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# Multi-channel Near-Infrared Spectroscopy (NIRS) System for Noninvasive Monitoring of Brain Activity

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***Abstract*—Near Infrared Spectroscopy is a noninvasive optical method to monitor hemodynamic activity in tissue using light in the range of 600 to 900nm. Various techniques and devices have been developed to utilize this method in a variety of medical fields such as, neuroscience, monitoring of newborn brain, muscle physiology and brain computer interface (BCI). In this paper we present design and implementation of a dual wavelength, multi-channel, continuous wave near infrared brain imager. The aim of this design is to produce a miniaturized, affordable, negligibly intrusive system that can monitor hemodynamic response of prefrontal cortex activity. The system consists of a sensor pad, a control board, a battery, and a data acquisition (DAQ) card. DAQ card acquires and digitize data and sends it to a computer for displaying the temporal and spatial information in real time as concentration changes in oxy-hemoglobin ($HbO_2$) and deoxy-hemoglobin (Hb). In addition the DAQ provides control signals to the control board. To test the system performance, experiments have been conducted with a static phantom that simulates optical properties of human brain tissue and changes in Hb and $HbO_2$ concentrations.**

## I. INTRODUCTION

UNLOCKING the brain and understanding better its capabilities, functioning, and pathologies is at the forefront of biological science research currently.

Near infrared spectroscopy (NIRS) was introduced in 1977 by F. F. Jobsis as a noninvasive way to monitor oxygen sufficiency. Since then NIRS and diffuse optical tomography using near infrared light has been explored for use in various clinical application. More recently, there's been a surge of research examining potential for use of NIRS technique in brain monitoring [2,3]. Since the nineties, it has been recognized that NIRS is well suited for brain monitoring due to the fact that light penetrates the skull well at near infrared range. The sensitivity of NIR light to local oxygenation changes makes it possible for direct measurement of hemodynamic [4]. This is the main advantage of NIRS over magnetic resonance imaging (MRI) techniques which calculate blood volume changes indirectly.

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The nature of NIRS technology makes it completely noninvasive. Also, the use of optical light in probing allows the equipment to be less restrictive, safer, and more portable than that of fMRI or PET. A very good review of NIR technology is provided by Boas et al. [5]. In this research design and implementation of a dual wavelength, 16 channels, continuous wave near infrared spectroscope for brain monitoring is presented.

In first section the basic concepts of optical physics behind NIRS system will be reviewed. Next we will discuss about instrument design and implementation and also how the functionality of the system validated. Finally the research will be summarized with a conclusion and discussion.

## II. OPTICAL BACKGROUND

NIRS equipments use either continuous wave (CW) light or pulsed light at picosecond resolution. The latter method is called time-resolved spectroscopy (TRS).

The equipment designed in this study is a CW type instrument. The CW-type method can detect dynamic changes in regional cerebral blood flow by measuring concentration changes in hemoglobin, both Hb and $HbO_2$, relative to a reference. With CW-type equipment, it is not possible to determine the absolute value of hemoglobin concentration changes due to its inability to obtain optical path length information. The CW-type equipments rely on the Beer-Lambert law to calculate the relative hemoglobin concentration changes. The Beer-Lambert law can be succinctly expressed as a linear relationship between absorbance and concentration.

$$A = -log\frac{I}{I_0} = \varepsilon^{\lambda} CL \qquad (1)$$

where A is the absorbance, I the intensity of received light, $I_0$ the intensity of transmitted light, $\varepsilon^{\lambda}$ the extinction coefficient at wavelength λ, C the concentration, and L the path length. For a highly scattering medium like brain tissue, a modified Beer-Lambert law is used . Change in absorbance at a specific wavelength λ can be expressed as:

$$\Delta A^{\lambda} = -\varepsilon^{\lambda} \Delta CL \qquad (2)$$

In terms of the concentration of two chromophores of interest, namely Hb and $HbO_2$, equation (2) becomes:

$$\Delta A^{\lambda} = (\varepsilon^{\lambda}_{Hb} \Delta[Hb] + \varepsilon^{\lambda}_{HbO_2} \Delta[HbO_2])L \qquad (3)$$

Assuming L = 1cm, there are two unknowns, the concentration changes in the two chromophores. By taking measurements at a second wavelength and using the known

