Development of a Wireless Near-Infrared Tissue Oxygen Monitor System with High Sampling Rate

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Abstract: We developed a portable near-infrared tissue oxygen monitor having both wireless data communication capability and high sensitivity. This device is able to measure relative changes in oxy- and deoxyhemoglobin concentrations in real time.
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1. Introduction

Near-infrared spectroscopy (NIRS) technology is utilized for non-invasively determining the amount of absorbing species in tissue, especially oxyhemoglobin and deoxyhemoglobin [1-3]. Near-infrared (NIR) light in the wavelength range between 700 nm and 1,000 nm or so called "optical window" can penetrate several centimeters of tissue because of the low optical absorption of hemoglobin and water.

The three technical approaches in NIRS instrumentation are continuous wave, frequency domain and time-resolved techniques. Our NIRS system uses the continuous wave technique because it is the simplest and the easiest way to monitor hemodynamics in real time at bedside or at home.

The conventional NIRS system however has several problems. For example, the optical fiber which delivers light to illuminate tissue and collects light from the tissue to the detector is very delicate to handle, the signal-to-noise ratio is poor because of analog signal handling from the probe to controller, the whole setup is large and heavy, the subject movement area is limited due to the cable length, and the repetition rate is insufficient.

We developed a new NIRS system to overcome these problems.

2. Instrumentation

Our newly developed NIRS System "PocketNIRS Duo" is shown in Fig. 1. This system consists of three parts which are optical probes, a controller and a PC.

Each of the two optical probes has three light emitting diodes (LEDs) which emit different wavelengths (735, 810 and 850 nm) and one Si PIN photodiode (PD) as a detector. The separation between LED and detector is 3 cm. The amplified analog signals from the PD are converted to 12 bit digital data by built-in A/D converters in the probes. The digital signals are transferred to the controller via 1 m length cables with no loss in signal quality. Flexible printed circuits were utilized to match the various tissue structure shapes and "latex-free" rubbers cover the whole probes. The probes are attached to the skin surface of the subject using double-sided medical adhesive tape. The probe size is 28 by 87 mm and the 32 g weight includes the 1 m cable.

The controller regulates the optimum LED drive current and amplifier gain to obtain stable and accurate measurements. The controller also regulates the timing between LED light emission and data acquisition. Digital signals from the probe are sent to a PC through a wireless data communication (Bluetooth®) by the controller. The maximum distance for data transfer between the controller and PC is about 10 m. The controller size is roughly equivalent to that of a cellular phone or 61 x 18.5 x 100 mm, and the 100 g weight includes two AAA batteries. The system can operate two probes simultaneously and operates continuously for at least 6 hours from two AAA alkali batteries with approximately 60 data/sec repetition rate.

The PC receives data from the controller by way of Bluetooth® wireless data communication, calculates the change in oxy- and deoxyhemoglobin concentrations according to a specified calculation formula and displays the graph on the monitor in real time. The data is saved in a csv file format so the operator is able to analyze the data on Microsoft Excel or analysis software specially designed for the PocketNIRS Duo. The PC may consist of a laptop or notebook PC running Windows XP/Vista/7 or a PDA (Personal Digital Assistant) running Windows Mobile 6. The software for the laptop is coded with Visual C++ 2005, while the software for the PDA is coded with Visual C# 2005. If using a laptop PC, then AVI video from a USB camera can be recorded synchronously with data acquisition. This feature is useful for analyzing the data and video simultaneously in order to understand how the hemodynamics relates to the subject's movements such as when the human subject is running or walking.

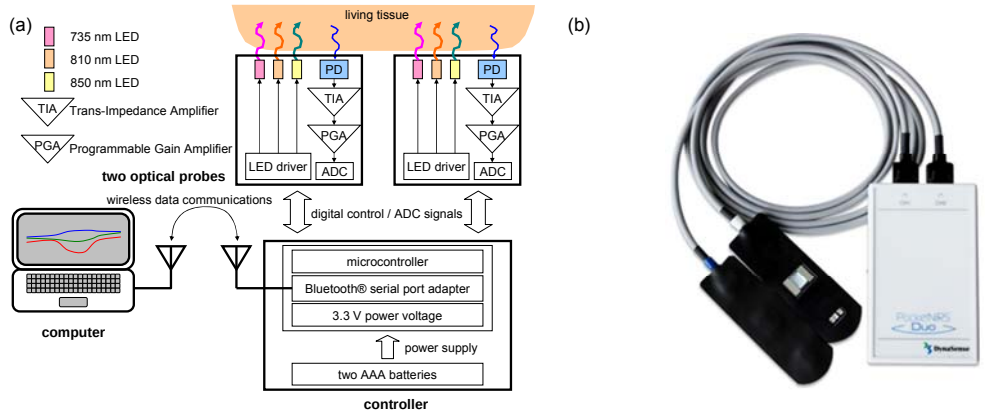

Fig. 1. (a) Concept diagram of PocketNIRS Duo. (b) External view of PocketNIRS Duo.

