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RESEARCH ARTICLE

Portable muscle oxygenation monitor based on near infrared spectroscopy

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Abstract In order to measure the relative change of muscle oxygenation non-invasively, dynamically and directly, a portable monitor based on near infrared spectroscopy (NIRS) was developed. The monitor consists of several function modules, including 735 nm, 805 nm and 850 nm integrated three-wavelength light emitting diode (LED) light source, LED driver, integrated detector, amplifier and filter, A/D sampling circuit, single-chip microcomputer and laptop. The distance between light source and detector is 3 cm and the photon migration depth in tissue is approximately 1.5 cm. The monitor is portable with low dark noise and good long-term stability. The relative change of muscle oxygenation measured by the monitor was in accordance with the real physiology status in the cuff ischemia experiment, verifying the performance of the monitor for living muscle. Two inflexions referring to an accelerated fall and a leveling-off phase in the muscle oxygenation index, respectively, were observed in *in vivo* incremental intensity exercises. Significant correlation was found between the first inflexion and the ventilatory threshold which was identified by the gas exchange measurement. These results demonstrated that the monitor can be used to detect the local lactate threshold of the measured muscle and reflect the changes of oxygen index in local muscle for *in vivo* exercises. The monitor may provide a meaningful approach to evaluate the subject's oxidative capacity effectively.

Keywords near infrared spectroscopy (NIRS), muscle oxygenation, lactate threshold (LAT), exercise

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1 Introduction

The study of lactate threshold (LAT) has always been the highlighted topic in exercise physiology and sports science. Lactate threshold is defined as the point during incremental intensity exercise at which there is an abrupt increase in blood lactate levels [1]. It is the most important determinant of success in endurance-related activities and events, and the main goal of endurance training programs should be the improvement of this parameter [2]. Two traditional methods have been widely used to determine the LAT. The most accurate and reliable one is through the direct testing of blood samples during an incremental exercise test. However, this method is often inaccessible to most performers due to its invasive character [3]. Another prevalent method is gas response determination. However, the accuracy of this method mainly depends on the respiratory patterns of the performers [4,5]. In addition, the respiration measurement machine has a few disadvantages, such as very high price, big size, poor portability, and the performers' respiration might be limited at high exercise intensities due to the mask of the machine.

Near infrared spectroscopy (NIRS), which could be used to measure the concentration changes of oxygenated and deoxygenated hemoglobin (HbO_2, Hb) in human tissue non-invasively, directly, and dynamically [6–10], provides a new approach to evaluate the subjects' oxidative capacities and determine the LAT during the exercises. It is well known that lactate is generated in skeletal muscles during exercise. The generation of lactate is affected by the concentration changes of the oxygen carriers, HbO_2 and Hb, in the skeletal muscles [11]. Thus, we may evaluate the performers' LAT during the exercises and predict their performances in endurance events by monitoring the concentration changes of HbO_2 and Hb with NIRS [12–14].

In this study, we combined NIRS with the microelectronics technique to develop a portable NIRS muscle oxygenation monitor. We will first give some introduction about the theoretical basis and principles of NIRS measurement. Then the design of this monitor and the performances of the device are evaluated. Finally, the NIRS muscle oxygenation monitor is applied in *in vivo* incremental rowing exercises to monitor the oxygenation changes in exercising muscles. The results of the *in vivo* experiment will be presented as well.

2 Design of monitor

2.1 Principle

Some studies demonstrated that most of the near-infrared light (700–900 nm) is absorbed by hemoglobin when it penetrates human tissue [7]. The light at 735 nm wavelength is mainly absorbed by the Hb chromophores, while at 850 nm wavelength the main absorption chromophores are in HbO_2 form. The 805 nm light is equally absorbed by both HbO_2 and Hb chromophores. Optical density (OD) can be used to describe the attenuation of light while it diffuses in tissue. The optical density change (Δ_{OD}) is linear with the hemoglobin concentration changes if the absorption coefficient just changes a little [8]. Usually, we just measure the relative changes of HbO_2 and Hb. Assuming I_0 as the baseline of the output light power, Δ_{OD} can be calculated using the formulas below according to Beer-Lambert when light penetrates the measured human tissue:

$$\Delta_{OD} = \ln(I_0/I) = \left(\alpha_{Hb}\Delta C_{Hb} + \alpha_{HbO_2}\Delta C_{HbO_2}\right)L, \quad (1)$$

where I is the measured output light power; L is the photo path length; α_{Hb} and α_{HbO_2} are the molar extinction coefficients of Hb and HbO_2, respectively, and values of these three parameters are known according to previous studies [12]. ΔC_{Hb} and ΔC_{HbO_2} are the relative concentration changes of Hb and HbO_2 from the baseline, and the values can be fixed according to Eq. (1) if Δ_{OD} at 735 and 850 nm are calculated.

2.2 Device setup

As shown in Fig. 1, the NIRS muscle oxygenation monitor can be divided into three main modules: the probe which contains the light source and a detector, the control box, and the laptop. The block diagram of the monitor is illustrated in Fig. 2. The light driver takes time division multiplexing technology (TDM) to lighten each wavelength light of the three-wavelength integrated light emitting diode (LED) (L4X735/4X805/4X850-40Q96-I, Epitex, Japan) under the control of the clock frequency set by the single-chip. The detector on the probe picks up the diffusely back-reflected photons from the measured muscle, and converts the optical signal into electric signal and pre-amplifies it. The analog signal will be post-amplified and filtered then sampled by an A/D converter. The digital signal will be sent to the laptop through the serial port.

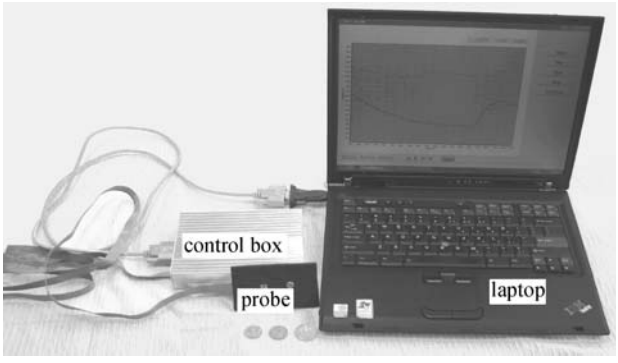

Fig. 1 Photograph of NIRS muscle oxygenation monitor

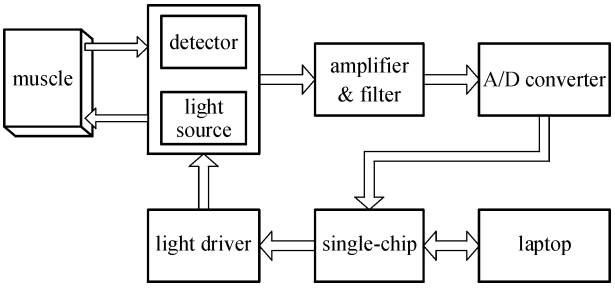

Fig. 2 Block diagram of NIRS muscle oxygenation monitor

We consider LED as the best light source for the NIRS muscle oxygenation monitor in our design. Its spectrum purity is about 30 nm and it is good for a continuous-wave (CW) NIRS monitor. LED illuminates tissue more diffusely than a laser but more like a point light source than white light, hence more light intensity can be utilized with less heat. In fact, laser is an ideal light source for many applications due to its excellent spectrum purity and collimation, but it is not best suited for a CW NIRS monitor. Laser focuses all the light energy into a very small area and over a very small wavelength bandwidth, even though its power is much less than white light source, it might still cause potential damage to the measured tissue. Therefore, a type of three-wavelength LED (735 nm, 805 nm, 850 nm), which is integrated in the package of TO18, is used as light source in our device. The three-wavelength anode common LED consists of 4 chips of AlGsAs LED for each wavelength light, and it can optimize the size of the probe visibly. When the positive drive current reaches to 50 mA, the radiated power of the LED is approximately 30 mW. A monolithic driver (TB62705AN, TOSHIBA) was chosen to supply a highly-

stable constant DC current for the LED. The output current value is set by an external resistor, so all the outputs have virtually the same current levels, ranging from 5 to 90 mA.

