A portable multi-channel wireless NIRS device for muscle activity real-time monitoring

Pengfei Yao, Weichao Guo, Xinjun Sheng*, Dingguo Zhang, and Xiangyang Zhu

Abstract— **Near-infrared spectroscopy (NIRS) is a relative new technology in monitoring muscle oxygenation and hemodynamics. This paper presents a portable multi-channel wireless NIRS device for real-time monitoring of muscle activity. The NIRS sensor is designed miniaturized and modularized, to make multi-site monitoring convenient. Wireless communication is applied to data transmission avoiding of cumbersome wires and the whole system is highly integrated. Special care is taken to eliminate motion artifact when designing the NIRS sensor and attaching it to human skin. Besides, the system is designed with high sampling rate so as to monitor rapid oxygenation changes during muscle activities. Dark noise and long-term drift tests have been carried out, and the result indicates the device has a good performance of accuracy and stability. In vivo experiments including arterial occlusion and isometric voluntary forearm muscle contraction were performed, demonstrating the system has the ability to monitor muscle oxygenation parameters effectively even in exercise.**

I. INTRODUCTION

NIRS is a noninvasive technique to monitor oxygenation and haemodynamics in human tissue. Human tissues are relatively transparent to light in the near-infrared (NIR) spectral window (650-1000 nm) [1]. When NIR light penetrates tissue, it is either absorbed by chromophores or scattered in tissues, and the strongest absorbers of light are oxy-hemoglobin (HHb) and deoxy-hemoglobin (HbO_2) with myoglobin also participating in the muscle [2]. Information about the oxygenation and haemodynamics can be acquired by detecting the light scattered by tissue. There have three kinds of NIRS techniques: continuous wave (CW) modality, frequency domain (FD) method, and time domain (TD) technique. The CW-based NIRS instrument is the most commonly used because it offers the advantages of low-cost and simplicity [1]. It detects the attenuated NIR light scattered by tissue, and calculates the concentration changes of HbO_2 and HHb or other non-hemoglobin chromophores through the modified Lambert-Beer's law (MBLL) [3].

Till now, many CW NIRS systems have been developed, mainly focus on brain and muscle monitoring. More recently, there has been increased interest in developing portable, multi-channel and wireless NIRS system which can quantify hemodynamic response in real-time.

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In order to monitor freely moving subjects, the application of cable connections is not practical, hence wireless communication is necessary. Babak Shadgan et al. reported the usage of a commercial wireless CW NIRS instrument (PortaMon, Artinis Medical Systems, The Netherlands) to monitor skeletal muscle oxygenation and hemodynamics during exercise [4]. An obvious disadvantage of PortaMon is that it has only one channel and size of the sensor is not small enough to deploy multi-channel sensors on some parts of body, such as forearm. More recently, N.L. Everdell et al. introduced a portable wireless NIR spatially resolved system in 2013 [5]. They applied LD as light source which needed optical fibre bundles and a sophisticated drive circuit to drive the LD. It leads the whole system relatively large.

In the meantime, monitoring hemodynamic response in muscle activity is actually different from that in head. Firstly, motion artifact affects the measured signal more when monitoring muscle activity. One of the biggest motion artifact in NIRS is uncoupling of source or detector from skin, which may result in sudden changes in the measured light attenuation [6]. Optical probes are usually fitted firmly to tissue using a cap or frame to lower the effects of motion. Babak Shadgan et al. used a tape when monitoring skeletal muscle oxygenation and hemodynamics during exercise, while J Safaie used an elastic tubular net bandage [4], [7]. However, the tape or bandage would be bounded tightly to limb to eliminate motion artifact in this case, while the binding pressure itself will change blood flow and finally exerts influence on the detected signal. Further-more, Choong-Ki Kim et al. and Jaakko Virtanen et al. introduced an accelerometer-based method to remove motion artifact [8], [9]. However, it will lead a more complicated system and algorithm.

Secondly, NIRS systems to monitor muscle activity should have a higher sampling rate. Hemodynamic response in contracting muscle is different from that in head. When muscle begins to contract, increased intramuscular pressure and the compressing to the small intramuscular blood vessels will lead to rapid decrease in muscle blood flow [4], [10]. Thus a system with high sampling rate is needed to monitor the rapid change. However, to our best knowledge, no work has taken special effort to develop a NIRS system with high sampling rate.

This paper describes a portable multi-channel wireless NIRS device which can eliminate motion artifact effectively and has a relative high sampling rate.

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II. Instruments and Method

The portable multi-channel wireless NIRS device is physically divided into four parts: the NIRS sensor module, the main board module, the power supply module and the PC-based GUI module. Fig. 1 is a block diagram of the system.

