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A hybrid time-of-flight-resolved parallel interferometric near-infrared spectroscopy (parallel iNIRS) with a fast two-dimensional and a single-channel iNIRS

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1. Introduction

Optical methods provide a noninvasive approach for continuous cerebral blood flow (CBF) monitoring in humans in vivo. Diffuse correlation spectroscopy (DCS) is an established modality for qualitative CBF monitoring. DCS decodes the CBF from an analysis of the temporal correlations of light scattered by the tissue [1]. However, DCS uses single-mode fiber (SMF) for light collection, which limits light throughput and decreases the signal-to-noise ratio (SNR).

A proven approach to tackle this problem is adopting parallel light detection. Early attempts used SMF bundle collector and an avalanche photodiode (APD) array to achieve N=23 parallel detection channels [2]. Recent advances in instrumentation have enabled highly parallel detection schemes for DCS. Specifically, instead of the SMF fiber bundle, the scattered light is collected using a multi-mode fiber and detected using a multi-element SPAD array. Each pixel in the array independently estimates the single-pixel autocorrelation function $G1,sp(r, \tau)$, where r denotes the pixel location in the detector array, and τ is the lag time. Autocorrelations are then spatially averaged over all pixels to improve the SNR: . This approach was recently demonstrated with N=1024 detection channels and applied to monitor rapid blood flow changes in the human forehead [3]. A SPAD array comprising 500x500 pixels was recently demonstrated, showing a clear path to further improve the SNR [4].
Parallel detection has also been demonstrated for interferometric methods. Samaei et al. Introduced continuous-wave parallel interferometric near-infrared spectroscopy (CW-πNIRS) using an ultra-fast area-scan (2D) camera with almost 10,000 parallel channels, detecting prefrontal cortex activation in the human brain in vivo [5]. However, CW-πNIRS lacked time-of-flight (TOF) resolution, necessitating operation at long source-collector separations (SCS), which led to poor spatial resolution and an inability to detect rapid blood flow changes at long SCS.

Here, we developed TOF-resolved parallel iNIRS. Using an ultra-fast area-scan (2D) camera and a rapidly tunable laser, we record wavelength-resolved autocorrelations, $G1(\lambda, r, \tau)$ which, after Fourier transform ($\lambda \rightarrow$ TOF) and spatial averaging, lead to the final TOF-resolved autocorrelation function $G1(TOF, \tau)$. This function is used to extract the photon time-of-flight distribution and TOF-resolved sample dynamics. By using nearly 2000 camera pixels, we demonstrate that πNIRS can achieve the same information a single-channel iNIRS but orders of magnitude faster: 1-10 ms instead of 1000 ms.
The camera-based system, while powerful for parallel detection, is inherently limited by its slower sampling rate, which can miss the rapid fluctuations in the interference signals critical for accurately capturing fast sample dynamics. To address this limitation, we augmented the πNIRS system by integrating a fast-sampling, single-channel iNIRS module along with a reference interferometer.

By leveraging nearly 2000 camera pixels, our expanded πNIRS system captures the same critical information as the single-channel iNIRS, but with a dramatic improvement in speed—achieving acquisition times of 1–10 ms compared to the 1000 ms required by the slower, camera-only approach. The integration of the fast-sampling iNIRS with the reference interferometer effectively overcomes the sampling limitations of the camera-based system, enabling robust detection of rapidly fluctuating interference signals and facilitating high-speed, time-resolved measurements.

2. Methods and results

Here, we developed an optical setup consisting of three blocks: πNIRS module, iNIRS module, and a reference interferometer. The reference interferometer was used to retrieve the resampling vector for πNIRS/iNIRS data resampling. The system utilizes a rapidly tuneable laser (λc=780 nm, $\Delta\lambda$=20 pm, tuning frequency of 10 kHz). The TOF-resolved πNIRS module uses an ultrafast two-dimensional camera operating at frame rate of 1.1 MHz [Fig 1 (a)]. The recorded wavelength-resolved autocorrelations $G1(\lambda, r, \tau)$ from πNIRS/iNIRS were processed in the following way [Fig 1 (b)]: first, the constant (DC) component was subtracted from the signal. Next, the data were resampled from the wavelength domain to the wavenumber domain to obtain $G1(k, r, \tau)$. After resampling, the data were transformed into the final TOF-resolved autocorrelation function $G1(TOF, \tau)$, used to extract the photon time-of-flight distribution and TOF-resolved sample dynamics. By using 2048 camera pixels, we demonstrate that πNIRS can achieve the same information as a single channel iNIRS setup, but 2-3 orders of magnitude faster.

