FetalSenseM: A Multi-Wavelength Near-Infrared Spectroscopy Device for In-Vivo Oxygenation and Metabolism Measurements

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Abstract: This work proposes a new design and novel wavelength selection for a multi-wavelength, multi-distance near-infrared spectroscopy device, which assesses in vivo changes in oxygenated and deoxygenated haemoglobin and oxidised cytochrome-c-oxidase concentrations, along with tissue saturation.

1. Introduction

Measuring tissue oxygenation and metabolism is essential for diagnosing and forecasting the progression of injuries and diseases. Near-Infrared Spectroscopy (NIRS) enables this non-invasively by detecting in-vivo shifts in key biomarker concentrations—oxygenated and deoxygenated haemoglobin (HbO2 and HHb), as well as cytochrome-c-oxidase (CCO). With growing applications in both research and clinical practice, NIRS has advanced significantly, particularly in the development of functional NIRS (fNIRS) devices designed for use outside the lab, aided by improvements in portability and wearability. Yet, most commercially available systems remain focused solely on oxygenation measurements, lacking the capability to effectively capture the metabolic shifts necessary for neurodevelopmental assessments [1].

Typical fNIRS technologies utilise 2 or 3 wavelengths to resolve for two chromophores; oxygenated and deoxygenated haemoglobin (HbO_2 and HHb). In theory, through the addition of one or more wavelengths ($\geq$ 3 total) we can resolve an additional chromophore, oxidised cytochrome-c-oxidase (oxCCO). The oxidation state of CCO reflects cellular metabolism, as the enzyme serves as the terminal electron acceptor in the electron transport chain, facilitating ATP production by reducing oxygen to water. Its copper A redox centre strongly absorbs NIR light, with a peak around 830-840 nm in its oxidized state [2]. Since total CCO levels remain stable over short periods, NIRS instead tracks fluctuations in oxidized CCO ([oxCCO]) as a metabolic marker.

The challenge in resolving this signal in vivo lies in its significantly smaller concentration compared to the haemoglobin, at around a tenth [3]. Work at UCL has shown that it is possible to constrain the number of measurement wavelengths and still achieve a high performance in estimating changes in concentrations of HbO_2, HHb, and oxCCO. While the use of a 3-wavelength combination leads to mean recovery errors of up to 10%, these errors drop to less than 4% with 4 or 5 wavelengths and to less than 2% with 8 wavelengths when compared to a gold standard [4].

This device is designed for oxygenation and metabolism measurements with dual-channel, dual-distance arrangement. To verify functionality, concentration changes in oxygenated and deoxygenated haemoglobin and oxCCO were tracked during a cuff-induced venous and arterial occlusion.

2. Methods

The FetalSenseM uses 6 wavelengths within the NIR range to ensure accurate recovery of change in chromophore concentrations: 780, 810, 830, 840, 850 & 890 nm. These are placed in source groups of 6 LEDs, with two of these groups centrally located on the rectangular sensor strip. Light detection is performed with two photodiodes placed symmetrically from the sources at the ends of the sensor strip. This arrangement provides 2 sets of 2 source detector separations (SDS), 3cm and 5cm. This makes it possible to employ algorithms such as spatially-resolved spectroscopy (SRS) and Dual Slope (DS) to recover absolute chromophore concentrations, and thus tissue oxygen saturations.

Table 1. Specification table for the FetalSenseM device

Specification	**Item**	**Description**
Dimensions	Control Module (mm)	70 x 120 x 32.5
	Sensor Module (mm)	150 x 50 x 8
	Cable Length (m)	1
Electrical	Supply	USB A: 5V 2.1A
	Power Requirements	5V, 100mA
Battery	Power Output (W)	10
	Capacity (mAh)	10000
Microcontroller	Device	SyncMOS Technologies SM59R16A5
	Processor	22MHz 8051 in 1T mode
	Memory	64kB
	Digital/Analog pins	40/8
	Processor Voltage	3.3V
Detector	Device	TI OPT101P
	Photodiode area (mm)	2.29 x 2.29
	Responsivity (A/W) @ 650nm	0.45
Light Source	Device	THORLABS LED"Wavelength"L
	Wavelengths (nm)	780, 810, 830, 840, 850, 890
	Forward Current (mA)	75
	Optical Power (W) @ 50mA	12 - 22
	Spectral FWHM (nm)	25 - 44

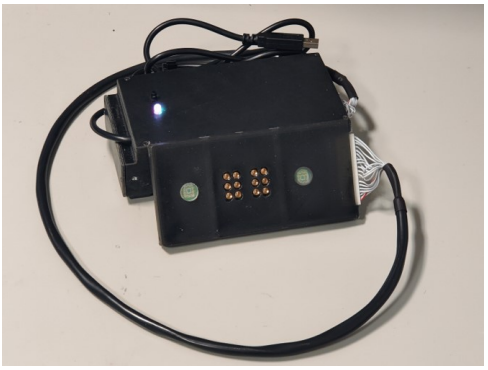

Fig. 1. Image of the FetalSenseM device, with sensor module displaying LED groups and detectors.

