A CMOS-SPAD Array Line Scanning Imaging System for Biophotonic Applications

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Abstract: We present a 512 pixel CMOS-SPAD array line scanning imaging system for biophotonic exploitation in the near-infrared. Specifically we discuss utilising this imaging system for the time-resolved study of photon scattering from deep within tissue.

1. CMOS-SPAD Line Scanning Imaging System

2D single photon imaging arrays have been used to study time-resolved light passage through scattering media [1,2], however in many cases the light capture ability of the system is heavily limited by the detector fill-factor and total area. This work describes the use of an alternate method, applying a line array scanned on one axis to form a 2D image. This can offer improved light capture ability and increased spatial resolution for time-correlated single photon imaging. We implement the *RaII* sensor [3], a 512x1 pixel CMOS-based single-photon avalanche diode (CMOS-SPAD) line array, combined with a single mirror scanning system to form a camera like imaging system. The single line detector scans across the desired field of view to create 2D image frames composing of a series of sequential slices. Photon arrival timing electronics are integrated in the CMOS architecture. Unlike many similar 2D imaging arrays, the *RaII* sensor has a high fill factor (approximately 50%) as the integrated control electronics can be placed above and below the pixels. The line of 512 pixels define an image of this dimension on one axis, with an arbitrary dimension on the perpendicular axis controlled by the scanning mirror. Here we demonstrate such a system optimised with a working distance of 50 cm to achieve a 30 cm field of view (figure 1 a-c). The advantage of this approach over using a 2D imaging detector array is that we effectively recreate a high resolution large format imaging system, a 12mm line (the length of the line array) multiplied by the number of scanning positions used. While the need to scan in 1D reduces collection efficiency, this is more than compensated by the ability to use larger optics for efficient light collection. We directly compare light collection efficiency between this system and one based on a 2D array and examine utility in biophotonic applications.

1.1. The RaII Sensor

The *RaII* sensor was designed within the Systems and Sensors group at the University of Edinburgh. It operates with full time resolved single photon counting (TCSPC) functionality across the 512 pixels enabled through the integrated electronics. Single photon detection timing is recorded with approximately 50 ps time stamping and 150 ps timing jitter. Alternatively the detector can be operate in fast photon counting or on-chip histogram creation modes. Each pixel of *RaII* consists of 16 individual SPADs. The number of operational SPADs per pixel can be varied down from 16 in accordance with characteristic *dark noise*, meaning we can eliminate a controlled number of the noisiest SPADs per pixel. Exhibiting single photon sensitivity in the near-infrared "optical window" for biological tissue (around 800 nm) allows the exploitation of this system in a series of biomedical applications. We can observe light emitted by low-power pulsed laser sources (≈1mW) through multiple centimetre thick tissue samples. This enables time-resolved optical probing of tissue scattering, and the location of medical devices deep within tissue [2].

2. Biophotonic Applications

2.1. Time-resolved Imaging through Biological Structures

Time-resolved techniques have previously been applied to diffuse optical tomography [4] with light collection at discrete locations. However, working in an imaging modality we are able to perform stand-off measurements of light scattering through large samples over a large FOV. We study the scattering of a point source from deep within tissue in a time-correlated fashion using time-correlated single photon counting (TCSPC) imaging. In carrying out TCSPC measurements, we observe how the media effects light pulses relative to an unperturbed pulse. This perturbation manifests itself via various effects including; broadening, amplitude reduction and induced temporal delay. [5] Quantifying such effects enables characterisation of media based on how near-infrared light spreads