ε at these wavelengths for each chromophores, equation (3) can be solved for concentration changes as follows:

$$\Delta \mathrm{Hb} = \frac{\log\frac{I^b(\lambda_2)}{I^s(\lambda_2)}\varepsilon_{oxy}(\lambda_1) - \log\frac{I^b(\lambda_1)}{I^s(\lambda_1)}\varepsilon_{oxy}(\lambda_2)}{\varepsilon_{oxy}(\lambda_1)\varepsilon_{deoxy}(\lambda_2) - \varepsilon_{oxy}(\lambda_2)\varepsilon_{deoxy}(\lambda_1)} \quad (4)$$

$$\Delta \mathrm{HbO}_2 = \frac{\log\frac{I^b(\lambda_1)}{I^s(\lambda_1)}\varepsilon_{deoxy}(\lambda_2) - \log\frac{I^b(\lambda_2)}{I^s(\lambda_2)}\varepsilon_{deoxy}(\lambda_1)}{\varepsilon_{oxy}(\lambda_1)\varepsilon_{deoxy}(\lambda_2) - \varepsilon_{oxy}(\lambda_2)\varepsilon_{deoxy}(\lambda_1)} \quad (5)$$

$\varepsilon_{oxy}(\lambda_x)$ and $\varepsilon_{deoxy}(\lambda_x)$ are constants also $I^s(\lambda_x)$ and $I^b(\lambda_x)$ can be obtained from the collected data. Thus $\Delta \mathrm{HbO}_2$ and $\Delta$Hb are the only unknowns and can be calculated. Substituting the values of extinction coefficients into equations (4), (5) yields:

$$\Delta \mathrm{Hb} = -0.3758 \log\left(\frac{\mathrm{I^b(\lambda_{850nm})}}{\mathrm{I^s(\lambda_{850nm})}}\right) + 0.9943 \log\left(\frac{\mathrm{I^b(\lambda_{730nm})}}{\mathrm{I^s(\lambda_{730nm})}}\right) \quad (6)$$

$$\Delta \mathrm{HbO}_2 = -0.6740 \log\left(\frac{\mathrm{I^b(\lambda_{850nm})}}{\mathrm{I^s(\lambda_{850nm})}}\right) + 1.1171 \log\left(\frac{\mathrm{I^b(\lambda_{730nm})}}{\mathrm{I^s(\lambda_{730nm})}}\right) \quad (7)$$

## III. INSTRUMENTATION

### A. System Objectives

The NIRS equipment developed in this study consists of the following components: the probe, control unit for desire source and photo-detectors selection and also for pre-amplifying and pre-filtering of signal, power supply, DAQ card and finally a computer for data analysis & displaying or in functional application for task presentation. figure 1 shows the overall NIRS system.

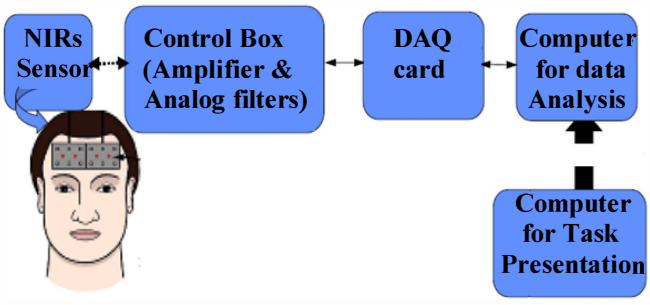


**Figure 1. Block diagram of the NIRS system [1]**

The participant wears a flexible headband that contains an array of four photodiodes and ten sensors (see figure 2). Each diode is coupled with its four neighboring sensors, yielding a total of 16 available channels. The raw data is acquired from the probe which is pre amplified and filtered in the control unit, is then sent to the DAQ card to be digitized and read by the computer. The computer either saves the data for off-line analysis or analyzes the received data in real-time.

Signals are also sent from the computer through the DAQ to the control unit in order to select the sources and photo-detectors.