A photodiode with an integrated transimpedance preamplifier (OPT101, Burr-Brown) was chosen as the detector in the monitor. This integration can eliminate problems commonly encountered in discrete designs such as leakage current errors, noise pick-up and gain peaking due to stray capacitance. The internal avalanche photodiode (APD) works under zero bias state so the chip has excellent linearity, frequency response characteristics and very low dark current. The detector is 3 cm away from the light source, so it can pick up the optical signal from about 1.5 cm deep tissue [8,11].

The monitor uses a second-order Butterworth low-pass filter to suppress the noise. The cut-off frequency is 10 Hz. It can eliminate most of the electromagnetic interference from space. The analog signals are sampled and converted to 16-bit digital signals by A/D converter (ADS1211, Burr-Brown). The digital signals are sent to the single-chip and coded, and then they are transmitted to the laptop to be processed and stored.

2.3 Performance tests

Dark noise is a very important property for optoelectronic detection systems. In the dark noise test, we put the probe in a black box to eliminate the stray light and then display the signal from the output of the amplifier when the light source is turned off for half an hour. The result of this test showed that the average voltage of the dark noise from the detector and amplifier is 15.16 mV, and the noise fluctuation range is $\pm$ 0.15 mV. The A/D resolution of the monitor is 16 bits, and the maximum distinguishable voltage is 0.15 mV. Thus, the range of the dark noise fluctuation is acceptable for the device. The 15.16 mV offset voltage caused by the dark current is much bigger than the noise fluctuation level, and we can eliminate the offset by software.

We also evaluated the stability performance of this monitor by long-term drift test. Long-term drift was calculated by measuring deviation of the initial and eventual voltage reading, when the probe was attached to a solid optics phantom for at least one hour. The relative drift error for 735 nm, 805 nm and 850 nm are 0.25%, 0.25%, and 0.27%, respectively, in over one hour monitoring. Most sports physiology tests take less than one hour, so the stability of our NIRS muscle oxygenation monitor is good enough for present sports physiology studies.

Other important performance properties of the monitor are shown below: time resolution is 340 ms, the power consumption of the whole device is approximately 400 mW, the total weight of the control circuit box and battery is only 280 g. This makes the device portable and consume low power.

3 *In vivo* experiments

3.1 Cuff ischemia

Cuff ischemia experiment verifies the performance of the monitor for living, nonmoving muscle. It tests the device through the range of maximum deoxygenation and hyperemic reoxygenation of normal muscle [12]. After an informed consent was received, the probe of the monitor was placed on the forearm of a seated volunteer and wrapped with elastic black strap which can block the room light. The cuff was placed around the upper arm so that blood supply to the forearm muscles below is stopped when the cuff is inflated. Baseline data was collected for 1 minute, followed by a two-step inflation cuff (first, 80 mmHg pressure was used to block the vein; second, 200 mmHg was used to block the artery and the vein together), after that the cuff was released.

The *in vivo* cuff ischemia experiment results are shown in Fig. 3. When the pressure increased to 80 mmHg, the vein was blocked; however, the heart could still provide blood to the forearm with no venous return to the heart. Thus, the blood volume (BV) increased rapidly while the concentration of deoxygenated hemoglobin (Hb) increased dramatically because muscle oxygen consumption was sustained while no blood returned to the heart from the local measured forearm. When the pressure increased to 200 mmHg, both the vein and the artery are blocked, so the blood volume was unchanged. Due to muscle oxygen consumption, the oxygenated hemoglobin (HbO_2) decreased continuously while the Hb increased oppositely. This nearly complete desaturation was rapidly reversed by the release of the cuff. Because the venous blood was released rapidly, the influxion of artery blood increased immediately, rapid re-oxygenation happened immediately with an observed overshoot before returning to the baseline. Then the blood volume and hemoglobin concentration returned to the baseline. As shown in the cuff ischemia, the blood volume and hemoglobin con-