3. Theory

The attenuation of NIR light intensity in a tissue can be defined as $OD(\lambda, t) = \log_{10} I_{in}(\lambda, t) / I_{out}(\lambda, t) = A(\lambda, t) + S(\lambda, t)$, where $I_{in}(\lambda, t)$ is the incident NIR light intensity, $I_{out}(\lambda, t)$ is the detected NIR light intensity and $OD(\lambda, t)$ is the optical density for wavelength λ at the time t. This attenuation is the superposition of absorption $A(\lambda, t)$ and scattering $S(\lambda, t)$ of NIR light at a wavelength λ at the time t. The oxyhemoglobin and deoxyhemoglobin concentrations at time t, $[HbO_2](t)$ and $[Hb](t)$ are the main absorbers of light in the NIR region of the spectra. The absorption of light can therefore be defined as $A(\lambda,t) = \varepsilon_{HbO_2}(\lambda)[HbO_2](t)L(\lambda,t) + \varepsilon_{Hb}(\lambda)[Hb](t)L(\lambda,t)$, where $\varepsilon_{HbO_2}(\lambda)$ and $\varepsilon_{Hb}(\lambda)$ is the specific extinction coefficient of oxyhemoglobin and deoxyhemoglobin at the wavelength λ [4], $[HbO_2](t)$ and $[Hb](t)$ are the concentrations of oxyhemoglobin and deoxyhemoglobin and $L(\lambda,t) = DPF(\lambda,t)\cdot d$ is the optical pathlength of the wavelength λ and the time t, where d is the distance between the NIR light sources and the photodetector and $DPF(\lambda, t)$ is the differential pathlength factor [5, 6].

When the scattering $S(\lambda, t)$ is assumed to be constant, the measurement of the differential OD value at the time t and the measurement of the OD value at the initial time t_0 can be expressed as:

$$\Delta OD(\lambda,t) = OD(\lambda,t) - OD(\lambda,t_0) = \varepsilon_{HbO_2}(\lambda)\Delta\{[HbO_2]L(\lambda,t)\} + \varepsilon_{Hb}(\lambda)\Delta\{[Hb]L(\lambda,t)\}, \quad (1)$$

The differential OD value can also be obtained as follows:

$$\Delta OD(\lambda,t) = \log_{10}\frac{I_{in}(\lambda,t)}{I_{out}(\lambda,t)} - \log_{10}\frac{I_{in}(\lambda,t_0)}{I_{out}(\lambda,t_0)} = \log_{10}\frac{I_{out}(\lambda,t_0)}{I_{out}(\lambda,t)}, \quad (2)$$

where $I_{in}(\lambda, t)$ at time t is equal to $I_{in}(\lambda, t_0)$ at the initial time t_0 because $I_{in}(\lambda, t)$ is consistently maintained at a constant value during measurement. Here, $I_{out}(\lambda, t)$ can be substituted by a value that is the measured voltage proportional to the detected photocurrent.

The relationship between changes of the product of the concentrations and the optical pathlength and the $\Delta OD(\lambda, t)$ measurements can therefore be derived from Eq. (1), (2) and least squares method as follows:

$$({}^t\boldsymbol{A}\boldsymbol{A})\boldsymbol{C} = {}^t\boldsymbol{A}\boldsymbol{M}, \text{ with } \boldsymbol{A} = \begin{bmatrix} \varepsilon_{HbO_2}(735) & \varepsilon_{Hb}(735) \\ \varepsilon_{HbO_2}(810) & \varepsilon_{Hb}(810) \\ \varepsilon_{HbO_2}(850) & \varepsilon_{Hb}(850) \end{bmatrix}, \boldsymbol{C} = \begin{bmatrix} \Delta\{[HbO_2](t)L(t)\} \\ \Delta\{[Hb](t)L(t)\} \end{bmatrix} \text{ and } \boldsymbol{M} = \begin{bmatrix} \Delta OD(735,t) \\ \Delta OD(810,t) \\ \Delta OD(850,t) \end{bmatrix}, \quad (3)$$

where $L(t)$ is the optical pathlength assuming the same value on each wavelength. The changes of the oxy-, deoxy- and totalhemoglobin, $\Delta\{[HbO_2](t)L(t)\}$, $\Delta\{[Hb](t)L(t)\}$ and $\Delta\{[tHb](t)L(t)\} = \Delta\{[HbO_2](t)L(t)\} + \Delta\{[Hb](t)L(t)\}$ can be determined by solving for Eq. (3).

