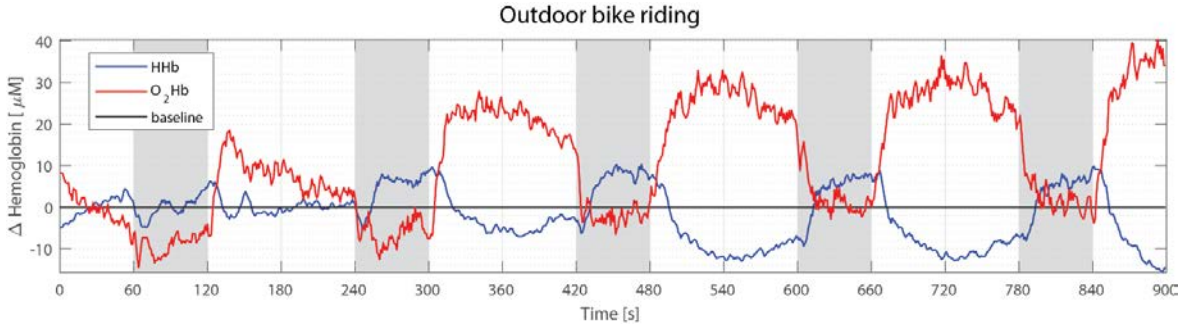

Figure 3. Outdoor bike riding exercise, task times are marked with gray rectangles. HHb and O_2Hb variations are relative to the first averaged 60s baseline.

3.3 Insensitivity to movement artifacts on optical coefficients retrieval in the bike riding protocol

To prove the system's low sensibility to movement artifacts, the same protocol descripted in the previous section has been executed with a tissue mimicking phantom between the probe and the vastus lateralis muscle. A picture of the measurement setup and probe are presented on the right side of Fig4.

Given that the phantom keeps constant optical properties during the bike riding exercise, all deviations from the baseline values would be attributed to artifacts due to movement of the probe, fibers and the whole system on the shoulders of the subjects. Optical coefficients were retrieved from the measurement and translated to O_2Hb and HHb concentrations, variation from baseline values are reposted in Fig.4. The retrieval of O_2Hb and HHb has been done to compare the two measures, even if the phantom doesn't have hemodynamic variations. From the graph on the top left of Fig.4 it is possible to see that there are no task-related artifacts, deviations of ±1μM from the baseline are expected as normal measurement noise considering the analysis procedure used (homogeneous model analysis). The graph on bottom left of Fig.4 presents the same data of the above graph on the same μM scale of data reported in Fig4 to have a direct visual comparison of the two measures.

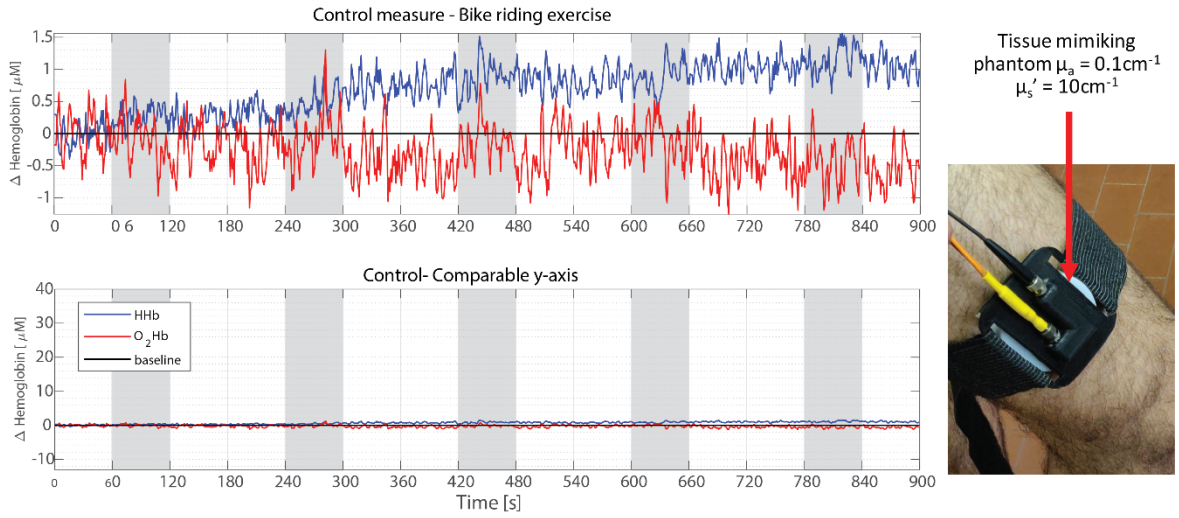

Figure 4. Results of the measurement proving the low sensibility to artifacts due to movement of the whole system, comprehensive of the fibers and probes. On the right, a photo of the measure set up, the 1.5cm thick phantom is placed between the probe and the vastus lateralis muscle. The two graphs on the left side, show the same results in different scales on the y-axes.

4. CONCLUSIONS

We showed the possibility to have accurate and reliable hemodynamic measures on cerebral and muscles tissues with the portable TD-system we developed. The system showed to work without any degradation in performances in outdoor measurement condition battery operated and wirelessly controlled, with very low sensibility to motion artifacts.

5. ACKNOWLEDGMENTS

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