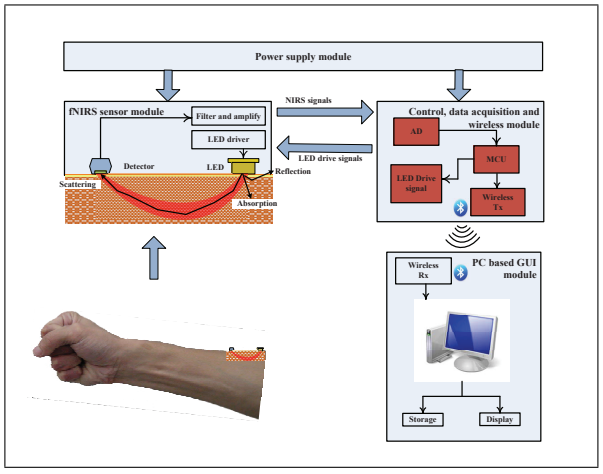

Fig. 1. Schematic diagram of the NIRS system.

A. NIRS sensor module

The NIRS sensor module and its associated electronics are shown in Fig. 2(a).

It illuminates human tissue with a LED (L4*730/4*805/4*850-40Q96-I, Epitex) emitting at the wavelength of 730, 805, 850nm, with a spectral half width of 15, 20, 20nm, respectively. The LED consists of 12 chips of AlGaAs LED mounted with AlN heat sink pedestal on TO-5 stem and sealed with a flat glass can. A silicon photodiode OPT101 (Texas Instruments) is used as detector. It is a monolithic photodiode with on-chip transimpedance amplifier, whose output voltage increases linearly with the light intensity. The LED is driven by a constant current chip wit a current of 30mA.

When the sensor working, NIR light of three wavelengthes illuminates human tissue time multiplexed with an 'ON' state less than 10ms per period (can be programmed by micro control unit, MCU). To avoid the LED causing too much heat, after the 'ON' state, following a same period of an 'OFF' state, which means a 50% duty ratio and a whole period less than 60ms for three wavelengthes. This means the sensor can give a group in oxygenation change data in less than 60ms, offering a good temporal resolution for investigating dynamic oxygenation changes of muscle activity. The output of OPT101 is low-pass filtered (cut-off frequency 300Hz) and amplified, and then conveyed to the main board module by a FPC cable.

The shell of the sensor has a dimension of 50×20×12 mm and is fabricated by a 3d printer. It has an elaborately designed curved surface which makes it fit the tissue surface very well. To avoid bandage or tape when attaching the sensor to skin, we use a customized double-sided adhesive tape. Through this way, the sensor can be attached firmly to skin with no uncoupling between the sensor and skin, thus can eliminate motion artifact. Besides, each sensor has an additional FPC connector, which enables the user can change channel number conveniently (see Fig. 2(a)).

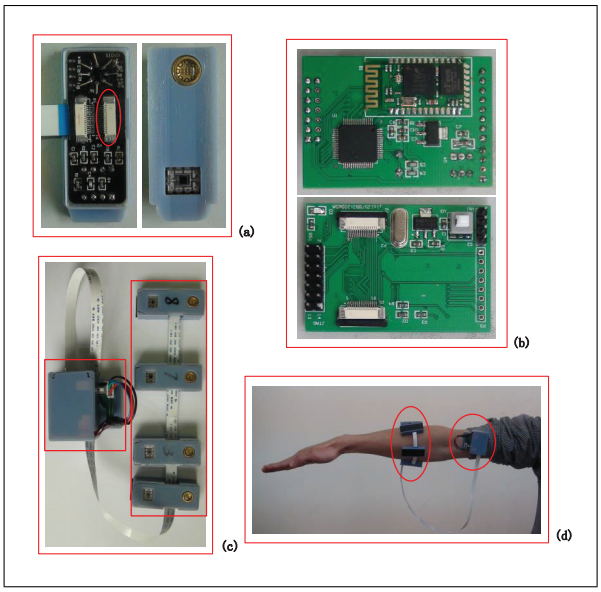

Fig. 2. System electrical schema: (a) NIRS sensor module; (b) main board module; (c) appearance of the whole device; (d) monitor muscle activity of the forearm.

B. Main board module

The main board module transfers filtered and amplified analog signals from multi-channel NIRS sensors into digital values, by using a MSP430 MCU (Texas Instruments). It has an integrated 12-bit analog to digital (A/D) convertor and can capture 12 channels data simultaneously. Sampling rate of the light intensity signal is set at 1000Hz. After the A/D conversion, the digitalized data is transmitted to PC by an integrated Bluetooth. The operating range of the Bluetooth is around 10m, and the baud rate is set at 230400. Besides, the MCU provides drive signal to the LEDs of the NIRS sensors through its output pins, and delivers it to the NIRS sensors through the FPC cable. The dimension of the main board module is 35×50×10mm, shown in Fig. 2(b).

