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ANIMATE: Wearable, Flexible, and Ultra-Lightweight High-Density Diffuse Optical Tomography Technologies for Functional Neuroimaging of Newborns

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Abstract: We have developed a series of wearable high-density diffuse optical tomography (HD-DOT) technologies specifically for neonatal applications. These systems provide an ultra-lightweight form factor, a low profile and high mechanical flexibility. This new technology is validated using a novel, anatomically accurate dynamic phantom.

1. Introduction

Neonates are highly vulnerable to brain injury. The risk of brain injury is greater during the first days and weeks after birth than at any other time of life [1]. Functional neuroimaging that can be performed repeatedly and at the cot-side could potentially help improve our understanding of the evolution of multiple forms of neurological injury over the perinatal period. However, there is currently no suitable technology to perform repeated and/or long-duration functional neuroimaging experiments at the cot-side.

Functional Near-Infrared Spectroscopy (fNIRS), and its extension Diffuse Optical Tomography (DOT), allow functional neuroimaging of the human cortex to be cheap, accessible, easy to use, and available at the bedside or in almost any other environment [2]. In the last decade, it has been demonstrated that using more sources and detectors packed into a "high density" array can provide improved spatial resolution and specificity relative to fNIRS and traditional DOT approaches [3]. However, due to the requirement of an increased channel count, the construction of wearable HD-DOT devices is challenging. For neonatal applications, the mechanical and optoelectronic design requirements of wearable devices are even more stringent. Wearable technologies need to be smaller, lighter, and able to conform to the highly-curved neonatal scalp.

Herein, we propose a series of wearable, modular, rigid-flexible HD-DOT technologies (named ANIMATE) that have been designed specifically for imaging the sensorimotor system of the term and preterm neonate. Our approach yields a system that is significantly smaller and lighter than all existing high-channel-count fNIRS/DOT devices, while also achieving a reconfigurable design and the mechanical flexibility necessary to allow each module to conform well to the highly-curved infant scalp.

2. Methods

2.1 Module Design

A sophisticated 10-layer rigid-flexible PCB technology was utilized to construct the HD-DOT modules. To date, we have currently developed two versions of the ANIMATE systems. Version one (v1) consists of two patterns of rigid-flexible module, dual-hexagon (dual-hex) and triple-hexagon (tri-hex), (see Fig.1a-b). Each module consists of a flexible chain of either 2 or 3 regular hexagonal units. Each hexagonal unit is adapted from the Gowerlabs LUMO module (www.gowerlabs.co.uk), and is equipped with 3 dual-wavelength LED sources (735nm and 850nm) and 4 silicon photodiode detectors (Fig.1a). Source-detector separations of 10 mm (9 channels) and 20 mm (3 channels) are produced within each hexagonal unit. In each hexagonal unit, the LEDs are modulated by an LED driver and the optical data acquired by each photodiode is transmitted to 1 of 4 channels of an on-board analog-to-digital converter (ADC). A local micro-controller unit is embedded in each hexagonal unit for logic control and two-way communication. In-built board-to-board connectors are implemented on a dedicated connector tab in each module so as to remove the need for conventional cabling (Fig.1a). A flexible section is present between each connector tab and the adjacent rigid hexagonal unit to provide additional flexibility and articulation of the connector.

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Building upon this flex-rigid design, another version of the ANIMATE system (named ANIMATE v2) has been implemented using the same individual hexagonal unit. However, in v2, a second rigid hexagonal section is folded back to produce a stacked board pattern. This additional board surface area allowed us to add connectors that permit the use of short lengths of cabling so as to build a stable daisy-chain of modules (Fig.1c-d). While exhibiting a higher profile than v1, the v2 system is expected to provide a more robust mechanical design, while the shielded cabling and stacked board pattern will provide additional noise isolation. This design should therefore facilitate longer-term application in clinical environments (where the environment is electrically noisy and devices will have to be handled by clinical staff).

