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RESEARCH ARTICLE

Changes of muscle oxygenation and blood lactate concentration of swimming athletes during graded incremental exercise

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Abstract The sport performance of swimming athletes in three different levels including 5 national high-level swimming athletes, 5 ordinary swimming athletes and 5 college students was investigated by near-infrared spectroscopy (NIRS). Four parameters of muscle oxygenation and blood lactate (BLa) concentration were simultaneously monitored during incremental exercise on the ergometer. It was found that inflection points of muscle oxygenation and BLa concentration were consistent with the human sport capacity. Moreover, inflection points of muscle oxygenation occurred earlier than those of BLa concentration in ordinary athletes and college students. It implies monitoring changes of muscle oxygenation is superior to BLa measurement under this condition, since BLa test has an unavoidable time lag. Significant correlation ($r^2 = 0.948$; $P < 0.05$) was observed between inflection points of muscle oxygenation difference and inflection points of BLa concentration on workload. This relationship suggests changes of muscle oxygenation detected by NIRS is beneficial to the evaluation of athletes' physiologic function and training load. Considering that muscle oxygenation could be in-vivo and non-invasively measured by NIRS, it may be a better indicator of exercise intensity than BLa measurement in the near future.

Keywords functional evaluation, muscle oxygenation, near-infrared spectroscopy (NIRS), blood lactate (BLa)

1 Introduction

During high-intensity sports training, it is crucial to understand in what conditions the body consumes and produces enough energy to avoid injuries. In recent decades, abundant research have been done to appropriately decide the exact exercise load and duration, focusing on the blood lactate (BLa) concentration [1–5]. BLa measurement has been a classical method in sports training for many decades [6,7]. Generally, BLa increases with exercise intensity and shows a clear transition from aerobic activity to anaerobic activity [8]. In details, BLa increases slowly at the beginning and then elicits an exponential rise during graded incremental exercise. The inflection point of BLa has been named as lactate threshold (LT), which means the body changes from aerobic status into anaerobic status. Meanwhile, lactate accumulates as it is produced much faster than its decomposition. Thus, LT is widely utilized to evaluate the sports capacity of athletes and investigate the energy metabolism of the body in exercise [6,9–12]. During the past 50 years, BLa concentration and thresholds measurements greatly promoted the evaluation of sport performance and sport training. Until now, BLa test is still a gold standard for endurance science and the most widely accepted test for aerobic efficiency. However, with the increasing understanding of BLa, some unavoidable limitations are found in BLa test. First of all, during high intensity exercise, lactate is produced in muscle, then accumulates and diffuses into the blood. The diffusion is slow and steady, which lasts about 5–10 min. Besides, BLa sampling is invasive and may cause discomfort of subjects. During exercise or sport, frequent BLa sampling may interrupt the normal movement.

Near infrared spectroscopy (NIRS) is a new biomedical monitoring technology with the advantage of *in vivo*, portability and real time [1,13–17]. It provides noninvasive measurements of the concentration changes of oxygenated hemoglobin ($\Delta[HbO_2]$) and deoxygenated hemoglobin ($\Delta[Hb]$), based on the absorption spectrum of main

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chromophores in tissue [18–20]. Coupled with the optical window (700 – 900 nm), infrared light penetrate in several centimeters deep below skin surface [19,21]. It was reported by Jöbsis that NIRS could be used to monitor oxygenated hemoglobin and deoxygenated hemoglobin concentration changes in the muscle and other tissues, then the NIR light path following a 'banana-shaped' curve into the tissue was simulated and the distance between the light source and the detector was calculated [3]. For the need to evaluate muscle oxidation in sports, portable NIR spectroscopy was developed and validated. In previous NIRS research, oxygenated hemoglobin of local muscle was reported to have some relationship with maximal oxygen consumption (VO_2max) and BLa, however, the comparison between muscle oxygenation parameters monitored by NIRS was not paid enough attention to and the information obtained was not fully exploited. In this study, concentration change of muscle oxygenated hemoglobin, deoxygenated hemoglobin, total hemoglobin (HbT) and hemoglobin oxygenation index (HbD) were defined as $\Delta[HbO_2]$, $\Delta[Hb]$, $\Delta[HbO_2 + Hb]$ and $\Delta[HbO_2\text{-}Hb]$ correspondingly. The physiological changes of four parameters during the incremental test were discussed and the relationship of inflection points between HbD and BLa was demonstrated. Four parameters of muscle oxygenation and BLa concentration were simultaneously recorded and investigated to ensure they can reflect the physiological function timely and accurately.