C. Power supply module

Three lithium batteries of 3.7V/600mAh in series provide energy running the whole system. The selected battery is featured with small volume, light weight and high capacity, to ensure convenience. There are three voltage levels, including +11.1V to drive the LED, 5V for the amplifier and driving circuits of the LED, and 3.3V for the MCU. The average working current of one channel is about 30mA, which means the system can work around 2h in 10-channel case. The main board module and the power supply module are integrated, shown in Fig. 2(c). It has a compact-size, thus can be easily held on clothes or put in pocket. As shown in Fig. 2(d), the system can be used very conveniently in muscle activity monitoring.

D. PC-based GUI module

A PC-based GUI is developed by C++. Usage of OpenGL technology enables the GUI can display data dynamically in a user-friendly way. The main function of the GUI is: receiving and saving the digitalized light intensity data; calculating the concentration changes of HHb, HbO_2 and tHb by MBLL; displaying the light intensity data and the muscle oxygenation parameters dynamically, as shown in Fig. 3.

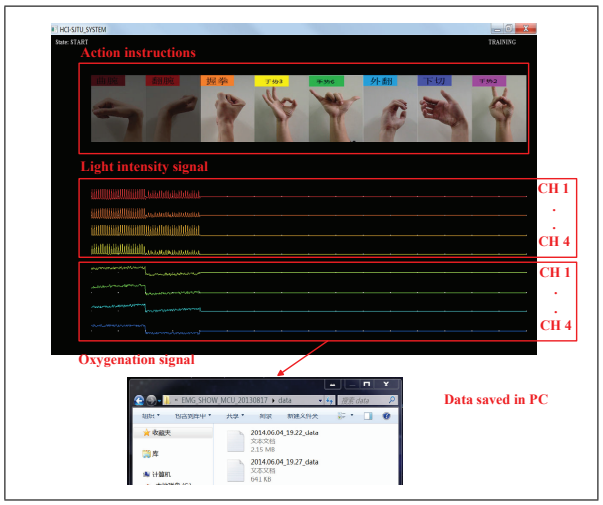

Fig. 3. PC-based GUI for the NIRS device. The upper part instructs the subject's action; the middle part displays the light intensity signals and the lower part displays the muscle oxygenation signals.

III. Results

A. Dark noise and long-term drift tests

To evaluate the basic performance of the system, dark noise and long-term drift were tested. The noise data was collected for 30 minutes when the system was placed in dark environment and all LEDs were turned off. The result showed that all 6 tested channels had a voltage about 15mV with standard deviation (SD) of $\pm$0.51-1.21mV. The output of the NIRS sensor was normally distributed around 1.5V-2.4V. Thus, the noise was about 0.05% of the light intensity signal and the signal to noise ratio (SNR) was 33dB.

When testing the long-term drift, the sensors were attached to a Static Calibration Phantom (NirX company, USA). After a 3-minute warm-up, data was collected for 1 hour when all LEDs illuminated normally. A straight line fit was used to the light intensity signals and result showed that overall drifts in 1h were 0.19%, 0.14% and 0.14% for 850, 805, 730nm, respectively.

B. In vivo experiments

To validate the functionality of the system, we performed arterial occlusion and isometric voluntary forearm muscle contraction on four healthy male subjects (24$\pm$1 in age), as described in [4]. Concentration changes of HbO_2 and HHb were calculated by MBLL. The differential path length factor (DPF) was from [11]. The absorption coefficients for the HbO_2 and HHb were taken from the web site of Department of Medical Physics and Bioengineering, University College London. DPF and absorption coefficients we use are shown in Table I.

TABLE I
DPF and absorption coefficients

wavelength(nm)	730	805	850
absorption coefficients for HbO_2(cm^{-1}·$uMol^{-1}$)	1.01	2.07	2.67
absorption coefficients for HHb(cm^{-1}·$uMol^{-1}$)	3.00	1.88	1.81
DPF	4.88	4.44	4.17

In arterial occlusion, a NIRS sensor was placed on the forearm of a healthy male volunteer, over the brachioradialis muscle. A standard blood pressure cuff was attached to the upper arm. After 90s baseline data collected, the cuff was inflated to a pressure of approximately 250mmHg quickly to prevent venous blood back flow and arterial blood inflow into the forearm. The occlusion was maintained for 30s, and then the cuff was released quickly and data was collected for a further 210s.

Fig. 4 shows an example of the HbO_2 and HHb concentration changes in arterial occlusion. HbO_2 concentration fell nearly time-linearly when the occlusion was applied, and rose steeply when the occlusion was removed, overshooting the baseline. The HHb concentration change was similar to the HbO_2 except the rises and falls were reversed. The absolute amount of the HbO_2 and HHb concentration changes was about 3.5 umol/L in 30s (Table II). After 250s, the concentrations of HbO_2 and HHb returned to normal.

