Exploring a new spectral range for time-domain near infrared spectroscopy

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Abstract: We propose to use the 1064 nm wavelength for near-infrared diffuse optical spectroscopy both alone (to retrieve concentration of only O_2Hb) or as a second wavelength (if also the HHb concentration has to be computed).

1. Introduction

Diffuse optics (DO) is a non-invasive technique that allows human tissues to be probed in depth (up to a few cm) [1]. Among the advantages of using the Time Domain (TD) implementation of DO, the possibility to disentangle reduced scattering (μ_s') and absorption (μ_a) as well as the encoding of the mean penetration depth in the photon arrival time [2] have to be cited. Generally speaking, the possibility to compute the concentration of N components (i.e., chromophores) at least N wavelengths are needed. In oximetry application, the oxy -O_2Hb- and deoxygenated -HHb- hemoglobin have to be recorded. In this case, most of scientists use 2 wavelengths across the isosbestic point (λ= 800 nm) which usually falls in the range between 650 and 900 nm to avoid large attenuation due to water and blood components [3]. Recently, several works demonstrated the possibility to perform Diffuse Correlation Spectroscopy (DCS) beyond the water peak and, more precisely, at 1064 nm [4–6]. The use of this longer wavelength has several main advantages: *i)* lower energy per photon thus allowing to increase the power injected in the tissue without exceeding safety limits; *ii)* photons experienced a lower μ_s' thus possibly increasing the penetration depth; *iii)* the large availability of sources at 1064 nm, developed for telecommunication application; *iv)* the much lower (about one decade) HHb extinction coefficient with respect to the O_2Hb one. On the other hand, the use of the 1064 nm wavelength poses several questions such as: *i)* a lack in the literature of a well-agreed extinction coefficients for O_2Hb and HHb beyond 1000 nm; *ii)* a not-negligible absorption of water and lipids with respect to hemoglobin; *iii)* a larger difficulty in finding detectors with suitable timing resolution and light harvesting capability. In this work, we will explore the possibility to use the 1064 nm to track concentration of O_2Hb in *in-vivo* Near Infrared Spectroscopy (NIRS) measurements as well as we will discuss the use of the 1064 nm in conjunction with other wavelengths for the retrieval of both O_2Hb and HHb hemoglobin concentration.

2. Methods

2.1. Experimental setup and task description

In-vivo measurements are done using two different laser sources: *i)* custom made tunable Titanium-Sapphire laser with active mode-locking and acousto-optical modulation providing pulses at 1064 nm with 100 MHz repetition rate; *ii)* a laser driver (Sepia PLD 828 from Picoquant GmbH) connected to two pulsed diode laser heads (LDH-P-C-670M and LDH-PC-830M from Picoquant GmbH) providing pulses at 670 nm and 830 nm respectively, with 40 MHz repetition rate. Light exiting from source is attenuated using a variable optical attenuator (one per wavelength) and sent to the sample through optical fibers. In the same way, photons remitted are collected using three 1mm-core optical fibers arranged in a close geometry to probe the same area (source-detector separation of 3 cm) and focused through suitable optics onto a custom-made Silicon PhotoMultiplier (SiPM) module. To avoid wavelength contamination, in the focusing optics of each module an interference filter (centered at the laser wavelength with few nm bandwidth) have been inserted. The distribution of remitted photons have been computed

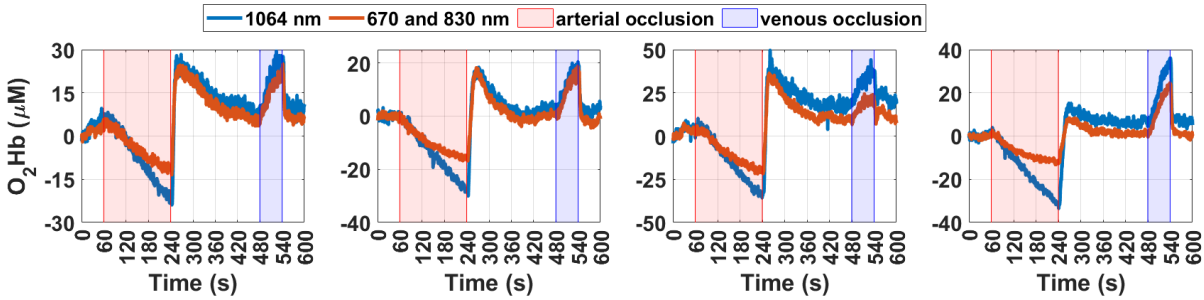

Fig. 1. O_2Hb concentration recovered using 670 and 830 nm wavelength together (orange lines) and with the single wavelength approach (1064 nm, blue lines). Each graph represents a single volunteer.

for each detector (i.e., wavelength) using a time-correlated single photon counting board (SPC-130, Becker&Hickl GmbH). The *in-vivo* measurements were conducted on 4 healthy volunteers and included both arterial and venous occlusion. More in detail, the task consisted of: *i)* 60 s of baseline; ii) 180 s of arterial occlusion (cuff inflated well above the systolic pressure); iii) 240 s of recovery phase; iv) 60 s of venous occlusion (cuff inflated between the systolic and diastolic pressure); v) 60 s of recovery. All subjects gave their written informed consent and experiments got approved by the Ethical Committee of Politecnico di Milano and were conducted in compliance with the Declaration of Helsinki.