2 Methods

All subjects were provided informed consent before testing, including 5 national high-level swimming athletes, 5 ordinary swimming athletes and 5 college students. Subject characteristics of three groups were shown in Table 1. All tests were performed under the supervision of a cardiologist. The starting power of the exercise was 40 W and increased by 30 W per 3 min until the subjects exhausted in the test. A portable NIR spectrometer used in this research was developed by Huazhong University of Science and Technology [22]. Incremental experiments were carried out on a bicycle ergometer (MONARK, Sweden), and all subjects were also monitored by a cardiopulmonary function monitoring system (MAX-II, AEI, USA). BLa concentration was measured using a portable lactate test meter (Lactate Pro, LT-1710, Japan). 5 μL of blood from finger tip was sampled for BLa analysis during the last 30 s of each workload during the exercise.

The probe of NIRS was tied to the surface skin on the muscle of vastus lateralis. The bottom edge of the probe was 10 cm upper to the crevice of the knee-joint. The elastic bandage was used to fixed probe without blocking the blood flow. The distance between probe light and source detector was 30 mm, with the detection depth greater than half the source detector distance. The demonstration of detection principle of NIRS was shown in layered tissue with muscle (see Fig. 1). The variation values of $\Delta[Hb]$, $\Delta[HbO_2]$ and BLa concentration were recorded simultaneously during the experiment. In the study, the muscle oxygenation refers to the total effect of the fine veins, arteries and capillaries in the muscle tissue.

3 Results

The exercise performance of college students, ordinary-level and high-level athletes are shown in Figs. 2 to 4. Top panels of the figures display the four muscle oxygenation parameters changes in vastus lateralis during exercise, while the bottom panels show the BLa concentration changes. With the increasing intensity in graded incremental exercise, the muscle oxygen consumption increased and $\Delta[HbO_2]$ decreased gradually. At the same time, lactate in muscle accumulated and diffused into the blood slowly. Comparing the results of three groups, we found the college students group had the fastest oxygen consumption and lowest BLa tolerance. Furthermore, in college students group below the exercise load of 130 W in Fig. 2, BLa had a progressive increase and $\Delta[HbO_2]$ dropped apparently, while BLa and $\Delta[HbO_2]$ remained relatively stable in ordinary-level and high-level athletes groups as shown in Figs. 3 and 4 (BLa < 2 mmol/L). These results suggest better aerobic capacity delay the BLa accumulation and facilitate the oxygen uptake, transport and blood circulation.

Among the changes of four parameters of muscle oxygenation, HbD has the largest variation, and it is a sensitive profile index of the graded incremental workload. For college students and ordinary-level athletes, the inflection point of HbD occurred at 130 W earlier than that of BLa at 160 W (Figs. 2 and 3). The results implied the inflection point is a crucial indicator of local muscle oxygenation and energy supply. If limitations of oxygen

Table 1 Subject characteristics, data are expressed as mean±standard deviation (SD)

	body mass/kg	height/cm	ATT/mm	VO_2max/(mL·kg^{-1}·min^{-1})
group A	76.8±4.1	178.7±3.5	5.2±2.1	50.6±4.7
group B	72.6±3.8	175.1±4.6	5.3±2.4	48.8±4.3
group C	75.2±4.2	173.7±4.3	5.5±2.6	46.2±4.6

Notes: Groups A, B and C represent high-level, ordinary-level athletes and ordinary college students respectively. ATT, adipose tissue thickness

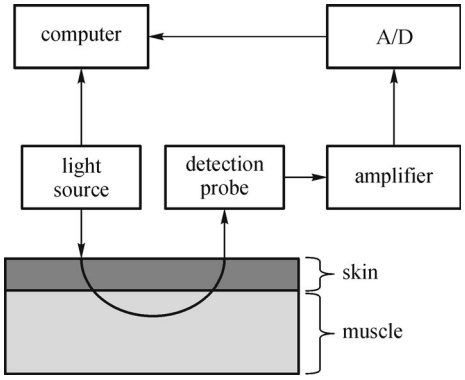

Fig. 1 Schematic diagram of near infrared spectroscopy in layered tissue with muscle A/D represents analog to digital converter. A/D: analog to digital converter