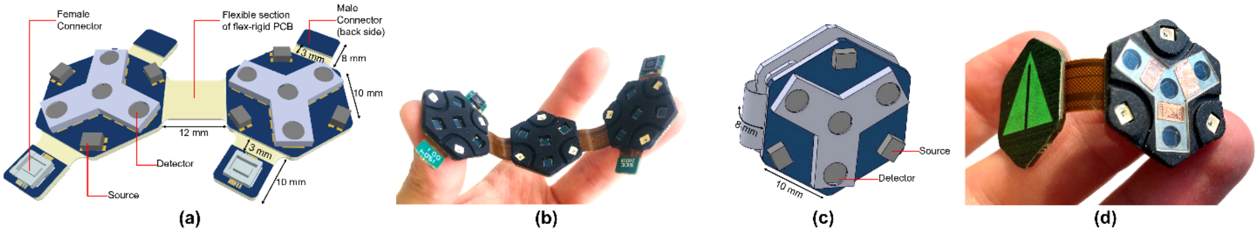


Fig.1. 10-layer rigid-flexible HD-DOT modules of two versions of designs: ANIMATE v1 dual-hex module (a) and tri-hex module (b); and ANIMATE v2 switch-back, stacked module (c-d).

2.2 Combining Multiple Modules

For ANIMATE v1, board-to-board connectors have been built into each module, thus modules can be easily connected together in a vast range of possible layouts. As a first demonstration of this system, 3 dual-hex and 2 tri-hex ANIMATE v1 modules were connected in a 2-3-2-3-2 layout configuration (Fig.2a). This 12-hex DOT imaging array produces coverage of ~60 cm^2, which will sufficiently cover the sensorimotor cortex of the term-age neonate. There are 36 source and 48 detector locations in this system so as to produce 1728 logical DOT channels per wavelength. For ANIMATE v2, modules connect together to form a daisy-chain as shown in Fig.2b, which can then be contorted into an arbitrary array layout.

For each system custom silicone encapsulations are applied to each hexagonal unit to provide electrical insulation and produce a cleanable, sealed surface appropriate for clinical application. A finished imaging array is connected to a commercial control unit (LUMO Hub, Gowerlabs Ltd) for interfacing, communication, and power transmission (via a single lightweight cable). The control unit is then connected to a laptop/PC via a USB port. Each system operates at a full frame rate of 10 Hz.

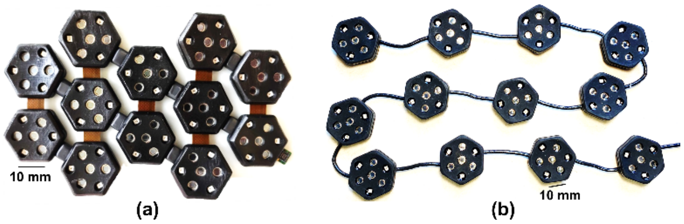


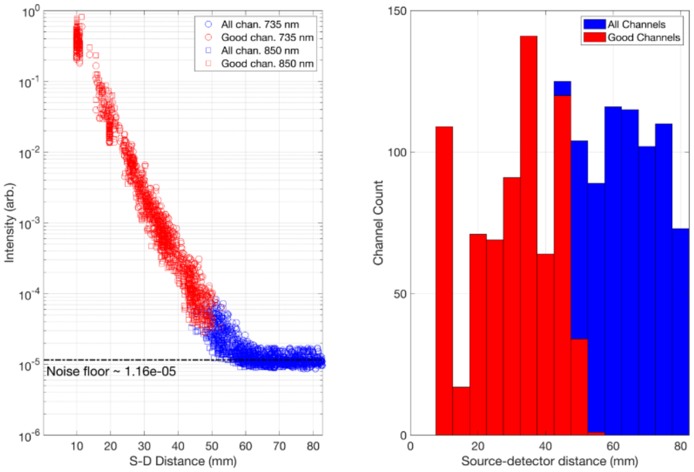
Fig.2. (a) The 12-hex DOT imaging array built using 3 dual-hex and 2 tri-hex ANIMATE v1 modules, with encapsulation. (b) A daisy-chain setting of twelve ANIMATE v2 modules.

