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Time-Resolved Diffuse Optical System with Spectral Parallelization over a 16-Channel SiPM Array

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Abstract: The compact (32×45 mm²) SiPM-based multi-channel system enables parallelized spectral acquisition (700–950 nm, Δλ = 16 nm), demonstrating reliable performance on phantoms and effective tissue characterization *in vivo* during scans on back and calf.

1 Introduction

We designed and conducted an initial validation of a time domain diffuse optical spectroscopy system incorporating a high-throughput 16-channel Silicon PhotoMultiplier (SiPM) array. This device takes advantage of its parallelization capabilities for diverse applications. The present study focuses on spectral parallelization within the 700–950 nm range for scanning large tissue areas in a clinical environment, allowing one to acquire extensive spectral data in real time for rapid tissue assessment, with minimal examination duration.
We introduce the system architecture and present its performance evaluation using tissue phantoms. Additionally, we validate it *in vivo* by conducting scans on volunteers along the back and around the calf, that are heterogeneous regions encompassing muscle, fat, and bone layers.
This work integrates for the first time to our knowledge the rich information content of the time domain method, the compactness and robustness of high-throughput SiPMs, and the acquisition speed of parallelization.

2 Materials and Methods

2.1 System design and calibration

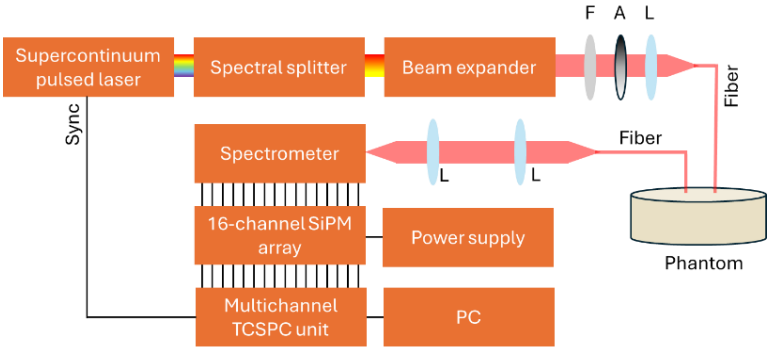

Figure 1: Schematics of the parallel setup that distributes light in the 700 – 950 nm range over 16 detection channels. F stands for filter, A for attenuator, L for lens, TCSPC for Time-Correlated Single Photon Counting.

The goal of the system (Figure 1) is to separate 16 spectral bands in the 700 – 950 nm starting from white light, to encompass significant absorption peaks of hemoglobin and lipids and the rising edge of water.
To do that, the parallel system utilizes a supercontinuum pulsed laser (SuperK Extreme, NKT Photonics, Denmark), whose output is limited to the 600 – 1000 nm range through a set of filters (SpectraK Split, NKT Photonics, Denmark; FESH1000, Thorlabs, USA). The subsequent effective separation into bands is performed by a spectrometer (Kymera 193i, Oxford Instruments, Andor, UK) and a compact high-throughput 16-channel SiPM array detector (32 × 45 mm²). The array features commercial detectors (S13360-1350PE, Hamamatsu, Japan), and custom-made front-end and read out board and amplifiers. The Distributions of Times-Of-Flight (DTOFs) are finally reconstructed by a time-to-digital converter (MultiHarp 160 N, PicoQuant, Germany).
Measurements to test the sensitivity of light dispersion over the array revealed the barycenter wavelength of each channel (reported in Table 1), for an average bandwidth of 16 nm.

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Table 1. Barycenter wavelength of each channel in nanometers.

#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	#16
949	933	917	901	885	869	853	837	820	804	788	772	756	740	724	708

3 Results and Discussion

3.1 Performance evaluation on phantoms

The MEDPHOT protocol [1] was applied to evaluate the performance of the system in retrieving the optical properties of a homogeneous medium. The optical properties of resin phantoms (labelled with numbers for absorption values and letters for scattering values) were extracted through the homogeneous solution of the diffusion equation for a semi-infinite medium in reflectance geometry at 2 cm source-detector separation.
The system demonstrated excellent linearity (worst R^2 values observed were 0.9973 for absorption and 0.9833 for scattering) and minimal cross-coupling between absorption and scattering (worst cases were $\Delta\mu_s' / \Delta\mu_a = 5.15$ and $\Delta\mu_a / \Delta\mu_s' = 0.01$), thus proving effective to track changes in tissue composition.
As regards accuracy (Figure 2), results from the parallel system were compared with values from a well-characterized time-resolved spectroscopy system [2]. The comparison showed excellent agreement in absorption measurements, with an average relative error of 3% in absolute value. Scattering values tended to be overestimated, with average relative errors of +17%. The retrieval of microstructure information is prone to errors because it is linked to scattering, but the absorption measurement is accurate to ensure a reliable tissue composition assessment, which is a critical factor for diagnostic applications.

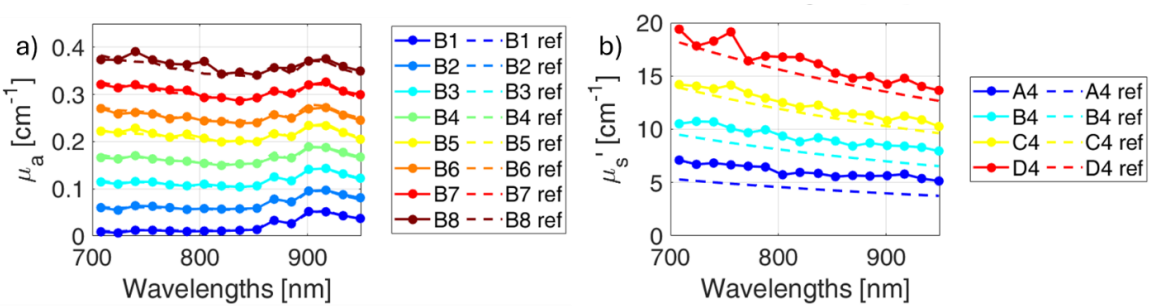

Figure 2: Results for the accuracy test. a) Measured absorption values, keeping scattering fixed. b) Measured scattering values keeping absorption fixed.