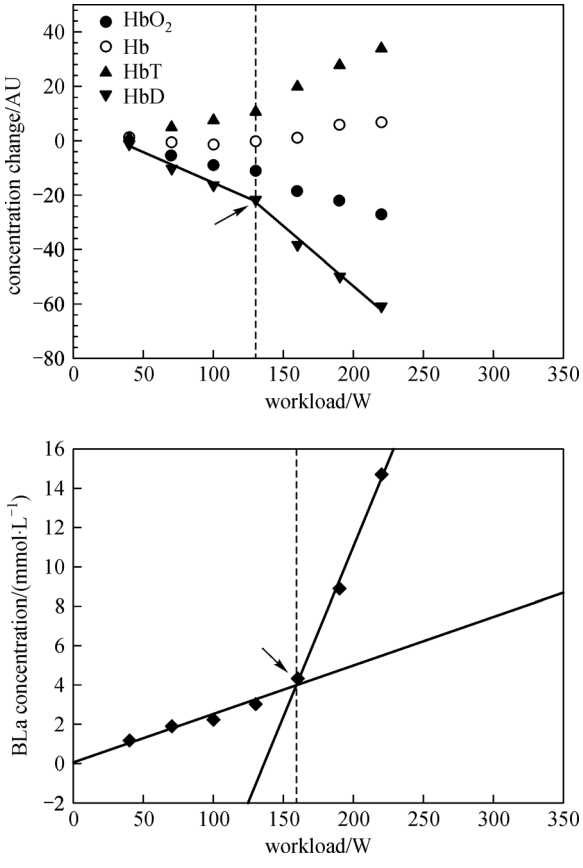

Fig. 2 Changes of muscle oxygenation and BLa concentration in college students group during graded incremental exercise

uptake and utilization happen, the inflection point of muscle oxygenation measured by NIRS is more sensitive than that of BLa concentration, as both BLa diffusion and its testing have unavoidable time lag. Although college students group and ordinary-level athletes group had the same HbD inflection points at 130 W and BLa inflection

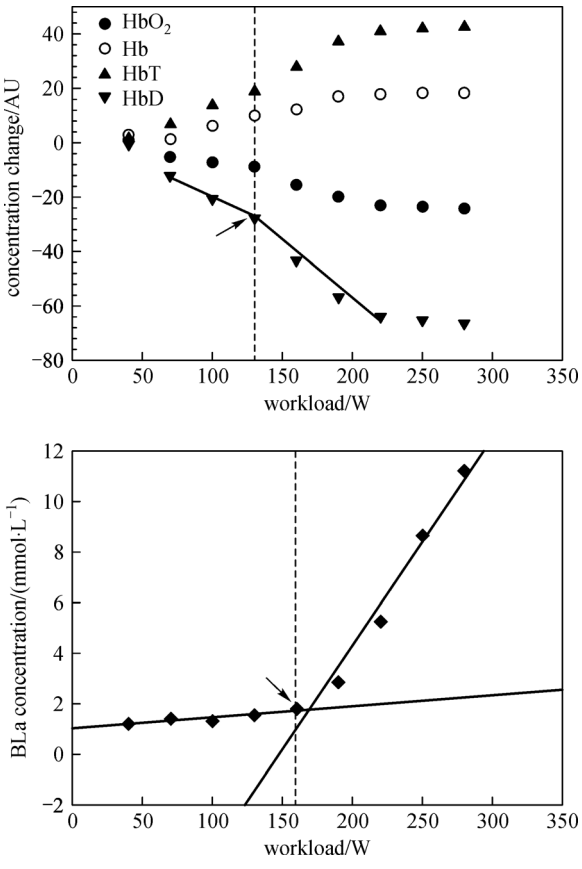

Fig. 3 Changes of muscle oxygenation and BLa concentration in ordinary-level athletes during graded incremental exercise

points at 160 W, sport capacity of them were different, as the maximal exercise intensity of college students group (210 W) was less than that of the ordinary-level athletes group (270 W). Besides, the slopes of HbD and BLa in ordinary-level athletes group were smaller than those in college students group, which demonstrate ordinary-level athletes can adjust the body better suitable to high intensity exercise.

Figure 4 indicate that there is a right shift of muscle oxygenation and BLa curves. The inflection points of HbD and BLa in high-level athletes group were at 190 W. Compared Fig. 4 with Figs. 2 and 3, HbD inflection points occurred earlier than BLa inflection points in college student and ordinary-level athletes groups, while inflection points of HbD and BLa in high-level athletes appeared at the same time, it suggested that the improved sport capacity for better oxygen supply and energy utilization could delay the occurrence of muscle oxygenation inflection points. For the same workload, the changes of HbD and BLa in high-level athletes group were less than those in college students and ordinary-level athletes groups, which implied there are a higher substance utilization and energy production rate in in high-level athletes group. A significant correlation (r^2 = 0.948;