To design an optimum system, each component and block diagram of the hardware and software should meet certain specifications. The design criteria that are followed throughout the design and implementation process are as follows:

1- A safe light source and stable source driver are needed to transmit the light with specific wavelengths in the NIR region.
2- Optimum photo-detector sensitivity in the NIR region is required to resolve small signal changes.
3- The probe should be comfortable to wear and should be stable during the experiments. In addition, it should provide good sensor-tissue coupling and rejection of ambient light.
4- Amplifiers need to be low noise with wide dynamic range.
5- An analog filter with optimum frequency response is required to detect signals and reject noise.
6- Analog to digital conversion should have small quantization levels at optimum sampling rate, considering the bandwidth of the biological signal.
7- In addition to hardware, software should be designed optimally to collect data from multiple sensors simultaneously, to control the dynamic range, gain, and sampling frequency and to implement signal-processing algorithms in order to achieve higher signal quality.

### B. Design and Implementation

A miniaturized CW system was reported previously, only with two sources and one detector, which is able to log data to a small unit for offline data analysis. Our aim was to design a lightweight, miniaturized real-time system with multiple source and detectors covering entire human forehead.

**Probe:** The flexible probe consisting of two parts: a flexible circuit board that carries the necessary infrared sources and detectors and replaceable medical grade black foam that serves to attach the probe to the subject's forehead. Because the circuit board and cushioning material are flexible, the components move and adapt to the various contours of the subject's forehead, thus allowing the sensor elements to maintain an orthogonal orientation to the skin surface, which dramatically improves light coupling efficiency and signal strength.

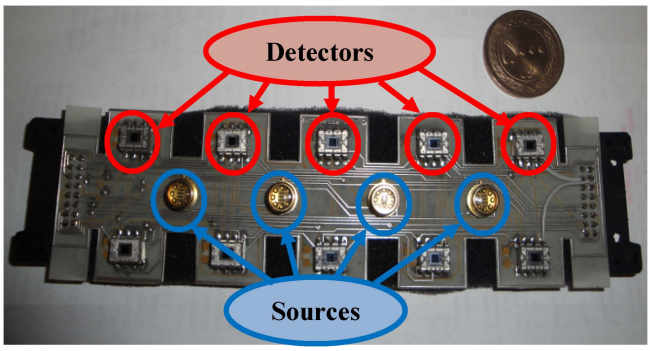


**Figure 2. NIRS Probe**

The probe contains four light sources and ten photo-detectors (OPT 101, Burr–Brown) which divides the forehead into 16 voxels, as depicted in Figure 3. In this probe geometry, one LED at a time is on, and data only from the adjacent four detectors is read.

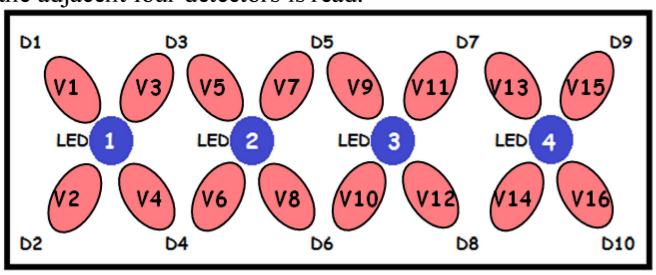


**Figure 3. Sensors configuration with related voxels**

The source detector separation is 2 cm. The light sources used in the system are two-wavelength LEDs, emitting light at 730 nm and 850 nm (Epitex Inc, Japan). Compared to the laser diodes, LED output is not collimated and therefore more photons can be injected safely into the tissue without violating medical regulations. Power consumption of LED is minimal with respect to laser source, hence the system can be battery operated. Laser light source also suffers from extreme heating of the semiconductor junction [8].

**Control Circuitry:** The circuit board contains a stable current source for LEDs, implemented with a high precision voltage regulator, timing control elements (counter, demultiplexer, multiplexers), amplifiers, filters and is powered by a 7.2 volt Lithium-Ion battery. The circuit is designed to use minimum digital and analog channels of the data acquisition card, so that different data acquisition (DAQ) cards can be used with the control box. Only two digital channels and four analog channels are required to operate the system.

Controlling the timing of the LEDs and photo-detectors is the key point in the design. The LEDs turn on and off sequentially, one at a time. The LED turn on sequence in one scan cycle is depicted in red, pink and black colors below the timing diagram in Figure 4. The LED turn on sequence is as follows: Turn on LED1 730nm, read D1, D2, D3, D4; turn on LED1 850nm, read D1, D2, D3, D4; dark, read D1, D2, D3, D4 (read offset); turn on LED2 730nm, read D3, D4, D5, D6 and so on.

