Time-Domain Diffuse Optics: the Dawn of Next-Generation Devices

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Diffuse Optics (DO) is a powerful tool to probe scattering media avoiding invasive techniques, hosting the potential to revolutionize clinical applications from oncology to neurology and also many other fields [1, 2]. The traditional Continuous-Wave (CW) approach has never reached the required performance being severely hampered by the strong interplay between absorption and scattering and the need to detect reemitted light at some centimetres from the injection point, thus lowering the useful signal and impairing the spatial resolution. Time-Domain (TD) approaches are potentially more effective in terms of quantitation, penetration depth and sensitivity, but traditionally affected by the need to use bulky, expensive and fragile instrumentation, thus strongly limiting the number of injection and detection points. We demonstrated with simulations that TD-DO must face three main challenges to reach a ultimate performance breakthrough: *i*) the use of a dense arrangement of pulsed sources directly hosted into the optical probe (*C1*); *ii*) an equivalent arrangement of large area time-resolved single-photon detectors (*C2*); *iii*) the fast-gating capability of each detector to increase the dynamic range by orders of magnitude, thus allowing small source-detector distances (*C3*) [3]. In this ideal case DO will reach a 6 cm penetration depth (Fig. 1 left), thus opening to novel applications like the lung or heart monitoring.

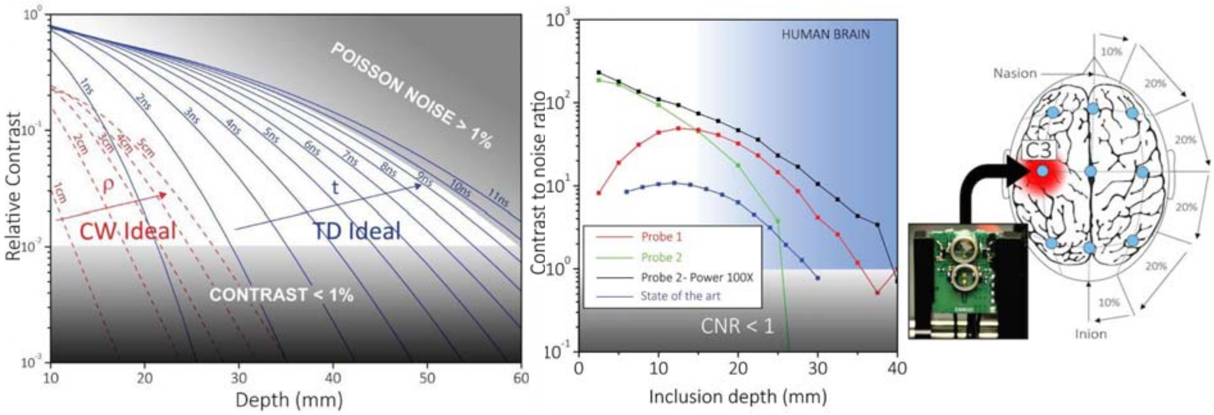

Fig. 1. (left) Simulation of the contrast produced in a realistic case using ideal CW and TD systems. (centre) Experimental results on contrast-to-noise ratio obtained using TD probes. (right) Probe positioning example for functional brain imaging.

Since technology is still far from allowing *C1+C2+C3*, we separately demonstrated these concepts using emerging technologies able to replace the traditional bulky instrumentation, thus allowing the direct hosting onto the probe and a large number of channels thanks to the low cost. We realized: *i*) a first probe (#1) using a pulsed Vertical-Cavity Surface-Emitting Laser (VCSEL) to potentially allow a dense arrangement (*C1*) and a time-resolved Silicon Photomultiplier (SiPM, never used in TD-DO) to fulfil the large area requirement of *C2*; *ii*) a second probe (#2) using a VCSEL and a gated Single-Photon Avalanche Diode (SPAD) to demonstrate the on-probe gating capability of the SiPM basic building block towards *C3*. Pulse generators and timing electronics are still external, yet full on-board integration using already proven technologies is feasible. Measurements showed that both probes yield already comparable contrast and better contrast-to-noise ratio (Fig. 1 centre) as compared to a state-of-the-art TD instrument. We also increased 100 times the source power using an external laser to simulate the potential improvement coming from a dense arrangement of many VCSELs (*C1*). The path is now opened, with the possibility of rapid progress thanks to the use of technologies developed for parallel fields like positron emission tomography systems. We are at the dawn of a new era for Diffuse Optics.

References

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