A wearable time domain near infrared spectroscopy system

M. Lacerenza*[a], M. Buttafava[b], M. Renna[b], L. Marchesi[a],
A. Torricelli[a,c], A. Tosi[b], A. Dalla Mora[a], F. Zappa[b], A. Pifferi[a,c], D. Contini[a]
[a] Dipartimento di Fisica, Politecnico di Milano, Italy
[b] Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, Italy
[c] Consiglio Nazionale delle Ricerche, Istituto di Fotonica e Nanotecnologie, Italy

ABSTRACT

We present a wearable TD-NIRS system (two wavelengths, one channel). The system is battery operated, can be remotely controlled and is able to perform measurements on brain and muscle on freely-moving subjects.

Keywords: Time-Domain Near-Infrared Spectroscopy, TD-fNIRS, Wearable instrument.

1. INTRODUCTION

Time-Domain Near-Infrared Spectroscopy (TD-NIRS) potentially shows two main advantages, with respect to continuous wave (CW) and frequency domain (FD) modalities, when using a single channel approach: improved accuracy in the determination of tissue optical properties (absorption coefficient and reduced scattering coefficient) and increased penetration depth [1,2]. Despite these two objective benefits, TD-NIRS instruments are not so widespread [3,4]. Indeed, to our knowledge, most of the TD-NIRS systems are mostly research prototypes and none of them can be considered wearable. The reason can be found in the bulkiness and fragility of the main components of TD-NIRS systems (pulsed lasers, single-photon detectors and timing electronics) [4]. We are proposing an evolution of a previous compact TD-NIRS system [5], fitting in a wearable backpack, which can be used to measure brain or muscle activity in freely-moving subjects.

2. INSTRUMENT DESCRIPTION AND CHARACTERIZATION

2.1 Hardware Description

The system is based on two semiconductor lasers operating in gain switching mode (670 nm and 830 nm), one silicon photomultiplier (SiPM) with an active area of (1.3 x 1.3 mm^2) as single-photon detector and a 10 ps resolution Time-to-Digital Converter (TDC) as acquisition electronics. For further details, see Buttafava et al. [5]. The system can be battery operated continuously for 6 hours, without any degradation of performances. The system is controlled by means of a single-board PC (LattePanda 4G/64G), with Windows10™ OS. The control PC is equipped with a 7" touch screen and can be wireless connected with other devices. This feature will allow, in the future, remote control of the instrument worn by the subject.

2.2 Characterization on Phantoms

The instrument has been characterized on calibrated homogeneous and heterogeneous solid phantoms using three different protocols [6,7], namely: the BIP, MEDPHOT and nEUROPt protocols. Characterization results of these three protocols (which are specifically designed to test the performances of the instrument hardware and data analysis algorithms) have shown excellent outcomes, in line with state-of-art TD-NIRS instruments. Fig. 1 shows the linearity of measured absorption coefficients over the set of MEDPHOT homogeneous phantoms (with different reduced scattering coefficients).

3. IN-VIVO MEASUREMENTS

Preliminary *in-vivo* measurements have also been performed, in order to monitor hemodynamic responses in the muscle during a cuff occlusion and in the motor brain cortex during a finger-tapping exercise. Furthermore, the motor brain cortex hemodynamic response has also been measured on freely-moving subjects during a walking exercise, thanks to the portability feature of the instrument.

* michele.lacerenza@polimi.it - phone (+39)022 399 6595

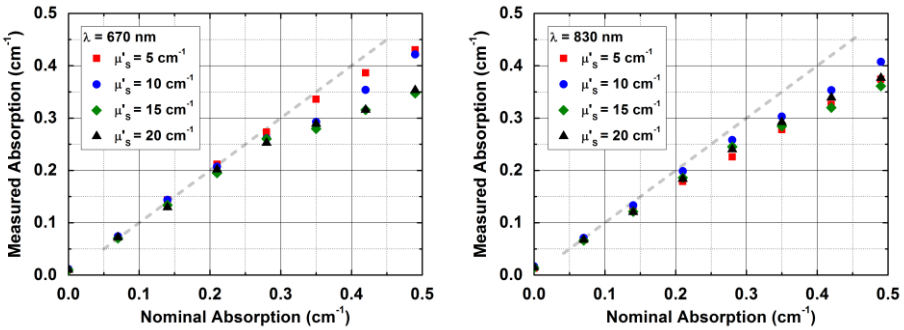

Figure 1. Linearity plot for the measured absorption coefficients over the nominal values of MEDPHOT homogeneous solid phantoms, having reduced scattering coefficients of 5, 10, 15 and 20 cm^{-1}.