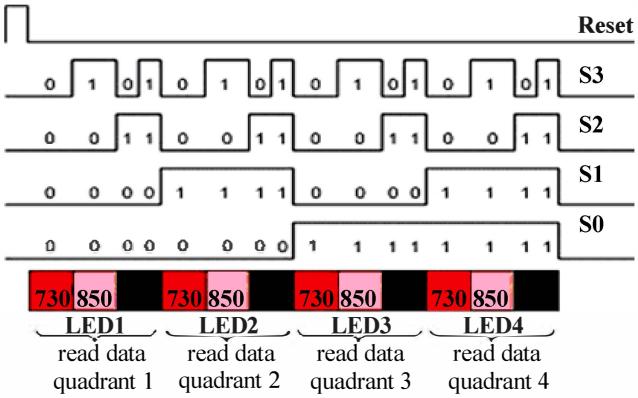


**Figure 4. Timing diagram of control circuit**

The timing in the circuit is controlled only by two digital signals, Reset and S3. Detailed timing diagram is presented in Figure 4 and block diagram of the circuit is given in Figure 5.

S3 and the counters together provide 4 bits, S0, S1, S2, S3, which serve as binary control inputs to the 4:16 demultiplexer as shown in Figure 5. Every LED has an analog, single pole single throw switch, total of eight switches that are turned on by the 4:16 demultiplexer selection. During the other 8 selections of the demultiplexer background light level is measured, all LEDs are off. The control of a scan cycle is as follows: The first bit (0000) of the 16 bit cycle, selects LED1 730nm, the second bit (0001) selects LED1 850nm, during the 3rd (0010) and 4th (0011) bits selected pin is floating and all LEDs are off. Meanwhile S1 and S0 also control two, dual 4-channel analog multiplexers, which is identical to four 2:4 multiplexers, and select the corresponding four detectors around LED1. We call the four detectors around an LED, a quadrant. At the beginning of a scan cycle, S1 and S0 are in 00 state. These two bits are the address bits all for the four 2:4 multiplexers, and 00 selects the detectors which are connected to the first input of the multiplexers.

As shown in Figure 5, the first inputs of these multiplexers are D1, D2, D3 and D4, which correspond to quadrant 1. After LED1, light from LED2 is measured. S0 and S1 are in state 01, which selects the detectors connected to the second inputs of the multiplexers. As shown in Figure 5, these detectors are D3, D4, D5 and D6. Same routine goes for quadrants 3 and 4.

The outputs of the analog multiplexers which select the detector outputs are amplified, filtered and digitized. The filters after the amplifiers are first order RC filters with time constant of 0.1ms to eliminate high frequency pickup noise.

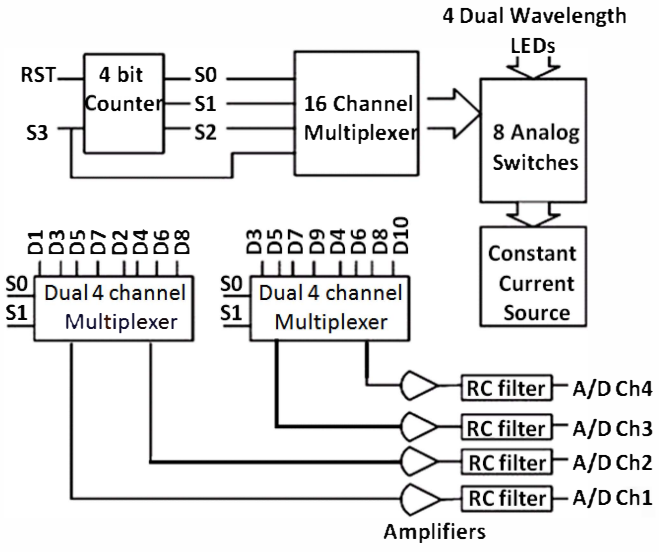


**Figure 5. Block diagram of the control circuit**

## IV. Test and Calibration

To validate the functionality of the system, it was required to conduct laboratory phantom experiments, which could prove the capability of the system to measure oxy-

hemoglobin and deoxy-hemoglobin changes occurring inside the tissue. The experiment was done using a static phantom which is included blood mixed with intralipid solutions as tissue phantom. The NIRS dual wavelength probe was in good contact to the phantom, and the measurements were taken while the blood was oxygenated and deoxygenated. The experimental set up used for this experiment is shown in figure 6. A beaker filled with a 1500-ml, 1% Intralipid solution mixed with 15 ml of pure blood was used as the static tissue phantom. The probe was wrapped on the side of the beaker, and the top of the beaker was covered to prevent air from contacting the surface of the solution.

