Wireless, Continuous Wave Near Infrared Spectroscopy System for Monitoring Brain Activity

Gunay Yurtsever, Hasan Ayaz, Frank Kepics, Banu Onaral, Kambiz Pourrezaei*

School of Biomedical Engineering, Science and Health Systems, Drexel University, Philadelphia, PA, USA

Near Infrared Spectroscopy is a noninvasive optical method to monitor hemodynamic activity in tissue. Various techniques and devices have been developed to utilize this method in a variety of fields such as, neuroscience, neuropsychology, education, muscle physiology and training. However, current devices do not enable complete freedom of motion; therefore they limit the fields where this technology can be used. In this paper, design of a 16 channel wireless, continuous wave near infrared brain imager is described. The aim of this design is to produce a miniaturized, wearable, affordable, negligibly intrusive system that can monitor hemodynamic response of prefrontal cortex activity. The system consists of a sensor pad, a circuit board, a battery, and a pocket pc with a data acquisition (DAQ) card. The pocket pc provides control signals to the circuit board, acquires the data and sends it to a distant computer displaying the temporal and spatial information in real time as concentration changes in oxy-hemoglobin (HbO₂) and deoxy-hemoglobin (Hb). Custom pocket pc application that has low level access to DAQ hardware has been developed by using eMbedded Visual C++. To test the system performance, experiments have been conducted with a dynamic phantom that simulates optical properties of human tissue and changes in Hb and HbO₂ concentrations.

I. INTRODUCTION

Near Infrared Spectroscopy (NIRS) is a method, which uses optical properties of the tissue in the spectral window of 700 nm–900 nm to monitor the hemodynamic activity. This window is the characteristic absorption band of the blood chromophores oxyhemoglobin (HbO₂) and deoxyhemoglobin (Hb). The absorbance of water, lipids, and other chromophores are relatively lower in this band. As a consequence, light can easily penetrate into the tissue and backscatter following a banana-shaped path due to highly scattering property of the medium. Since emitted light is mainly absorbed by the oxy- and deoxyhemoglobin, the oxygenation and blood volume changes can be reckoned by utilizing modified Beer – Lambert law. Mainly three near infrared (NIR) spectroscopic techniques have been developed to measure optical properties of tissue. Continuous wave (CW) method measures only the change in intensity of the light and is used to detect changes in absorption. The frequency domain method uses modulated light at radio frequencies and by measuring both the amplitude and phase of the backscattered light, absorption and scattering coefficients of the medium are estimated. Another technique called, time resolved spectroscopy, also provides absorption and scattering information, where a very short laser pulse is emitted into tissue and time of flight of the photons is recorded after propagation in the medium. Among these, CW systems are the smallest and comparably lowest-cost systems suited for applications which only require information about the change in absorption.

Currently these different methods of NIR technology are utilized in several research areas, such as neuroscience, neuropsychology, sports medicine, pediatric and clinical applications. However, current research systems, despite of their portability, do not enable complete freedom of motion, which limits experimental designs. In order to use this technology both for indoors and outdoor applications and integration with other physiological measurement systems; a compact wearable NIR system is needed.

II. INSTRUMENTATION

A. System Objectives

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: A safe light source and stable source driver are needed to transmit the light with specific wavelengths in the NIR region. Optimum photo-detector sensitivity in the NIR region is required to resolve small signal changes since measurements are done non-invasively. 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. Amplifiers need to be low noise with wide dynamic range. An analog filter with optimum frequency response is required to detect signals and reject noise. Analog to digital conversion should have small quantization levels at optimum sampling rate, considering the bandwidth of the biological signal.

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.

* Address correspondence to Dr. Kambiz Pourrezaei
Email: pourrezk@drexel.edu Phone: (215) 895-2215
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. In a later report, that system was connected to a wireless transmitter and became real time. Our aim was to design a lightweight, miniaturized real-time system with multiple sources and detectors covering entire human forehead. This whole system can be carried on subjects and provide freedom of motion. The system consists of two parts: A wearable part to collect and transmit data and a stationary computer for data analysis and display, see Figure 1a. The wearable system consists of three main parts: A pocket PC, control circuit with battery holder and a probe that carries light sources and photodetectors. The implemented system is shown in Fig 1b.

Sensor Pad (Probe): The flexible sensor pad is a modular design 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. The flexible circuit provides a highly reliable integrated wiring solution, as well as consistent and reproducible component spacing and alignment. 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. The probe is attached to forehead by using double sided medically graded adhesive tape (Adchem Corporation, NY) with one side attached to the foam and other side attached to the skin.

The probe contains four light sources, ten photodetectors (OPT 101, Burr–Brown), and divides the forehead into 16 voxels, as depicted in Figure 2. The source detector separation is 2.5 cm. The light sources used in the system are two-wavelength LEDs, emitting light at 730 nm and 850 nm (Epitex Inc, Japan). In this probe geometry, one LED at a time is on, and data only from the adjacent four detectors is read.

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. However, excessive current may increase the temperature of the LED package and has to be taken into consideration.

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 camcorder battery. 5V voltage regulator is used to provide constant voltage to the circuit since battery voltage is decreased throughout operation.
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 photodetectors 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 signals in Figure 3. 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.