3.1 Arterial Cuff Occlusion

A standard arterial cuff occlusion of the right arm muscle was performed with a protocol consisting of: 60 s of baseline (no occlusion), 140 s of arterial occlusion (cuff pressure: 250 mmHg) and 160 s of recovery (no occlusion), with a sampling time of 1 s. The distance between source and detection points was set to 3 cm. Results are reported in Fig.2, as changes with respect to the baseline. The increase of deoxygenated hemoglobin (blue line) with the simultaneous decrease of oxygenated hemoglobin (red line) following the cuff occlusion, and the post occlusion overshoots following the cuff release are clearly visible. The initial rise of oxygenated hemoglobin immediately after cuff occlusion is due to the closing of veins which happens before the closing of arteries as expected.

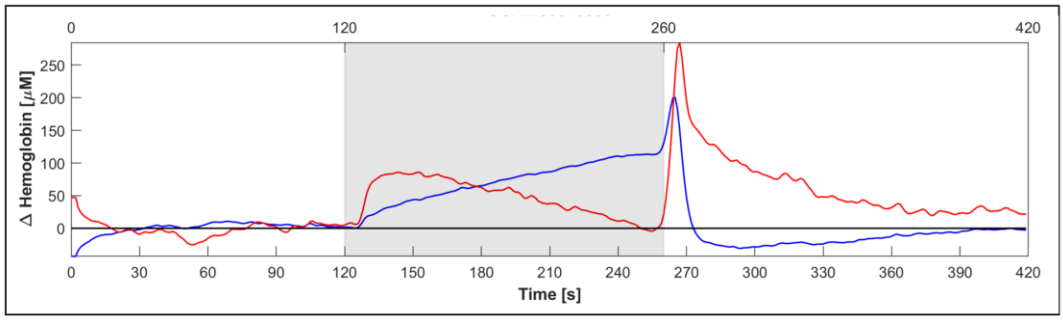

Figure 2. Oxygenated hemoglobin (red) and deoxygenated hemoglobin (blue) changes during the arterial cuff occlusion experiment. The gray area indicates the occlusion period (starting at 120 s, ending at 260 s, cuff pressure: 250 mmHg).

3.2 Motor task – Finger tapping

A finger tapping experiment has been carried out on different subjects to probe deep hemodynamic variations in the upper limb lateral motor cortex area. The protocol consisted in 20 s baseline, 20 s task (finger tapping with the dominant hand at about 2 Hz) and 20 s rest (no movement) repeated five times. The probe was placed on the C3 position (or C4, depending on the dominant hand), referring to the 10-20 standard EEG-cap map. The source-detection separation was kept to 3 cm. Fig.3 shows the hemodynamic response (changes in oxygenated hemoglobin and deoxygenated hemoglobin with respect to the baseline) during the five repetitions for one subject. The time-domain analysis of the collected photons makes it possible to discard any possible superficial systemic variation, by comparing the early and late portions of the Distribution of Time-of-Flights (DTOF) curves (time gates) exploiting an algorithm already described in literature [8].

3.3 Motor task – Walking

The portability and compactness of the presented instrument (see Fig. 4a) have been fully exploited in the monitoring of hemodynamics in the lower limb motor cortex area during a walking exercise on freely-moving subjects. The device, together with a dedicated small computer-on-board, was placed into the subject's backpack powered by a battery. The measurement probe is the same of finger-tapping measurements (3 cm source-detection separation) with the optical fibers exiting the backpack. The followed protocol consisted in five repetitions of 20 s baseline, 20 s of walking on a straight

** michele.lacerenza@polimi.it - phone (+39)022 399 6595*

line, and 20 s of rest. Results are shown in Fig. 4b, where the five repetitions have been folded and averaged. The hemodynamic response (increase in oxygenated hemoglobin and corresponding decrease of deoxygenated hemoglobin) is clearly visible during the exercise (from 20 to 40 s).