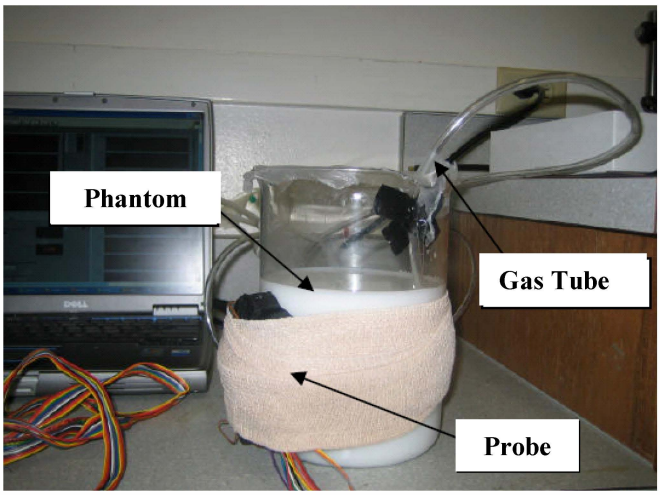


**Figure 6. Set up for Static Phantom Measurement**

The blood was initially deoxygenated by bubbling nitrogen gas into the solution, and then the measurement was started. Thus, the baseline represents the case of deoxygenated blood in the solution. After 260 seconds (~4.3 min), bubbling of nitrogen was stopped, and the gas was switched to oxygen with a slow bubbling rate to prevent the solution from forming too many bubbles.

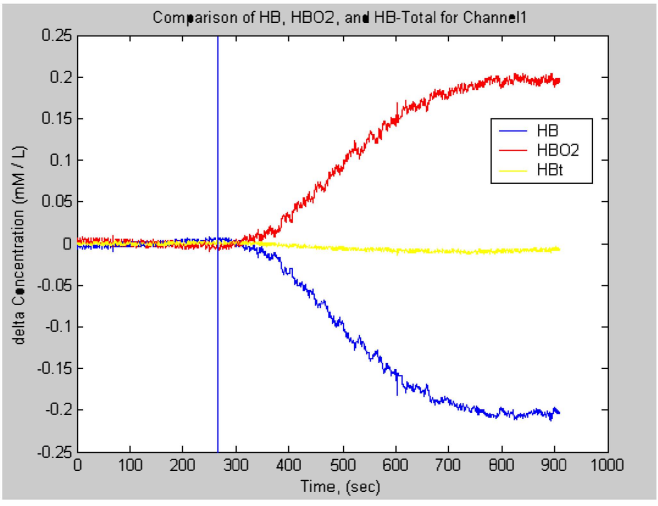


**Figure 7.Static Blood Phantom data for NIRS system channel-1**

The vertical blues line in the above figures represent the time at which nitrogen was switched to oxygen. By close inspection on the plots, it can be seen that $HbO_2$ concentration starts increasing and Hb concentration starts decreasing soon after the blood Intralipid solution is oxygenated. The fact that the total hemoglobin concentration remains almost constant throughout the oxygenation is clearly evident for all channels, and this is what expected to see if the NIRS system operates and functions correctly.

## V. Conclusion and Discussion

Usefulness of Functional Near Infrared Spectroscopy has been validated in the last decade. Current efforts focus on developing advanced hardware and software to bring the power of this technique to researchers and clinicians.

We have described a continuous wave NIRS system which enables to monitor concentration changes in oxy and deoxy hemoglobin. The design includes fabrication of a multi-channel, CW hardware with improved sensor pad and our software platform. Such a system is likely to enable deployment of NIR technology in many new fields of application like brain activity monitoring. Technology for further miniaturization even with increased functionality is possible. Next step would be to embed units into the sensor pad by using surface mount components. However, all these depend on the demand to such systems and progress on the commercialization of the technology.

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