2.3 Phantom Design and Experiment

In order to evaluate the capability of the proposed ANIMATE HD-DOT imaging arrays, a new dynamic thermochromic phantom was developed. Epoxy resins were utilised to construct this optical new phantom with background optical properties of $\mu_a = 0.02$ mm^{-1} and $\mu_s' = 1$ mm^{-1}. The phantom shape was based on the 39-week infant scalp surface that from the 4D neonatal head model published by Brigadoi et al. [4]. Two thermochromic targets were produced for the dynamic phantom (one for left and right side) and positioned in the location of the primary motor cortices) [5].

3. Results

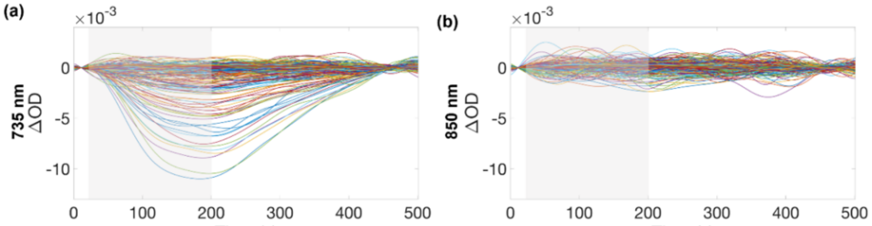
As shown in Fig.3a, the noise floor of the HD-DOT array is measured as 1.16×10^{-5} (arbitrary intensity units). Given that the upper measurement limit is 2.5 (arbitrary intensity units), it implies a measured dynamic range of 106.6 dB. Fig.3b shows the histogram of all possible channels and the accepted channels (good channels) generated on the dynamic phantom as a function of source-detector separation. This 12-hex HD-DOT array produces 1728 logical DOT channels in total per wavelength, and 717 of them are classified as good channels per wavelength (<= 45 mm).



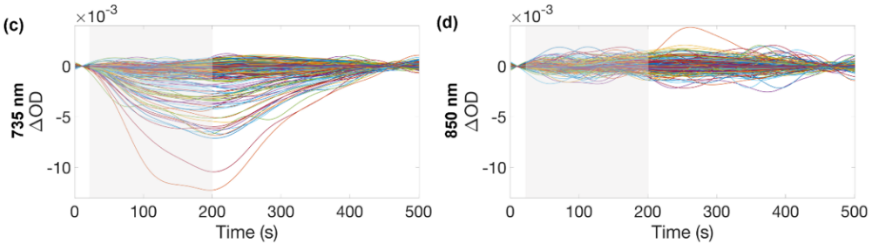
(a) (b)

Fig.3. (a) The channel optical intensity measurements as a function of their source-detector separation for the ANIMATE v1 system on a phantom. Channels that passed out pre-processing thresholds are depicted in red. (b) Histograms of all possible channels (blue) and accepted channels (red) generated on the dynamic phantom as a function of the source-detector separation.

Fig.4 demonstrates the response to the phantom target activations (both left and right sides) for 735 nm and 850 nm. The channels that exhibited a response show clear changes in optical density with the latency to peak of approximately 160-180s from the start of the activation (the thermochromic heating phase). The changes in optical density are evident in a number of channels at 735 nm.



Left hemisphere target



Right hemisphere target

Fig.4. The change in optical density as a result of the activation of the left/right hemisphere target for the 735 nm (a)/(c) and 850 nm (b)/(d) wavelengths, respectively. The heating period is indicated by the grey shaded area.

4. Conclusion

The HD-DOT (ANIMATE) systems presented here are small, ultra-lightweight, reconfigurable, have a high dynamic range, and can conform to the highly-curved infant scalp. It is expected that the ANIMATE technology will make functional neuroimaging of the neonatal brain at the cot-side significantly more practical and effective.

5. References

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