4. Evaluation

4.1. Liquid phantom test

We measured a liquid phantom to evaluate the performance of the PocketNIRS Duo system. The phantoms were prepared by adding a specified amount of black india ink as the absorber, to 2000 ml of 1 wt% Intralipid® solution

which is the scatterer. The precise absorbance of the ink was measured by spectrophotometer before the experiment. The PocketNIRS Duo probe was attached to the exterior surface of a container filled with the 2000 ml solution. The inner walls of the container were painted black except for the area where the probe was attached. In order to emulate the typical μ_a observed in human subject, we tried to measure between approximately 0.01 mm^{-1} (assuming lower limit of forehead) and approximately 0.04 mm^{-1} (assuming upper limit of muscle). The results are shown in Fig. 2 (a). The change in OD measured by the PocketNIRS Duo showed good S/N in the wide range of absorption coefficient (μ_a). The ΔOD can be seen to be a non-linear function due to the optical pathlength change according to the absorber concentration [5, 6]. PocketNIRS Duo treats the slope of ΔOD as linear because the actual change of human forehead's μ_a is very small during measurement.

4.2. Applications

We demonstrated the hemodynamics on a human subject during breath-holding (BH) using our PocketNIRS Duo system as shown in Fig. 2 (b). During BH, one optical probe was attached to the right side of the subject's forehead, and a commercial pulse-oxymeter sensor (8000R, Nonin Medical Inc.) which measures SpO_2 was attached to the left side of the forehead with double-sided medical adhesive tape. At 75 sec after the subject started BH, the oxyhemoglobin decreased and the deoxyhemoglobin increased along with a decrease in the SpO_2 as expected. Between 25 sec and 75 sec after BH, the oxyhemoglobin increased and the deoxyhemoglobin decreased in spite of the drop in SpO_2. Further investigation is needed to explain this result, but different behavior by the subject might be the reason for the difference in source-detector separation between our PocketNIRS Duo and the pulse-oxymeter.

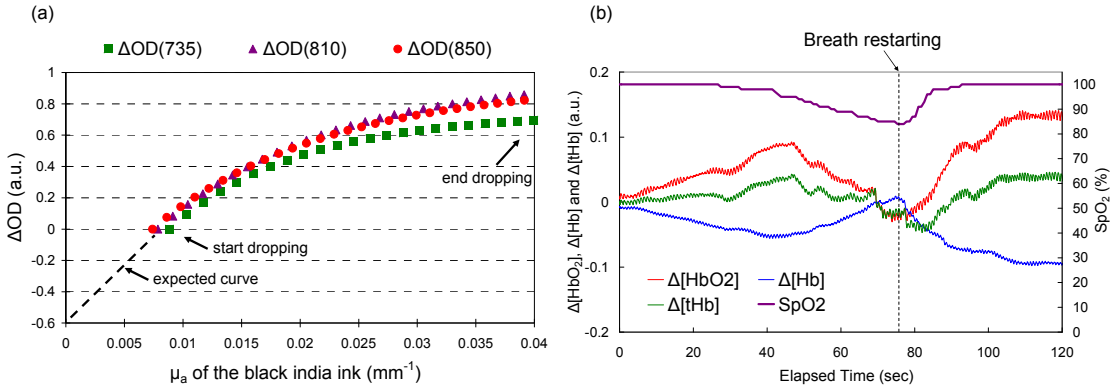

Fig. 2. (a) Plots of the acquired ΔOD versus black india ink content in the phantom. (b) Plots of changes in the product of hemoglobin concentrations and the optical pathlength in the right forehead and SpO_2 in the left side of the forehead during BH.

5. Conclusion

We developed a portable wireless NIRS system called the "PocketNIRS Duo". The system drives two optical probe channels and is capable of monitoring human hemodynamics continuously for at least six hours powered by two AAA batteries. Our system features not only long-term measurement capability by battery operation but also a small size, light weight, wireless data transfer, and a high data acquisition rate of up to approximately 60 Hz.

This unique device will prove a powerful tool for opening up a whole new range of NIRS applications including brain research, brain machine interface, sports fields and cognitive function evaluation.

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