The µNTS: a wearable, modular, high-density diffuse optical tomography system

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Abstract: We present a wearable, high-density diffuse optical tomography system that can provide a channel density exceeding 6 channels/cm^2, with source-detector separations from 10 mm to >60 mm, as measured in-vivo in the adult.

OCIS codes: (170.6960) Tomography; (170.0110) Imaging systems; (230.0250) Optoelectronics.

1. Introduction

In diffuse optical tomography (DOT), depth-resolved images of the concentration of the oxygenated and deoxygenated forms of haemoglobin are obtained using multiple sources and detectors of near-infrared light arranged to provide a multiple source-detector separations and overlapping sensitivity profiles [1]. While DOT has numerous advantages (it is non-invasive, non-ionizing, inexpensive and well tolerated by a wide range of subjects) its uptake as a functional neuroimaging methods has been limited by several fundamental challenges. These challenges include its traditionally limited resolution and the sensitivity of diffuse optical methods to haemodynamics in the superficial tissues (particularly the scalp) [2], which can corrupt measurements of the brain.

In recent years, a range of studies have demonstrated that increasing the sampling density of DOT methods significantly improves both their resolution and their ability to separate scalp and brain haemodynamics [3,4]. However, the continued use of optical fibre bundles limits how far researchers have been able to push high-density DOT methodologies. The size and weight of optical fibre bundles restricts how many sensors can be applied to the scalp, which in turn limits sampling density and/or field-of-view. Increasing the number of optical fibre bundles also quickly undermines one of the key advantages of DOT; i.e. that the technique is highly portable.

The ability to image human brain function using a wearable device has long been a goal of near-infrared spectroscopy (NIRS) and diffuse optical tomography research, and several wearable diffuse optical technologies are already commercially available. However, these technologies are either cumbersome, have a limited field of view, or provide insufficient channel number and density to perform effectively as imaging systems.

In late 2016, we presented the first functional images of the human brain obtained using a fibreless, high-density DOT system [5]. Known as the micro-NTS (µNTS), this system consists of multiple independent DOT modules that each contain multiple sources and detectors and can easily be coupled to the scalp in any arrangement. We previously demonstrated a 4-module system, with each module based on a 30 × 30 mm printed circuit board (PCB), on which were mounted two dual-wavelength LED sources and four photodiode detectors (Fig. 1a). Here we present several significant developments to our module design that improve dynamic range, channel density, field of view and data quality.

2. Materials and Methods

2.1. The µNTS

The upgraded µNTS system consists of twelve independent DOT modules, each constructed from a 27 × 27 mm PCB. Each module now includes 6 photodiodes detectors (Hamamatsu, Japan) and 2 dual-wavelength LED sources comprised of 740 and 855 nm LEDs (OSA-Opto, Germany) (Fig. 1b). Each photodiode is connected to the analogue input of a charge-to-digital converter (DDC118, Texas Instruments, USA), which includes a charge integration amplifier and a 20-bit analogue-to-digital converter (see Chitnis et al. for more information). Each module PCB also now incorporates a motion sensor (Invensense Inc. USA) that provides 3-axis accelerometry and 3-axis gyroscope data at a rate of 100 Hz.

The optical layout of the tile has been re-designed to accommodate the additional photodiodes and is shown in Fig. 1b. Each module is housed in a multi-layer encapsulation that includes improved electromagnetic shielding and incorporates silicone light-guides to couple light from the module surface to the scalp of the subject. In addition to improved EM shielding the charge-integration timing sequence has been redesigned to improve the effective dynamic range of the system and prevent the detector saturation that was evident in Chitnis et al. [5].

