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Citation Format:

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DOI abstract link:

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Large area SiPM and high throughput timing electronics: toward new generation time-domain instruments

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ABSTRACT

We present here a novel time-domain diffuse optical detection chain consisting of a large area Silicon PhotoMultipliers (SiPM) coupled to a high count-rate timing electronics (TimeHarp 260 PICO) to achieve sustainable count-rates up to 10 Mcps without significant distortions to the distribution of time-of-flight (DTOF). Thanks to the large area of the detector (9 mm^2) and the possibility to directly place it in contact with the sample (thus achieving a numerical aperture close to unity), the photon collection efficiency of the proposed detection chain is almost two orders of magnitude higher than traditional fiber-mounted PMT-based systems. This allows the detection also of the few late photons coming from deeper layers at short acquisition times, thus improving the robustness of the detection of localized inhomogeneities. We then demonstrate that, despite the high dark count rate of the detector, it is possible to reliably extract the optical properties of calibrated phantoms, with proper linearity and accuracy. We also explore the capability of the new detection chain for detecting brain activations. This work opens up the possibility of ultimate performance in terms of high signal and photon throughput, with compact, low cost, relatively simple front-end electronics detector coupled to innovative timing electronics, with exciting opportunities to expand it to tomographic applications.

Keywords: Time-Domain Diffuse Optics, Large area SiPM, High throughput systems

1. INTRODUCTION

Non-invasive clinical diagnostics[1] is becoming increasingly popular among clinicians and researchers alike. Diffuse Optics[2] (DO) is a powerful tool that can be used to probe highly scattering media such as biological tissue by injecting photons and collecting the re-emitted photons at a certain distance. DO has been employed to tackle a wide variety of applications such as detection of task related brain activation, optical mammography, muscle oximetry, food quality assessment, etc. In recent years, many advancements in terms of laser sources, detectors, timing electronics, optical fibers and measurements techniques[3,4,5,6,7,8,9] have been proposed to improve the TD technique and to make it more competitive with its most common and commercially available counterpart such as Continuous Wave (CW). TD not only exploits the fact that when injecting a laser pulse into the tissue, photons undergo many scattering and absorption events, but also that the pulse exiting the tissue encodes in its shape the optical properties of the medium, thus bringing information about its main constituents. Moreover, the depth information is encoded in photon arrival times.

Since the scattering media strongly attenuates the photon intensity, especially for the late photons, it is essential to have a detection chain with a large photon collection efficiency, thus being able to detect in a short acquisition time even the faint late signal that carry information about the deeper region. The field of single-photon detection in TD-DO has been mostly dominated by Photo Multiplier Tubes (PMTs), thanks to their large active area and low dark counts. However, they are bulky, expensive and highly sensitive to strong ambient light illumination. In last few years SiPMs have emerged as an attractive new alternative to PMT-based systems. They are compact, low cost, rugged and they need relatively simple front-end electronics, making them ideal for clinical and point-of-care diagnostics. It has already been demonstrated that SiPMs can be used reliably in TD-DO[10] in conjunction with time-correlated single-photon counting (TCSPC) boards.

However, the maximum achievable count-rate for traditional TCSPC boards is limited to a few million counts per second due to their relatively long dead times[11] (>100 ns). By reducing it, it is possible to substantially improve the count-rates (up to few tens of millions of counts per second). Another possible approach is to use a time-gated detection (i.e. to acquire only the late photons, see [12,13]) but in this case the non-idealities of the detector/laser can limit the achievable performances (see [14,15]).

Here we evaluate the effectiveness of a novel detection chain employing a commercial 9 mm^2 active area device (S13360-3050CS, Hamamatsu Photonics, fill factor of 74%) with home-made front-end electronics in some cases combined with the TimeHarp 260 PICO[16] (dead time of < 25 ns and a minimum time bin width of 25 ps) capable of handling large count-rates. As a preliminary step, we assess the detector performances using protocols meant for DO systems/imagers such as: i) the basic instrumental performance (BIP)[17] to evaluate the detector response and its light collection efficiency; ii) the MEDPHOT[18] protocol to assess the retrieval of absorption and scattering properties in homogenous media ; iii) nEUROPt[19] protocol to test the ability to detect localized absorption inhomogeneity in depth within a semi-infinite diffusive. Finally, preliminary in-vivo measurements were performed on a healthy adult to show the suitability of a high-count rate system in monitoring hemodynamic changes in the motor cortex during a finger tapping exercise.

2. INSTRUMENT DESCRIPTION AND CHARACTERIZATION

The SiPM and associated electronics was hosted in a compact 3D printed probe (27 x 34 x 20 mm), cooled to 17°C using a 1 W Peltier cooler and operated at an excess bias of 4V above its breakdown voltage (52.3 V). The resulting Dark Count Rate (DCR) is about 300 kcps. The injected laser pulses (repetition rate: 40 MHz) were provided by pulsed diode lasers with wavelength 670 nm and 830 nm (LDH-P-C-670M and LDH-P-C-830M, Picoquant GmbH, Germany) at 670 nm and 830 nm respectively. The detector was preliminary characterized coupled to standard TCSPC electronics (SPC-130) following the BIP protocol. The Instrument Response Function (IRF) of system was found to be around 280 ps at 670 nm. The responsivity, as defined in BIP (a measure of photon collection efficiency) was $3.18 \cdot 10^{-6}$ m^{2}sr at 670 nm, which is about two orders of magnitude higher than the state-of-the-art fiber bundle based hybrid PMTs[20]. This is due to the large collection area and the direct placement of the detector in contact with the phantom resulting in larger numerical aperture compared to the standard fiber-bundle based systems.