The timing in the circuit is controlled only by two digital signals, DIO0 and DIO1, that feed a negative edge triggered 3 bit counter. Detailed timing diagram is presented in Figure 3 and block diagram of the circuit is given in Figure 4. DIO0 is the reset signal that resets the counter before data acquisition starts and also at the beginning of every scan in order to prevent possible counter errors due to glitches or other noise sources. DIO1 and the counter together provide 4 bits, S0, S1, S2, S3, which serve as binary control inputs to the 4:16 demultiplexer as shown in Figure 4. That demultiplexer controls selection of the LEDs. LEDs share one constant current source. 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 4, 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 4, these detectors are D3, D4, D5 and D6. Same routine goes for quadrants 3 and 4, after quadrant 4, no data is read, and the data collected for that scan cycle is transmitted from the pocket PC to the data analysis and display computer. The outputs of the analog multiplexers which select the detector outputs are amplified, filtered and digitized. From our experience with controllable gain NIRS system used for prefrontal cortex activation imaging, the optimum signal gain among different detectors and individuals is at most 2.

Based on our observation we fixed the gain of the amplifiers. Although this design does not optimize A/D noise, trade off is made to significantly reduce the complexity and required digital control signals. However, simply controlling the reference voltage in the LED driver, detector outputs can be adjusted. The filters after the amplifiers are
first order RC filters with time constant of 0.1 ms to eliminate high frequency pickup noise. The data is sampled with 1000 samples per second and 20 data points are collected for each wavelength and averaged. Wireless transmission of a single scan data takes 60 ms, and a scan cycle is completed in 300 ms. That makes the effective sampling rate of the system to be 3.3 Hz.

Figure 4. Block diagram of the control circuit.

**Pocket PC: Software Design of Wireless fNIR Device**

The software is designed as a module to our existing cognitive optical brain imaging (COBI) Studio software platform that we have been using with our other functional NIR (fNIR) systems. COBI Studio is an extendable framework that has been developed in Optical Brain Imaging Lab at Drexel University. It can be used for control and data analysis on different fNIR hardware that have been developed in our lab. For this study, it has been used to communicate and control the wireless device.

Software architecture of the system is depicted in Figure 5. Software is composed of two main applications at two different platforms. The first part runs on the pocket pc which can be carried easily on the subject with the control box, thus enabling the subject to be ambulant during measurements. The acquired data can be either transferred to a server application on a PC which constitutes the second part or stored in the Pocket PC.

The multi-threaded embedded application, called CobiPDA, has been developed using eMbedded Visual C++ 4.0 and runs on HP IPAQ 5555 PocketPC which uniquely has a dual pc-card (PCMCIA) expansion pack. This pocket pc is capable of using regular PCMCIA cards. National Instruments DAQcard 6024E 16 has been used to create the digital control signals and sample the analog channels. CobiPDA has low-level, direct access to the daq card.

As shown in Figure 5 CobiPDA runs on Microsoft PocketPC 2003 operating system. CobiPDA application saves the acquired data on to the storage of PocketPC that has 128MB disk space. Also, for extended run-time investigation data can be transmitted to a server application running on a PC. An add-on to the COBI Studio has been developed to monitor a TCP/IP port and gather data via wireless local area network. The wireless link is preferably peer-to-peer to have stable and faster connection by eliminating unnecessary routing at access points. However, it is still possible transfer the data via an access point with the current sampling rate.

Graphical user interface at the pocket pc is plain. In Figure 6, the main window and settings dialog box of CobiPDA are shown. On the top of the widow, there’s a “start/stop operation” button and the status message goes underneath it. Wireless settings are seen on the main window and the server address can be changed. Application has two modes of operation: simulation and data acquisition. In simulation mode, 48 channels of random and static data are created. Simulation mode is used to test the connection between CobiPDA and the server.

In data acquisition mode, data is grabbed from the analog channels of the PCMCIA daqcard. Frame is formed when all 48 channels are sampled. Frame rate of
the application is 300 milliseconds. During operation, number of processed frames is shown at the bottom of the main window with a label “Frame counter”. All frames with respective time tags are sent to the server at real time.

To run the system, first server on the pc should be started. Then, the client on pocket pc should be started. When CobiPDA is started by pressing the start button on the main window, handshaking starts between COBI and CobiPDA. Settings like number of channels available, sampling rate and the interval of the sampled signal are transmitted to COBI. When handshaking is complete, CobiPDA starts transmitting frames to COBI. Raw and filtered data can be visualized in COBI Studio. Apart from anti-aliasing filter in the hardware, a post-sampling linear-phase digital filter is applied to eliminate the inherent noise due to environmental conditions or electronics.

### C. System Evaluation

**Dynamic Phantom:** To evaluate the response of the system for changes in Hb and HbO2 concentrations, a tissue stimulating phantom was used. Liposyn III solution of 1% was prepared in a cylindrical glass beaker from %30 Liposyn III in 1000 ml phosphate buffered saline at pH 7.4. This solution has reduced scattering coefficient of 10 cm⁻¹ at 830 nm, which is a good estimate for human forehead. The mixture was continuously stirred with a magnetic stirring rod to keep the solution homogeneous. To simulate the blood content in tissue, around 50 μM, 22mL of human blood was added to the beaker. The probe was attached to the side of the beaker and baseline was recorded. After that, 4g of baker’s yeast was added to the mixture. The yeast respiration deoxygenates HbO2, so [HbO2] decreases and [Hb] increases. Data of one channel is presented in Figure 7. After 13 minutes, the [Hb] and [HbO2] reached a steady state, where oxygenation of hemoglobin and yeast respiration are at equilibrium. Then we provided oxygen to the solution from an oxygen tank, green line in the graph, to reoxygenate deoxyhemoglobin. As a result of oxygen bubbling inside the beaker, hemoglobin saturation exceeds the initial saturation and steady state is reached at a higher saturation level.
III. CONCLUSION

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 wireless, miniature, continuous wave fNIR system which enables freedom of motion to subjects. The design includes simplification of the existing CW hardware with improved sensor pad design, and its integration to a PDA with wireless functionality and our software platform COBI. Such a system is likely to enable deployment of NIR technology in many new fields of application.

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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