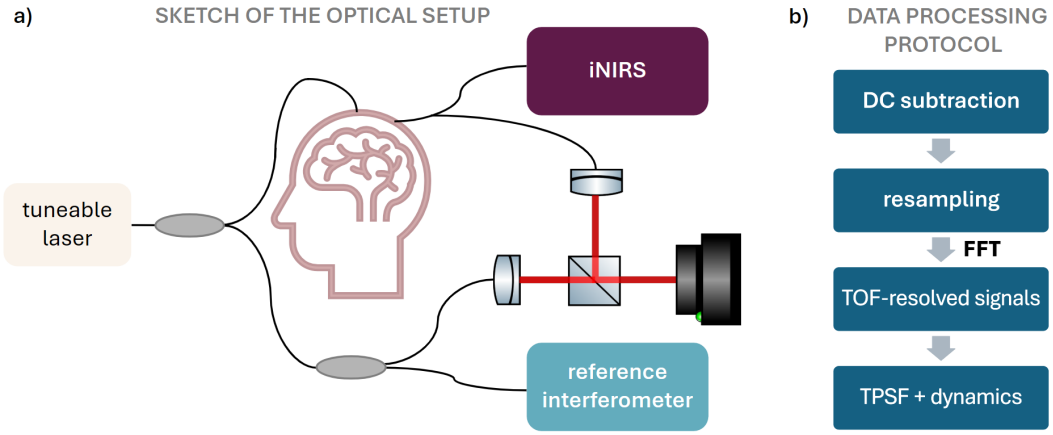

Fig 1. (a) Schematic diagram of the optical πNIRS system. The interferometer output is projected on a two-dimensional camera and each pixel serves as an individual detection channel. (b) Data processing pipeline.

First, we validated the above-mentioned approach in a 10-meter-long multi-mode fibre as a sample. A total of 30,000 camera frames were acquired and processed to extract the TPSF function. In the next step, we validated the system in a liquid phantom – milk dissolved in water (volumetric concentration of 13%) [Fig. 2]. The source and collector fibres were positioned on the top surface of the liquid phantom and separated by 10 mm. We then recorded 30,000 camera frames and after processing them, we extracted the TPSF [Fig. 2(b)], autocorrelation functions [Fig. 2(c)], and the speckle contrast [Fig. 2(d)]. As predicted by DWS theory, autocorrelation decays faster for longer paths, at the same time the speckle contrast saturates more quickly.

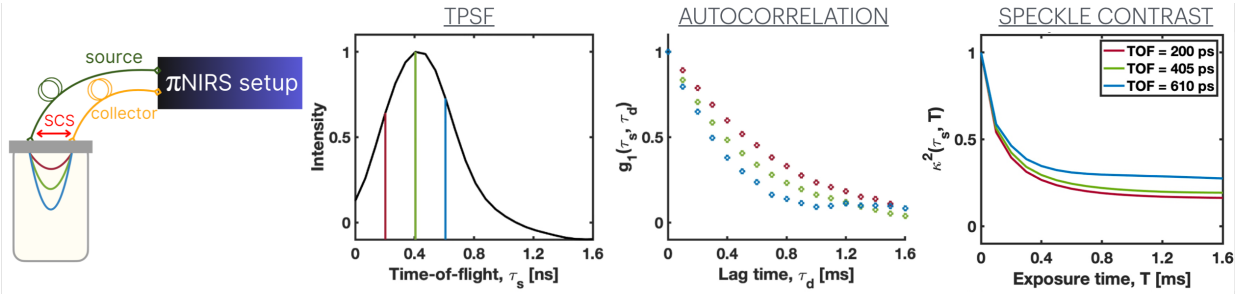

Fig 2. Schematic diagram of experimental setup for a liquid phantom validation.

Finally, we applied this approach to evaluate speckle contrast in the human forearm in vivo (SCS of 10 mm) [Fig. 3]. The speckle contrast was analysed for different time-of-flights within the sample. Similarly to the phantom study, the speckle contrast saturates faster for late photon paths than for shorter paths.

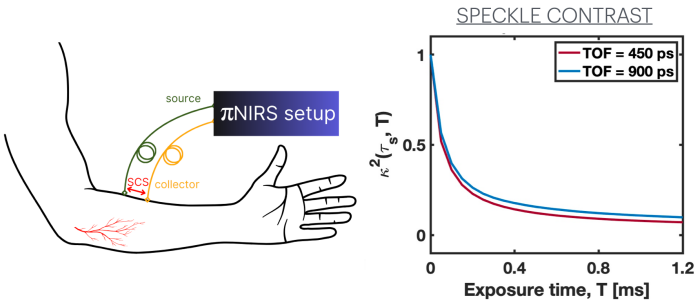

Fig. 3. Validation in a healthy 42-year-old human forearm.

3. Acknowledgement

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4. References

[1] Durduran, T., Choe, R., Baker, W. B., & Yodh, A. G., "Diffuse Optics for Tissue Monitoring and Tomography", Reports on progress in physics. Physical Society (Great Britain), 73(7), 076701 (2010).

[2] Dietsche, G., Ninck, M., Ortolf, C., Li, J., Jaillon, F., & Gisler, T., "Fiber-based multispeckle detection for time-resolved diffusing-wave spectroscopy: characterization and application to blood flow detection in deep tissue," Applied Optics 46, 8506-8514 (2007).

[3] Liu, W., Qian, R., Xu, S., Konda P.C., Jönsson, J., Harfouche, M., Borycki, D., Cooke, C., Berrocal, E., Dai, Q., Wang, H., & Horstmeyer, R., "Fast and sensitive diffuse correlation spectroscopy with highly parallelized single photon detection", APL Photonics 6(2), 026106 (2021).

[4] Wayne, M. A., Sie, E. J., Ulku, A. C., Mos, P., Ardelean, A., Marsili, F., Bruschini, C., & Charbon, E., "Massively parallel, real-time multispeckle diffuse correlation spectroscopy using a 500 × 500 SPAD camera", Biomedical Optics Express, 14(2), 703–713 (2023).

[5] Samaei, S., Nowacka, K., Gerega, A., Pastuszak, Ż., & Borycki, D, "Continuous-wave parallel interferometric near-infrared spectroscopy (CW πNIRS) with a fast two-dimensional camera", Biomedical Optics Express, 13(11), 5753–5774 (2022).