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A Hybrid DCS and TD-NIRS Device for Monitoring Tissue Oxygenation and Perfusion, towards ICU Applications

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Abstract: A multi-distance Diffuse Correlation Spectroscopy system combined with a compact state-of-the-art Time Domain Near-Infrared Spectroscopy device is presented. The device was used to validate the protocol of VASCOVID project on healthy subject.

1. Introduction

Intensive Care Units (ICU) have been severely challenged by the COVID-19 pandemic. Indeed, 5% of COVID-19 patients suffer from acute respiratory failure and need intensive care treatments. In this scenario, the use of Near-Infrared Spectroscopy (NIRS) techniques, which allow to assess tissue oxygenation and perfusion, could be extremely important for monitoring the disease progression, microvasculature impairment and reducing extubation failures[1]. VASCOVID is a European research project, founded by European Union's Horizon 2020 framework. In this project, a hybrid system that combines two NIRS techniques will be developed and optimized for its employment in ICU dealing with COVID-19 and all other patients requiring ventilation. In this work we present a system which is similar to that will be developed for the VASCOVID project: a hybrid device which combines simultaneously Diffuse Correlation Spectroscopy (DCS) and Time-Domain NIRS (TD-NIRS)[2]. These two techniques allow for monitoring of blood flow index (BFI)[3], and hemodynamic parameters[4], such as oxygenated haemoglobin (HbO_2), deoxygenated haemoglobin (HHb), total haemoglobin (tHb = HbO_2 + HHb), and tissue oxygen saturation ($S_tO_2 = HbO_2/tHb$). The system was characterized by performing measurements on phantoms and volunteers. The hybrid device was eventually used to monitor hemodynamic parameters and blood flow of a healthy subject's thenar muscle during an arterial occlusion, following the preliminary protocol of the VASCOVID project.

2. Instrument Description

The hybrid-instrument is hosted in a 19'' 4U enclosure, with dimensions of 45x40x16 cm^3, and it contains both a TD-NIRS system (for more information about this module see[5, 6]) and a DCS system. The DCS injection path includes a highly-coherent continuous-wave diode laser (@784 nm, i-Beam Smart, TOPTICA Photonics AG). The emitted laser light is sent to an optical switch (2x(2x2), LEONI Fiber Optics GmbH), which alternatively directs the photons in two branches. In one branch, light passes through an optical attenuator (DD-200-55-785-400/430, OZ Optics LTD.) and reaches the measurement point with a 1 cm inter-fibre distance. In the other branch, the light is divided, by an optical beam splitter (FOBS-12P-111-400/430, OZ optics LTD.), in two more lines, directly connected to the measurement points at 2.5 cm inter-fibre distance. Concerning the DCS detection part, light is collected by a bundle of single-mode optical fibres (5 µm core), connected to four single photon avalanche diodes (SPCM-AQRH-3XSPAD, Excelitas Technology Corp.). The output of the four detectors is analysed by 4-channels digital correlator (ALV 70004USB/FAST, ALV GmbH), which retrieves the intensity autocorrelation functions of each channel.

3. Characterization measurements

3.1. Measurements on phantoms

In this section we focused the attention to the DCS module characterization, for the TD-NIRS module characterization see [5, 6]. DCS module performances were assessed over time: stability measurements (estimating β and D_b of a liquid phantom over 3 hours) and reproducibility tests (10 repeated measurements spanning 17 days) were performed. The coefficient of variation for each measured parameter x ($CV=\sigma(x)/\langle x \rangle$) was computed, obtaining results in accordance with state-of-the-art DCS device[7]: CV_β = 1.4%, CV_{Db} = 2.4% for stability, and CV_β = 1.2% and CV_{Db} = 1.9% for reproducibility. We estimated the ability of DCS device in retrieving D_b variations when phantom viscosity (η) and temperature (T) were increased. The results are in accordance with previous findings and theory [8, 9] (see Figs. 1a) and 1b)): $D_b \propto \eta^{-0.93}$ and $D_b \propto T/\eta$. Moreover, we estimated the influence of count rates in retrieving β and D_b parameters, obtaining a reduction of D_b when the total count rates were increased, with a threshold of 45 kcps in each detection channel. Finally, the influence of TD-NIRS source on DCS signal was estimated, by varying the distance between the DCS detection and the TD-NIRS source positions (*d*). Results are shown in Figs. 1c) and d): β increases with *d* (reaching a plateau for *d* = 20 mm); on the contrary D_b decreases with an increase of *d* and reaches a plateau for *d* = 16 mm. These results led us to design our hybrid probe with more than 20 mm distance between the TD-NIRS source and DCS detection channels.

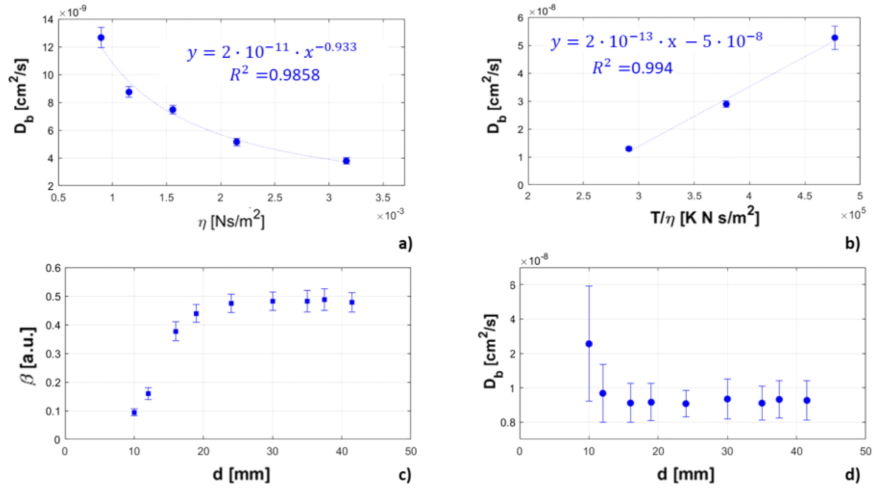

Fig. 1: In panels a) and b): D_b estimated when phantom viscosity (panel a)) and temperature (panel b)) were increased. In panels c) and d): dependence of β and D_b with respect to the distance of the TD-NIRS source from the DCS detection (d).