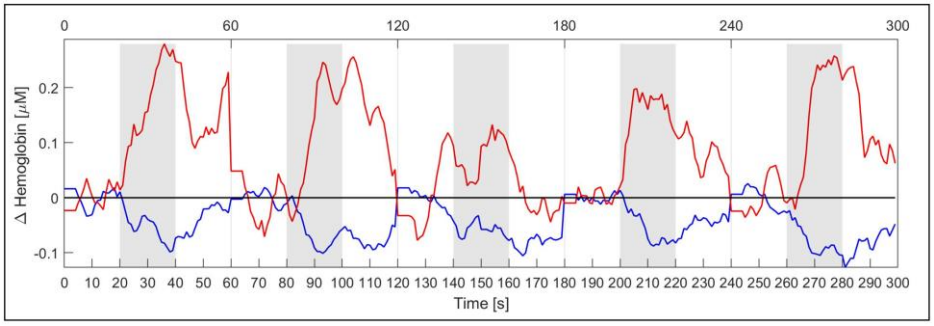

Figure 3. Oxygenated hemoglobin (red) and deoxygenated hemoglobin (blue) changes during the finger tapping task: five 60 s repetitions are shown in a continuous time line, and task time is highlighted in grey.

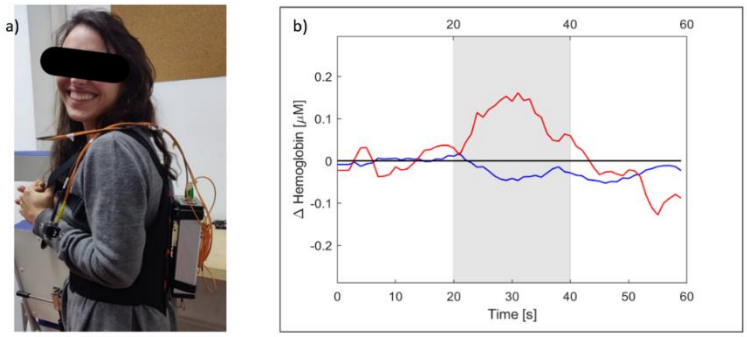

Figure 4. (a) The subject wearing the TD NIRS backpack system. (b) Oxygenated hemoglobin (in red) and deoxygenated hemoglobin (in blue) concentrations changes with respect to the baseline averaged over the 5 repetitions.

4. CONCLUSIONS

We showed the possibility to build up a wearable TRS system which can fit in a backpack, able to perform measurements on freely moving subjects both on brain and muscles.

REFERENCES

[1] Martelli F. et al., “There’s plenty of light at the bottom: Statistics of photon penetration depth in random media” Scientific Reports 6, (2016).

[2] A. Pifferi et al., “ New frontiers in time-domain diffuse optics a review ” J. Biomed. Opt., 21(9), 091310 (2016)

[3] A. Torricelli et al., "Time domain functional NIRS imaging for human brain mapping" NeuroImage, 85, pp. 28-50 (2014)

[4] D. Contini et al,. "Review: Brain and muscle near infrared spectroscopy/imaging techniques" J. NIRS, 20(1), pp. 15-27 (2012)

[5] M. Buttafava et al., “A Compact Two-Wavelength Time-Domain NIRS System Based on SiPM and Pulsed Diode Lasers,” IEEE Photonics J., vol. 9, no. 1, (2017).

[6] Pifferi, A. et al. “Performance assessment of photon migration instruments: the MEDPHOT protocol” Applied Optics 44, 2104 (2005).

[7] H. Wabnitz et al., “Performance assessment of time-domain optical brain imagers, part 1: basic instrumental performance protocol” Journal of Biomedical Optics. 19, 086010 (2014)

[8] Contini D. et al., “Novel method for depth-resolved brain functional imaging by time-domain NIRS” art. no. 662908. Diffuse Optical Imaging of Tissue 6629, 62908 (2007).

** michele.lacerenza@polimi.it - phone (+39)022 399 6595*