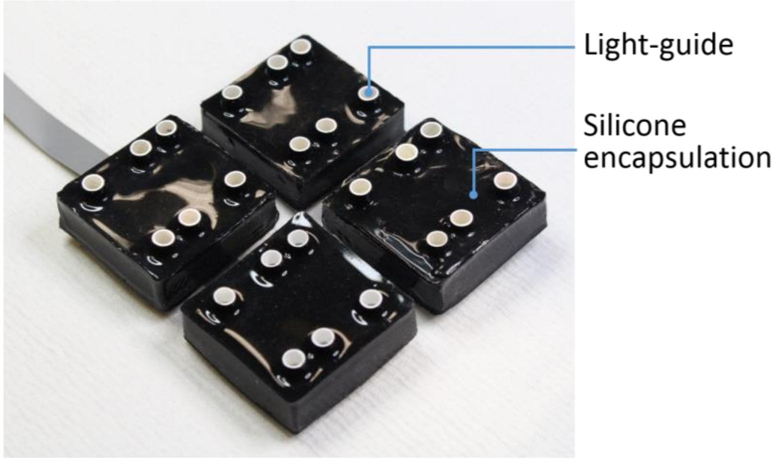

Fig 1a. The original module design

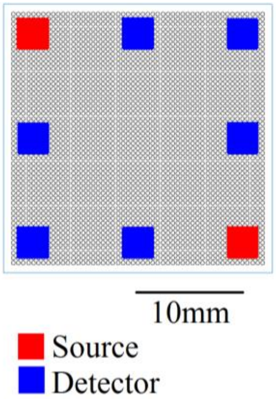

Fig 1b. The re-designed module with two additional photodiode detectors.

2.2 In-vivo data acquisition and pre-processing

In an initial test of the dynamic range and signal quality obtained using the upgraded μNTS system, a 33 year-old male was recruited to take part in a functional imaging study, which was approved by the UCL Research Ethics Committee. The subject was seated, and after measurements of the head were obtained, the μNTS system was placed carefully over the primary somatomotor cortex. Note that little effort was made to remove hair from underneath the μNTS modules.

To demonstrate the improved sensitivity and dynamic range of the μNTS, output values were converted to optical power measurements (in Watts), and compared with source-detector separation. The ratio of the standard deviation of an intensity measurement to its mean (SDMratio) was also used as a measure of signal quality. Two different thresholds of this ratio were used to identify good-quality channels. In the first case, channels were included if the SDMratio was below 7.5%, which is a value that has been used repeatedly in previous studies [4]. The second (less conservative) processing stream included channels where the SDMratio was below 25%, a value found in our previous study to be more appropriate [5].

3. Results and Discussion

Fig. 2 provides a plot of the measured optical power as a function of source-detector separation for the upgraded μNTS system. The noise floor of the system (calculated as the maximum standard deviation of dark counts) is indicated with the black dashed line. The effective dynamic range of the system now exceeds 120 dB and can be increased further through optimization of the charge integration strategy. Fig 3 shows a stacked histogram of the channels deemed acceptable by the SDMratio approach as a function of source-detector separation, showing that high-quality data is obtained upto and beyond 60 mm, in an adult subject with hair.

We are now finalizing the 12-module system that when arranged in a 2 × 6 pattern will provide approximately 700 DOT channels over an area of ~100 cm^2, which is sufficient to cover the entire adult somatomotor cortex. Initial experiments also suggest that the μNTS is far less vulnerable to motion artifacts than a traditional fibre-based system. By taking advantage of the 6-axis motion sensor that is now present on each module, we intend to use this system to produce high-quality images of human brain function during naturalistic movement for the first time. This will demonstrate the vast range of functional neuroimaging experiments which are now possible due to advances in wearable, high-density DOT technology.