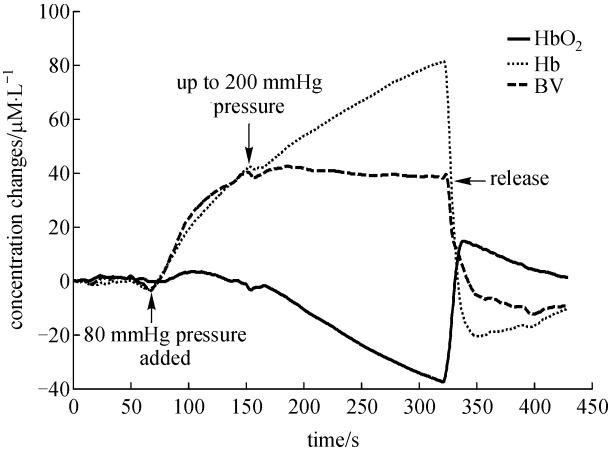

Fig. 3 Blood volume and oxygenation change in cuff ischemia

centration changes during the cuff ischemia are consistent with the known physiology changes. Thus, the monitor can detect the oxygen concentration changes in the measured tissue effectively.

3.2 *In vivo* incremental intensity exercises

Five volunteer subjects performed incremental rowing exercises on a rowing ergometer (Concept, USA) after they gave informed consent. Each test was initiated with a 150-s rest period while the subject was seated on the rowing ergometer. Then the subject began to complete a stepwise incremental protocol of 50 W every 180 s until voluntary exhaustion, or reaching two of the following end points: a) age predicted maximal heart rate (HR) which was calculated as 220-age in years, b) leveling off in the $\dot{V}O_2$ (increase of less than $100\,mL\cdot min^{-1}$) with increasing power output, and c) respiratory exchange ratio (RER) $R_{RER} \geqslant 1.10$. During the exercise, the probe of the device was firmly attached on the motor point of the right vastus lateralis (VL) muscle, approximately 14–18 cm above the knee, parallel to the major axis of the thigh. The heart rate (HR) and respiratory gas exchange parameters, such as minute ventilation ($\dot{V}e$), oxygen uptake ($\dot{V}O_2$), carbon dioxide output ($\dot{V}CO_2$), and RER were monitored by a metabolic system (MAX II, Physio-Dyne, USA) during the experiment. $\dot{V}O_{2max}$ was defined as the maximal $\dot{V}O_2$ observed during each test. The ventilatory threshold (VT) was determined as the point at which the $\dot{V}e/\dot{V}O_2$ versus time plot was still increasing without a simultaneous increase in the $\dot{V}e/\dot{V}CO_2$ versus time plot [1]. VT could be used to detect the LAT [1,13]. HbO_2-Hb was used as the muscle oxygen index, which reflects the balance of oxygen demand and consumption [14]. The result of one typical subject is shown in Fig. 4.

At the beginning of the exercise, blood volume increased due to more blood supply induced by vasodilatation. During the low exercise intensities, blood volume (BV) remained stable due to the balance between muscle contraction and vasodilatation. When the work load reached a high level, muscle contracted strongly and the blood vessel was pressed, so the blood volume decreased. When the exercise stopped, the pressure from muscle contraction to blood vessel disappeared, thus the blood volume increased and reached a level higher than the baseline. Due to the oxygen consumption for aerobic energy supply in the local muscle, [HbO_2-Hb] decreased in the whole exercise period. When the exercise stopped, an overshoot came forth, for two reasons: a) local muscles do not need as much oxygen as during exercise and b) arterial blood flows into the measured local muscle again.