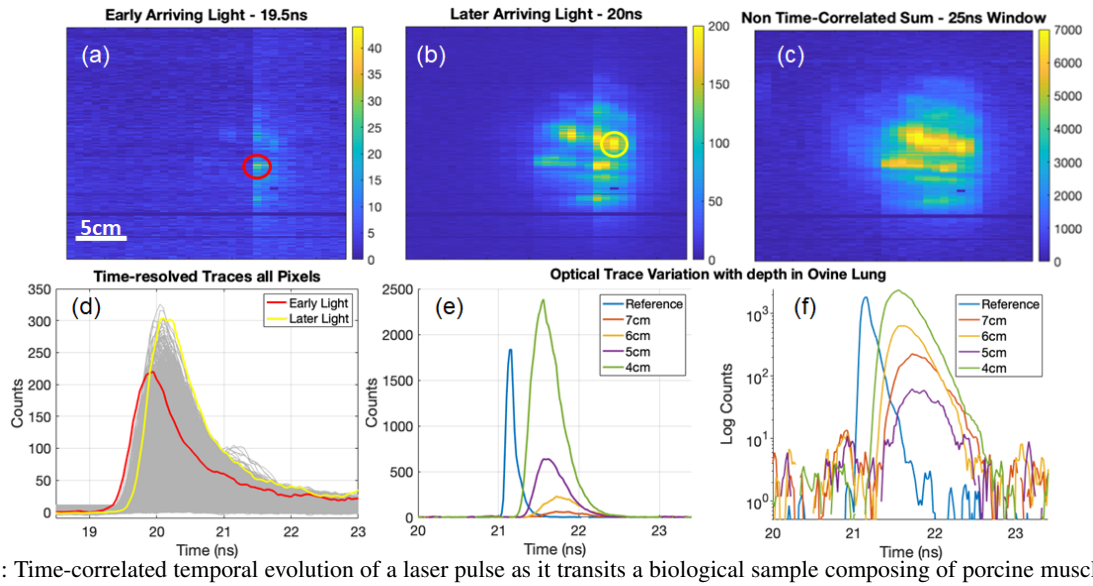

Fig. 1: Time-correlated temporal evolution of a laser pulse as it transits a biological sample composing of porcine muscle and bone (ribs), two time points separated by 0.5ns are shown (a,b) as well as a cumulative image over the whole 25ns measurement window (c). (d) shows the full TCSPC traces, earlier and later arriving scattered light are highlighted corresponding the pixels marked in (a) and (b). (e) Shows TCSPC observation of increased light scattering through increasing depths of lung tissue, (f) displays the same data, placed on a logarithmic scale to highlight the induced changes.

through the scattering system, and the ability to probe media characteristics inherently linked to light passage. [1] By placing a pulsed laser source behind a biological sample, we can image and analyse how light passes through the system at the single photon level, revealing details about sample structure and optical properties. Models consisting of porcine ribs and ovine lungs were used to create the plots shown in figure 1. Figures 1(a,b,c) describe evolution of an optical pulse through a porcine rib model. Figure 1(c) displays the total sum over the entire 25ns measurement window, revealing the muscle and bone rib structure, essentially displaying information available from a conventional imaging system. However, by selecting a single time-point from early within the measurement window, we can highlight the point at which first light was captured at a meaningful level above the noise floor (figure 1(a)) and compared to later exiting light (figure 1(b)). The brightest images pixels in (a) and (b) are highlighted, corresponding to the coloured lines in figure 1(d). Figure 1(d) displays the transient signal from every pixel in our scan, revealing scattering information about the light passage in every case. The highlighted early light which can be seen in figure 1(a) can be clearly distinguished as arriving earlier than the following, more diffuse photons. Figure 1(e,f) display results of pulsed laser light signal variation with depth inside an ovine lung, we can see that with ever increasing depth, the intensity of the signal will of course change, but critically, relative to an unperturbed pulse, we can view other effects such as temporal shifting and pulse broadening as we vary the amount of scattering media the light is travelling through. We quantify these effects to characterise scattering in tissues.

2.2. Medical Device Location

By monitoring NIR light passage in a time-correlated fashion, we have the ability to locate pulsed light sources deep within tissue by exploiting arrival time differences between early arriving photons and their diffuse, later-arriving counterparts. This camera development aims to improve the existing medical device location technique introduced by Tanner et al. (2017) [2]. A pulsed light source can be packaged with existing medical devices for placement within full-sized clinically relevant models, this represents the next stage of trials using the *RaII* based imaging system. Critically, *RaII*'s increase in active area relative to the previously used 2D detector array leads to increased photon detection capability. This provides the key motivation for upgrading the previously implemented 2D detector array.

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