3.2 Scanning measurements in vivo

Three distinct body regions were selected, each with varying fat and muscle layer thicknesses, sometimes interrupted by bone: the back, horizontally crossing the spine and vertically in the lumbar region, and the left calf, clockwise from 6 to 3 o'clock crossing the tibia.
An operator slid the probe along a linear grid of 21 points spaced 1 cm apart, marked on the target area. The source-detector axis of the probe was positioned perpendicular to the grid. Measurements were taken in two modes: at discrete steps, where the probe was held still at each point (5 repetitions per point, for a total of 8 minutes), and continuous scan (40 seconds in total), where the probe moved smoothly across the grid. The discrete measurements were used as the optical ground truth to check for motion artifacts. Concurrent ultrasound (US) data served as ground truth for interpreting and validating the optical measurements. Three healthy volunteers were measured, after written informed consent. All measurements were approved by the Ethical Committee of Politecnico di Milano.
Results were derived by applying a spectrally constrained approach to the diffusion equation for a homogeneous medium at 2 cm source-detector distance [3].
Figure 3 illustrates the behaviour of lipids, water, total hemoglobin and oxygen saturation for Subject 1 across the back (sagittally), along the back (longitudinally) and around the calf.
In the first row, curves are symmetrical with respect to position “10 cm”, reflecting the expected equal distribution of fat (lipids) and muscles (mostly water and hemoglobin) on the two sides of the spine, with the fat layer thinning out closer to it, but without exposing the bone completely. In the second row, optical data underline the increase in fat moving along the back in the lumbar region downwards. Finally, in the third row, measurements show peaks/valleys corresponding to the tibia (position “15 cm”). Contrary to the first row, the bone now is in direct

contact with dermis due to an abrupt interruption of the muscle, causing a rapid decrease in water and hemoglobin concentrations, with a concurrent growth in lipid content. This is compatible with a homogeneous approach for analysis, with a 2 cm separation. Overall, discrete and continuous acquisitions retrieve consistent results. Also, all trends are confirmed by US images.

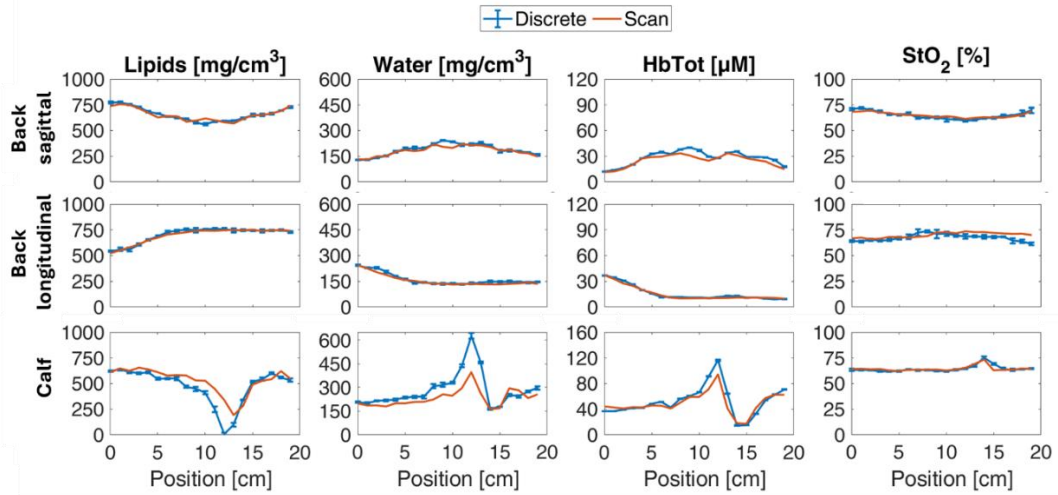

Figure 3: Variation in tissue composition for in vivo measurements across the back (sagittal), along the back (longitudinal) and around the calf (rows), for Subject 1. Composition is estimated in terms of lipids, water, total hemoglobin (HbTot) and oxygen saturation (StO_2) (columns). Error bars in discrete measurements represent the standard deviation over 5 acquisitions.

4 Conclusion

In this study, we presented a parallel time-resolved diffuse optical spectroscopy system utilizing a compact 16-channel SiPM array. The setup was designed to parallelize spectral acquisition across the 700–950 nm range, with a step of $\Delta\lambda = 16$ nm, aligning with key absorption peaks of hemoglobin, lipids, and water (primary components of muscle, fat, and bone tissue). Performance assessment on homogeneous phantoms returned excellent results. Further, the system proved effective in characterizing tissue with smooth, continuous scans that covered 20 cm in just 40 seconds on the back and the calf, consistent with complementary US information.
In future work, we aim to test the system's performance during functional tasks, such as monitoring breathing or tracking brain activity, taking full advantage of the time efficiency offered by spectral parallelization compared to sequential approaches. We will also explore the reconfiguration of the 16 channels for spatial parallelization.

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