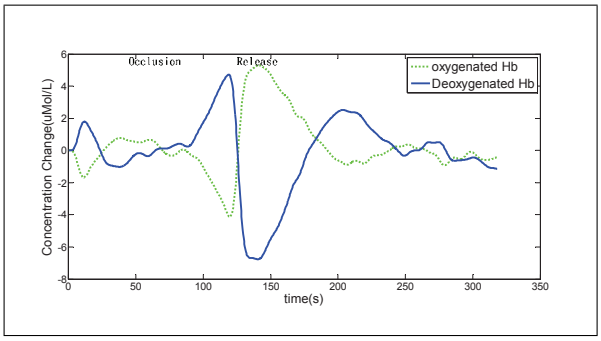

Fig. 4. Oxygenation changes in arterial occlusion

To validate the system's ability in monitoring muscle activity, isometric voluntary forearm muscle contractions at 10%, 30% and 50% of maximum voluntary contraction (MVC) were performed. A dynamometer was used to measure MVC of the subject and values for 10%, 30% and 50% MVC were calculated. A NIRS sensor was placed on the forearm of the subject, over the brachioradialis muscle. 60s baseline data was collected and then the subject performed 10%, 30% and 50% MVC contractions in turn. Every contraction sustained for 30s with 90s rest between two contractions.

Fig. 5 shows an example of the concentration changes of HbO_2 and HHb observed in the protocol. Concentration of HbO_2 decreased and HHb increased in a nearly timely-linear trend. Concentrations of HbO_2 and HHb returned to the baseline rapidly. The maximum concentration changes of

TABLE II

MEAN CHANGES OF HbO_2 AND HHB DURING 10%, 30%30, %50 MVC AND OCCLUSION

	Mean change($uMol \cdot L$)
HbO_2-10%MVC	-3.5
HbO_2-30%MVC	-10.2
HbO_2-50%MVC	-12.08
HbO_2-Occlusion	-3.5
HHb-10%MVC	4.67
HHb-30%MVC	16.3
HHb-50%MVC	19.58
HHb-Occlusion	3.36

HbO_2 and HHb were positively correlated to the contraction intensity (Table II).

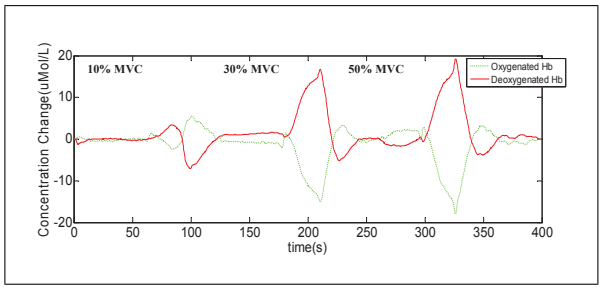

Fig. 5. Oxygenation and tHb change in isometric voluntary forearm muscle contractions at 10%, 30% and 50% of MVC

Table II shows the mean value of concentration changes of HbO_2 and HHb observed in four subjects.

IV. DISCUSSION

The dark noise of the device is about 0.05% of the light intensity signal and the SNR is about 33dB. SNR is lower than the system introduced in [5], and comparable to the system described in [12]. The worst case of the drifts is 0.19% in 1h which is better than the result in [5]. Thus, the dark noise and the drift can be neglected, and the device can fulfill the requirements of accuracy and stability.

The result of the arterial occlusion is consistent with the result published in [12], [5], including the trends and the absolute values of HbO_2 and HHb concentration changes.

In isometric voluntary forearm muscle contraction, the decrease in HbO_2 concentration and increase in HHb concentration indicate a decrease in muscle oxyhaemoglobin saturation (S_mO_2) or tissue oxygenation index (TOI). The result is consistent with the result published in [4], [10], [13].

The result of the in vivo experiments demonstrates the system can monitor muscle oxygenation parameters effectively even in exercise.

V. CONCLUSION

We have presented a portable multi-channel wireless NIRS device for real-time monitoring of muscle activity. The miniaturized NIRS sensor and and the usage of wireless communication make the whole device have a compact-size, thus can be used in muscle monitoring. The modularized design of the NIRS sensor makes multi-site monitoring can be very easy. Moreover, there is not any motion artifact detected even the subject has large amplitude movement. The high temporal resolution makes it possible to monitor rapid muscle oxygenation changes during activities. The result of dark noise and long-term drift indicates a good performance of accuracy and stability; arterial occlusion and isometric voluntary forearm muscle contraction demonstrate the system has the ability in monitoring muscle oxygenation parameters effectively even in exercise. We believe that the system can be widely used in muscle monitoring.

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