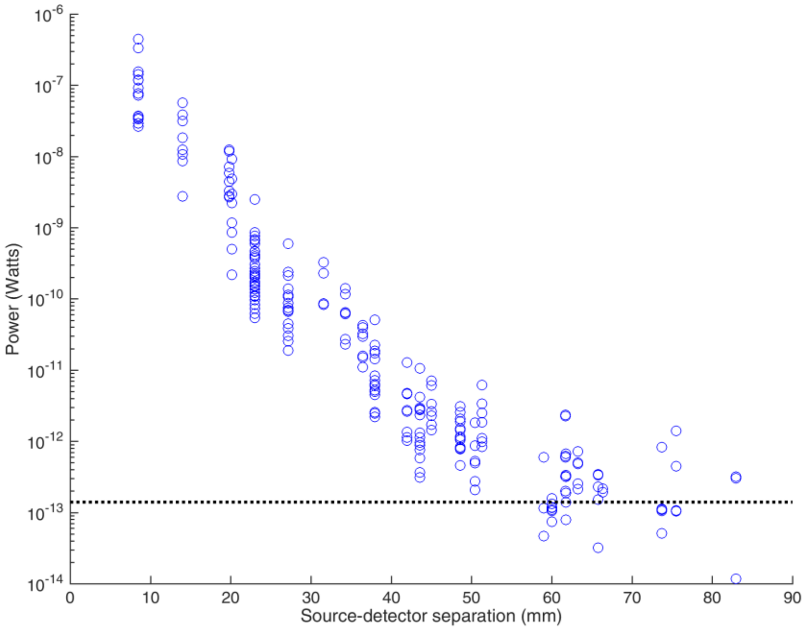

Fig 2. The mean measured power as a function of source-detector separation in one adult subject

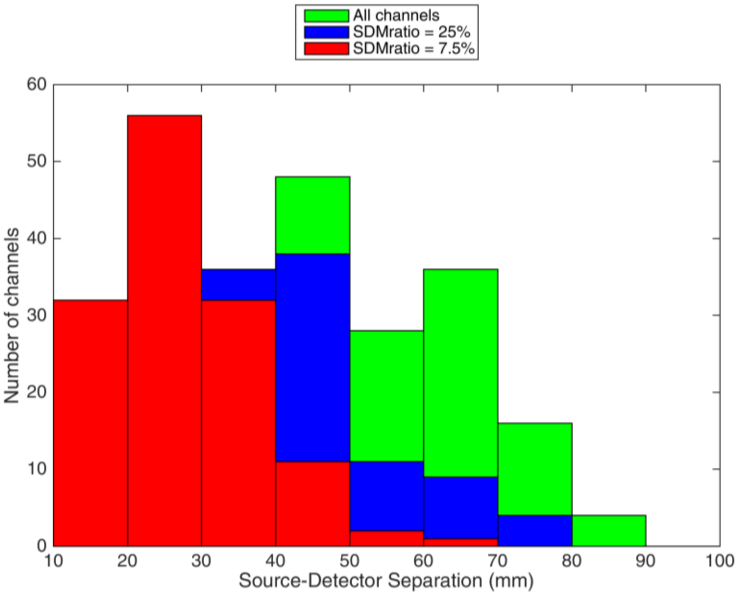

Fig 3. A stacked histogram of channels identified as good quality via the SDMratio approach at two thresholds.

References

1. S. R. Arridge, “Methods in diffuse optical imaging,” *Philos. Trans. R. Soc. Math. Phys. Eng. Sci.*, vol. 369, no. 1955, pp. 4558–4576, Nov. 2011.
2. L. Gagnon, K. Perdue, D. N. Greve, D. Goldenholz, G. Kaskhedikar, and D. A. Boas, “Improved recovery of the hemodynamic response in diffuse optical imaging using short optode separations and state-space modeling,” *NeuroImage*, vol. 56, no. 3, pp. 1362–1371, Jun. 2011.
3. B. W. Zeff, B. R. White, H. Dehghani, B. L. Schlaggar, and J. P. Culver, “Retinotopic mapping of adult human visual cortex with high-density diffuse optical tomography,” *Proc. Natl. Acad. Sci.*, vol. 104, no. 29, pp. 12169–12174, Jul. 2007.
4. A. T. Eggebrecht, S. L. Ferradal, A. Robichaux-Viehoever, M. S. Hassanpour, H. Dehghani, A. Z. Snyder, T. Hershey, and J. P. Culver, “Mapping distributed brain function and networks with diffuse optical tomography,” *Nat. Photonics*, vol. 8, no. 6, pp. 448–454, Jun. 2014.
5. D. Chitnis, R. J. Cooper, L. Dempsey, S. Powell, S. Quaggia, D. Highton, C. Elwell, J. C. Hebden, and N. L. Everdell, “Functional imaging of the human brain using a modular, fibre-less, high-density diffuse optical tomography system,” *Biomed. Opt. Express*, vol. 7, no. 10, pp. 4275–4288, Oct. 2016.