The muscle oxygen index of 5 subjects all showed 2 special time points. As shown in Fig. 4, the first time point

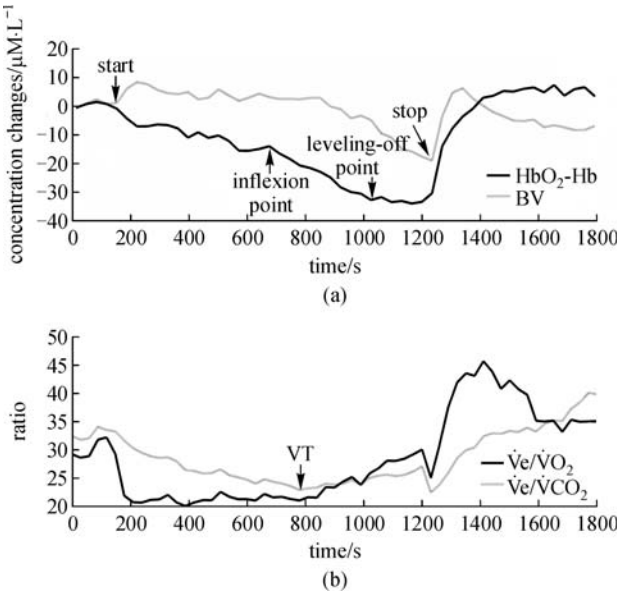

Fig. 4 Typical results of *in vivo* incremental intensity exercise. (a) Changes of muscle oxygenation in right vastus lateralis muscle; (b) changes of respiratory parameters

is the inflexion point which appeared when the muscle oxygen index dropped rapidly. This point of all 5 subjects appeared at $55.6 \pm 2.4\%$ $\dot{V}O_{2max}$, and has a significant correlation with the ventilatory threshold (VT) ($r = 0.97$, $P < 0.01$). Since VT could be used to detect the LAT, the inflexion point of muscle oxygen index might also be used to predict the emergence of LAT. The physiological basis for the inflexion point may be that the increased great amount of lactate in the blood during the exercise facilitates oxygen release from hemoglobin via the Bohr effect, consequently accelerating the decrease in muscle oxygenation [14]. We also found that the first inflexion of muscle oxygen index appeared earlier than VT in all the subjects' results. The physiological explanation for this might be that the first inflexion of muscle oxygen index indicates that lactate acid increased in a large amount and it is buffered by the bicarbonate in the blood, leading to the increase of partial carbon dioxide pressure and hydrogen ion which would stimulate the respiratory center and arouse the change in the frequency of breath to promote the appearance of VT [4]. Therefore, the first inflexion point of muscle oxygen index may reflect LAT in the local muscles directly. Another special time point is the leveling-off point of muscle oxygen index, which appears at $86.6 \pm 2.2\%$ $\dot{V}O_{2max}$ and indicates the beginning of a leveling-off phase in the muscle oxygen index. The leveling-off phase may indicate that the aerobic metabolism capacity of the muscle reaches its limit during the incremental rowing exercise. These results demonstrated that the monitor can be used to detect the local LAT of the measured muscle and reflect the changes of the oxygen index in the muscle during *in vivo*

exercises. Thus, it can be used to evaluate the aerobic metabolism capacities of the subjects effectively and sufficiently.

4 Conclusion

A portable near-infrared spectroscopy muscle oxygenation monitor with high stability, low noise and low power consumption is designed. The monitor can be used to measure the local muscle oxygenation changes *in vivo* to detect the lactate threshold of the measured muscle and evaluate the aerobic metabolism capacities of the subjects non-invasively and effectively. In contrast to the traditional invasive lactate acid detection method, monitoring with the NIRS device is non-invasive, in real time, and dynamical. Compared with the non-invasive gas exchange measurement method, the NIRS measurement method has the advantage of low power consumption, portability, and can measure the muscle oxygen concentration changes directly, which may realize the detection on aerobic metabolism during the dynamic exercise. This design may provide a new method for further study in physiology education and the evaluation of the aerobic capacity, fatigue level of sportsmen and guiding the selection of sportsmen.

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