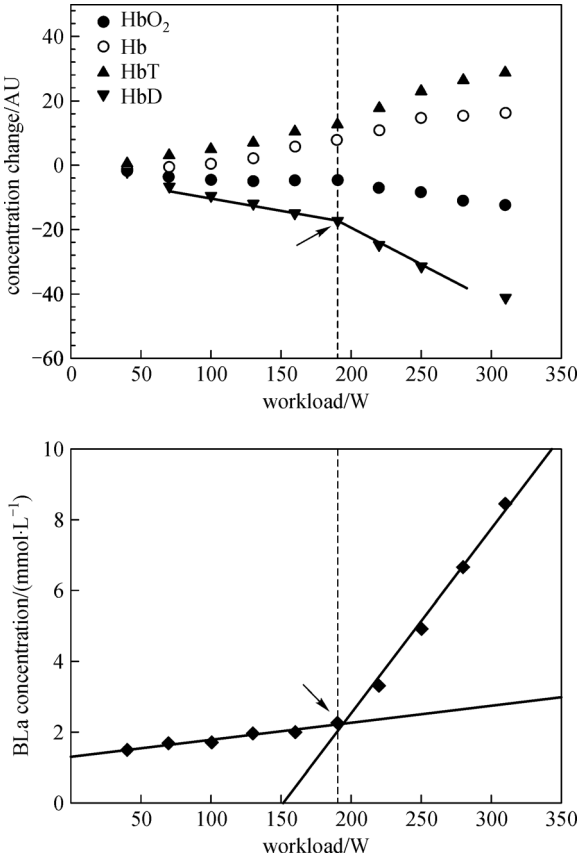

Fig. 4 Changes of muscle oxygenation and BLa concentration in high-level athletes during graded incremental exercise

$P < 0.05$) was observed between the HbD inflection point and BLa inflection point at workload from all subjects. This relationship between muscle oxygenation and BLa presented in graded incremental exercise indicated that muscle oxygenation information detected by NIRS is helpful for the evaluation of athletes' physiologic function and training intensity.

4 Discussion and conclusion

A series of physiological and biochemical changes occur during sport and exercise, which reflect the stress of body under the training load. For coaches and athletes, how to determine the load and duration of training scientifically has been a difficult problem for many years. If the training load and duration is larger than athletic ability, it always cause injuries to athletes. On the contrary, the load is too small to effectively improve the sport ability and level. During the past decades, BLa concentration and thresholds measurements have greatly promoted the evaluation of sport performance and sport training. It is still a gold standard test for aerobic efficiency. With the development of biotechnology and information technology, accurate, non-invasive and real time physiological and biochemical information are recommendable in scientific experiments, BLa test method was found not suitable due to some unavoidable limitations. During the exercise, if exercise intensity increases to a certain grade, at which the body can no longer aerobically convert enough fuels into energy, anaerobic process will be triggered to produce lactate and yield sufficient ATP for muscle movement. Lactate is first produced in muscle, then accumulated and diffused into the blood. The diffusion is slow and steady, which lasts about 5–10 min. The sampling and calculating in lactate test meter cost about 1–2 min. That means when we acquired the value of BLa concentration, it is the concentration of muscle lactate delayed by 6–12 min. This is the reason for that HbD inflection point occurred earlier than BLa inflection point in Figs. 2 and 3. The results suggest BLa test has an unavoidable time lag in muscle lactate accumulation and diffusion, but NIRS could be used to monitor changes of muscle oxygenation during the exercise continuously and in real-time. Both changes of muscle oxygenation and BLa concentration reflect the tissue oxygenation and energy supply in local muscle, but changes of muscle oxygenation by NIRS demonstrates greater advantage [23,24]. However, limitations of NIR method are inevitable, such as NIRS instrument used to measure muscle oxygenation cannot yield absolute values, it only provide semi-quantitative changes of muscle oxygenation. In previous research, changes of muscle oxygenation was mainly investigated in term of $\Delta[HbO_2]$ [25–27]. However, changes of muscle oxygenation include not only $\Delta[HbO_2]$, but also $\Delta[Hb]$, $\Delta[HbO_2 + Hb]$ and $\Delta[HbO_2\text{-}Hb]$. This study presents the monitoring and evaluating capability of NIRS in sports training and propose great potential of predicting BLa threshold. Considering the muscle oxygenation could be *in-vivo* and noninvasively measured by NIRS, it would be a better indicator of sport performance than BLa in near future.

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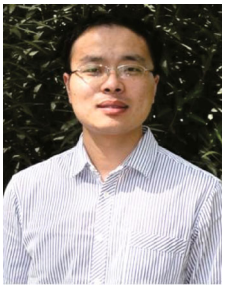

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