2.2. *Data analysis*

Notwithstanding the chromophore concentration to be computed, we always used the modified Lambert-Beer law, taking as extinction coefficients those reported in [7]. The value of μ_a (as well as μ_s') were computed fitting the experimental curves to the radiative transfer equation under the diffusion approximation. The finite response of the system was considered by convolving the theoretical curves with the instrument response function. To compute O_2Hb and HHb concentrations, for all wavelengths, the contribution of μ_a due to lipid (30% of the overall composition) and water (70%) absorption have been removed. Having 3 wavelengths the analysis can be splitted in two main aims: firstly, the capability to retrieve the concentration of O_2Hb considering only the data acquired with the 1064 nm (since the extinction coefficient of HHb is negligible at this wavelength) and secondly, the possibility to use the 1064 nm wavelength in conjunction with another "standard" wavelength to detect both O_2Hb and HHb. For the first aim, concentration of O_2Hb have been computed using the 1064 nm wavelength alone and compared to the concentration obtained using a standard NIRS approach (i.e., using 670 and 830 nm). For the second aim, we compare the results obtained using 670 and 830 nm (standard NIRS) with those obtained substituting the 830 nm with the 1064 nm one (i.e., 670 and 1064 nm).

3. Results and discussion

Fig. 1 reports for each subject (rows), the O_2Hb concentration variations computed using the only 1064 nm (blue line) as compared to what obtained with a standard dual-wavelength system (i.e., 670 and 830 nm, orange line), normalized to the baseline value. Using the only 1064 nm, a larger variation of O_2Hb concentration during arterial occlusion is obtained with respect to concentration retrieved using 670 and 830 nm. In this latter case also a change in the slope of the O_2Hb concentration can be noticed while it is absent when analysing the 1064 nm. The same overestimation can be seen in the baseline values (data not shown). During venous occlusion, variation in O_2Hb concentration in the two cases is fairly comparable both in terms of slope and absolute value. Similar behavior can be seen if comparing O_2Hb concentration (left column of Fig. 2) recovered using two wavelengths (670 and 830, green line or 670 and 1064 nm, blue line). On the other hand, the HHb seems not to be significantly affected by the choice of the wavelengths used (see right column of Fig. 2). The overestimation of both the O_2Hb baseline and variation when using the 1064 nm can be ascribed to several issues: i) extinction coefficient of the O_2Hb and HHb not correct at 1064 nm; ii) photons experience a different penetration depths (at 1064 nm they are expected go about 20% deeper) which may determine changes in O_2Hb concentration, while HHb is less affected (veins are in general more superficial than arteries); iii) other absorbers which may give contributions.

4. Conclusions and future perspectives

We demonstrated the possibility to use the 1064 nm wavelength to track hemodynamics changes for *in-vivo* TD-NIRS measurements. Firstly, we demonstrated the possibility to use a single wavelength (1064 nm in our case) to recover O_2Hb concentration changes even though some discrepancies with respect to what achieved with standard

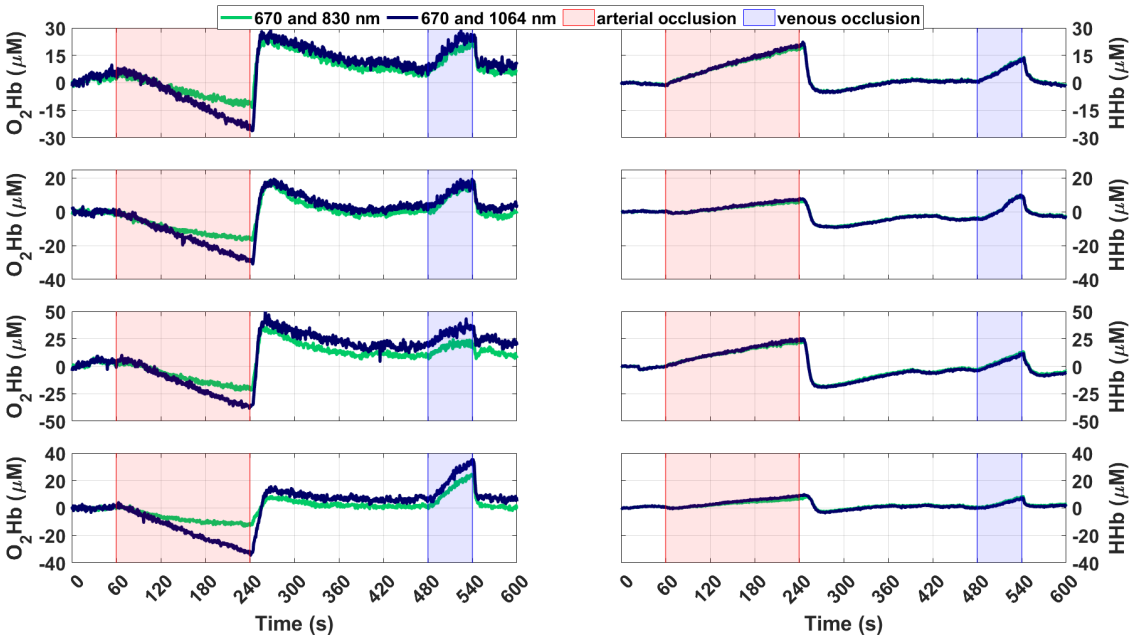

Fig. 2. O_2Hb and HHb concentration (left and right column respectively) recovered using 670 and 830 nm wavelength (green lines) and 670 and 1064 nm wavelength (blue lines). Each row represents a single volunteer.

NIRS system (based on 2 wavelengths, *e.g.,* 670 and 830 nm) have been detected. Indeed, an overestimation of the O_2Hb baseline value and changes is reported when using the single wavelength approach. Secondly, we explored the possibility to use the 1064 nm as a second wavelength used to retrieve both O_2Hb and HHb. Also in this case, similar discrepancies with respect to what obtained with standard NIRS system are reported. For the future, a measurements campaign where several wavelengths in the range between 650 and 1100 nm will be switched fast to see which is the second wavelength to be coupled to 1064 nm to obtain the more reliable concentration of O_2Hb and HHb.

5. Acknowledgment

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