As described in the MEDPHOT protocol, measurements were performed over a series of 32 phantoms with nominal absorption coefficient (μ_a) ranging from 0-0.5 cm^{-1} and nominal reduced scattering coefficient (μ_s') from 5-20 cm^{-1} using a source-detector separation of 3 cm and 5 cm at 670 nm and 830 nm wavelengths. The optical properties were retrieved by fitting the time-resolved reflectance curve, according to the model described in literature[21]. It was verified that the detector can follow linear changes in scattering and absorption over the range of optical properties corresponding to biological tissues (data not shown). To evaluate the sensitivity to localized inhomogeneities buried within a medium, we measured the contrast produced by inclusions set at different depths as described in the nEUROPt protocol. The mechanically switchable solid inhomogeneous phantom[22] was used with an inclusion corresponding to an equivalent absorption value of 0.17 cm^{-1}. The contrast (see[15]) was calculated as a function of inclusion position for both depth scan and lateral scan for various time-windows of width 400 ps starting at the IRF barycenter. The contrast achieved for depth scan is shown in Figure 1.a.The measurements were carried out at a source-detector separations of 3 cm at 670 nm wavelength.

3. IN VIVO MEASUREMENTS

Preliminary in-vivo measurements were carried out to evaluate the effectiveness of the detection chain in following changes in oxy and deoxyhemoglobin concentrations (O_2Hb and HHB, respectively) in healthy human volunteers in motor cortex during finger tapping exercises[23]. Contralateral activation was monitored by placing the probe on C3 position (left hemisphere) according to the 10/20 EEG system while performing left and right hand finger tapping exercise consisting of 20 second blocks of rest, activation and recovery. The exercise was repeated 5 times for each hand used. A source-detector separation of 4 cm was used along with two wavelengths at 670 nm and 830 nm. Changes in O_2Hb and HHB were calculated using the Beer-Lambert law.

Figure 1.b and c show the variation of O_2Hb and HHb during left hand and right hand finger tapping respectively. The values averaged over 5 repetitions are shown and the error bars represent the deviation over the repetitions. In the contralateral hemisphere an appreciable activation is observed corresponding to right hand finger tapping whereas no noticeable activation is observed in the ipsilateral hemisphere corresponding to the left hand finger tapping clearly showing task-related activation. The high count-rate capability of the TimeHarp 260 PICO allowed us to perform the measurements at a count-rate to 10^7 counts per second, resulting in substantially larger signal even at late photon arrival times, making it possible to probe deeper into the tissue.
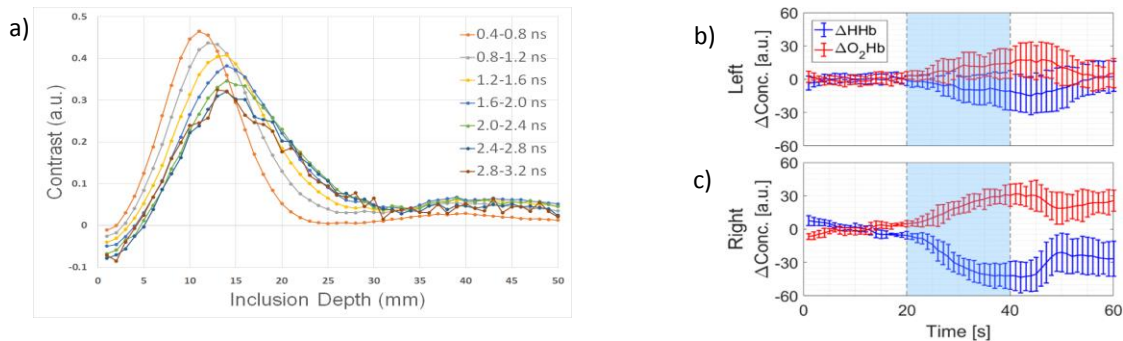
Figure 1.a) Contrasts as function of inclusion depth for different temporal windows; b) oxy- and deoxyhemoglobin corresponding to left hand finger tapping and c) right hand finger tapping.

4. CONCLUSIONS

We presented here a high throughput large-area SiPM-based detection chain with a photon collection efficiency about two orders of magnitude higher than state-of-the-art Hybrid PMT-based systems. Following the guidelines of well-established protocols for performance assessment of diffuse optical systems, we demonstrate the large-area SiPM is linear in following changes in optical properties and capable of detecting inhomogeneities. Finally, the high achievable count-rate allows to clearly monitor hemodynamic changes during cortical activation in finger-tapping exercises. In conclusion, this novel high throughput system opens up interesting avenues in the field of neuromonitoring.

ACKNOWLEDGMENTS

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