A summary of the device specification has been provided in table 1. The design consists of two modules; a control module where the driving electronics are held and a sensing module that houses the sources, detectors and other environmental sensors. By having the two modules separate, it is possible to apply the sensing module directly to the monitoring site on the patient, with the larger control electronics kept in a bag or a belt besides them. Figure 1 shows the completed device with each module connected by a flexible cable.

The device has two channels, created by alternating power to each of the 12 LEDs (6 per source group) at each of the distances, 3cm and 5cm. The light sources are monochromatic LEDs, which direct the light into the skin by a spherical glass lens. The photodiodes are coupled to NIR optical windows (THORLABS N-BK7) set into the sensor module casing to increase light throughput and providing electrical isolation. The sensor casing is constructed of rubberlike black photopolymer (Stratasys TangoBlack) at a shore hardness A of 95, to allow for conformity to the monitoring area on the patient. LED power and timing is regulated in the control module, where acquisitions of the photodiode voltage is made via an external 12-bit ADC. Here a single push button and RGB LED are available for user interface, the push button controls acquisition start and stop, and the LED indicates the status of the device; on, acquiring or off.

To verify the response of the FetalSenseM device when measuring in-vivo changes in oxygenation and metabolism, an arterial cuff occlusion can be performed to induce changes in chromophore concentration and validate the response in the measured spectra. The sensor module is placed on the participant's bare forearm,

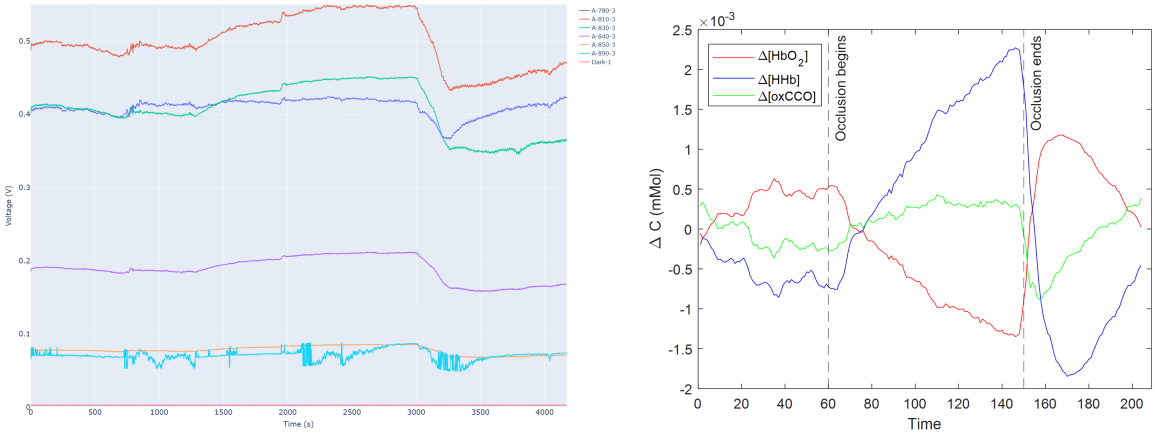

Fig. 2. Left: Intensity per wavelength received at one detector over the course of the occlusion. Right: Changes in chromophore during brachial occlusion.

along with a blood pressure cuff on the upper arm. Data was collected in the following periods: (A) baseline, (B) arterial occlusion, (C) baseline. Aterial occlusion was achieved by applying inflation pressure of 230 mmHg. Each period lasted 60 seconds for a total acquisition duration of 3 minutes. To convert the measured spectra into values for change in concentrations, the modified Beer-Lambert law-based UCLn algorithm was applied [5], using 3 cm SDS and a differential path factor (DPF) of 4.16 [6].

3. Results

Figure 2 shows an expected outcome from a cuff occlusion validation test. The overall spectral intensity is reduced during the vascular occlusion and recovering during the rest period. There is also a large increase in deoxygenated haemoglobin during the occlusion, with a converse response in the oxygenated, until the pressure is released, and the two concentrations sharply return to baseline, with some overshoot and then recovery.

4. Conclusion

This work introduces a multi-wavelength NIRS device designed to track in vivo changes in haemoglobin and cytochrome-c-oxidase, providing improved metabolic monitoring. Its six-wavelength selection and dual-channel design enhance measurement accuracy while maintaining a compact form. Validation via arterial occlusion confirms expected spectral responses, supporting its utility in both clinical and research settings.

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