3.2. *In-vivo measurements*

We tested the ability of the hybrid device in retrieving hemodynamic parameters and blood flow. The subject included in these measurements cooperated voluntarily and previously provided written informed consent to the procedures of the study, which was approved by the Ethics Committee of Politecnico di Milano. The venous and arterial occlusions on the arm of a healthy volunteer (male, 42 years old) were monitored via simultaneous measurements of hemodynamic parameters and BFI. The occlusion protocols were divided in three sections. Baseline: the subject was asked to seat, with a deflated pressure cuff on his left bicep, and his left arm placed at the same height of the heart; occlusion: pressure cuff was inflated at 100 mmHg in case of venous occlusion, and 250 mmHg for arterial occlusion; recovery: the cuff was gently deflated, and the hemodynamic parameters were measured. The duration of each protocol section in the venous (arterial) occlusion was: 1 min (2 min) baseline; 30 s (6 min) occlusion; 2 min (5 min) recovery. The results, averaged over three repetitions are reported in Fig. 2 and are in accordance with previous findings [7]. During the venous occlusion, we observed an increase of tHb and a reduction of BFI. When the cuff was released, the tHb and rBFI return to their baseline values. Immediately after the end of occlusion, an increase of rBFI is clearly visible. During the arterial occlusion, tHb S_tO_2 and rBFI decrease (rBFI reached almost 0), and rapidly increase immediately after the cuff release.

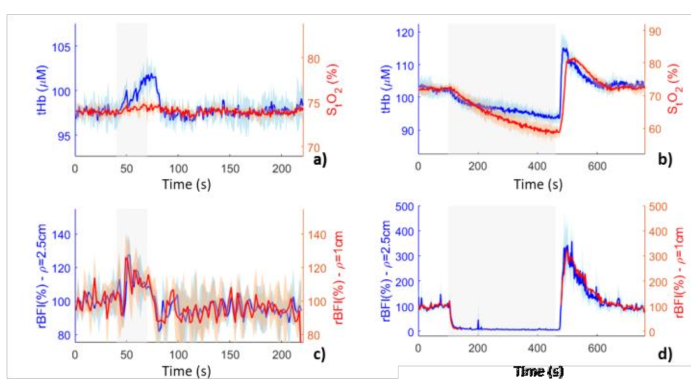

Fig. 2: Hemodynamic parameters monitored during venous (left panels a, c) and arterial (right panels b, d) occlusion on the left forearm of a healthy subject. Solid lines are the average over the three repetitions, shadows represent the range of variations over the three repetitions. The superficial skin thickness was: 4.8 mm.

4. In-vivo applications: VASCOVID protocol on healthy subject

The preliminary VASCOVID protocol consists in recording the hemodynamic response to arterial occlusion on thenar muscle of ICU patients. Preliminary measurements were performed with our device to study the hemodynamic response of a healthy subject. The arterial occlusion protocol is the same reported in the previous paragraph, the only difference is that the probe is positioned on the thenar muscle. Due to the small dimension of the probed muscle, the inter-fiber distance used for this measurement was 2 cm for both TD-NIRS and DCS. In Fig. 3 we reported the results obtained for the same subject of Fig. 2. Comparing results from Fig. 2 (arterial occlusion) and Fig. 3, the hemodynamic response is stronger in thenar muscle than on the arm (S_tO_2 decrease is more evident and it reaches a plateau and also rBFI variations are higher).

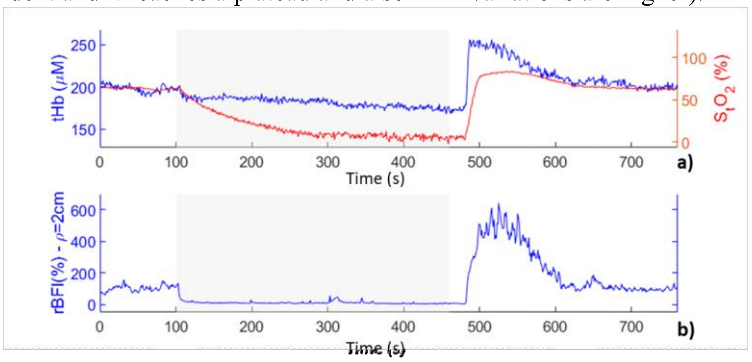

Fig. 3: Hemodynamic parameters of thenar muscle during arterial occlusion. The reported results are related to measurements performed on the same subject as in Fig. 2. The superficial skin thickness in the probed area was: 1.6 mm.

5. Discussion

We presented a hybrid diffuse optics device, which combines TD-NIRS and DCS techniques. A custom-designed probe with multiple detection channels allows for simultaneous measurements with 1 s acquisition time, and two inter-fiber distances (1 cm and 2.5 cm) in DCS device. The instrument performances were tested on phantoms and in-vivo measurements. Finally, we tested the hemodynamic response of a healthy subject undergoing the VASCOVID protocol (arterial occlusion, on thenar muscle). We are working for recruiting other healthy subjects to increase the statistical consistency of our preliminary results.

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7. Conflicts of interest: M.L., M.B., A.T., A.T. and D.C. are co-founders of pioNIRS S.r.l., (Italy). Other authors declare no conflicts of interest related to this article.

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