Relationship between muscle oxygenation by NIRS and blood lactate

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Abstract: The aim of the study was to investigate the relationship of muscle oxygenation in term of oxy-hemoglobin concentration change ($\triangle HbO_2$) by NIRS and blood lactate (BLA) in local skeletal muscle and evaluate the capability of NIRS in the research of exercise physiology. Twenty-three athlete in the national fin-swimming team took the increasing load training on the power bicycle while their $\triangle HbO_2$ and BLA were simultaneously recorded. The initial powers used in the training were set as 100 w for males and 40 w for females. During the experiment, the power kept constant for 3 min before each abrupt increment of 30 w until the limit of the athlete's capability. Statistical analysis and data visualization were performed. Following the increasing load training, $\triangle HbO_2$ step-likely increased in the phase of aerobic metabolism but linearly decreased in the phase of anaerobic metabolism. The variation tendency of BLA was the same as $\triangle HbO_2$ and the concurrency of crucial turning points between $\triangle HbO_2$ and BLA was revealed. This relationship between $\triangle HbO_2$ and BLA presented in the increasing load training suggested that $\triangle HbO_2$ might be capable for taking the place of the invasively measured parameter BLA. Considering that $\triangle HbO_2$ can be noninvasively measured by NIRS, $\triangle HbO_2$ has the potential in the evaluation of athletes' physiological function and training

effect on the athletes and accordingly NIRS can be well used in this field.

Key words: near-infrared spectroscopy (NIRS), increasing load training, oxy-hemoglobin concentration change ($\triangle HbO_2$), blood lactate (BLA), exercise physiology

1. Introduction

As a traditional method, Blood lactate (BLA) played a critical role in sports training. Generally, BLA would first slowly increase and then intensely increase in incremental exercise. The turning point of such procedure has been named as lactate threshold (LAT), at which time point the body changed into anaerobic status from aerobic status. LAT is widely used to evaluate the sports capacity of the sportsmen and study the body mechanism in exercise. However, the current method to measure BLA is invasive and non real-time.

Near-infrared spectroscopy (NIRS) can provide noninvasive measurements of the concentration changes of oxy-hemoglobin ($\triangle HbO2$), deoxy-hemoglobin (Hb) and total hemoglobin (blood volume, BV) simultaneously and in real-time [1-3]. Since Jobsis reported that NIR light can penetrate to the muscle and the reflected light intensity signal was quantitatively related with the concentration of those O_2-dependent materials, quite a lot of researchers devoted to the research of NIRS [4-9]. Some of them had successfully tested the feasibility of NIRS in measuring the muscle O_2 consumption (VO_2) [10]. Some had used NIRS to measure the blood flow [11, 12] and found NIRS is super in providing the measurement of local muscle compared to plethysmography [13-16].

Among the parameters measured by NIRS, $\triangle HbO_2$ reflects the oxygen metabolism especially the oxygen supply in the local skeletal muscle. Accordingly, some researchers began to apply NIRS in sports training in use of $\triangle HBO_2$. Finally, the reliability and the validity of this application had been approved [1, 17, 18]. Recently, the application research of NIRS in specific ports training was highlighted, although it is just at the beginning.

Considering that BLA is the product of glucolysis and that glucolysis is closely related to the supply and consumption of oxygen, $\triangle HbO_2$ might be related with BLA. This study attempted to

study the relationship of BLA and $\triangle HbO_2$ and further discuss the feasibility and superiority of replacing BLA with $\triangle HbO_2$ in sports training. In the study, we also use other technique to record physiologic indices, such as the respiration exchange ratio (RER) which has been commonly used for monitoring sports training. Of note, the measurement of these indices is used as supplemental evidence in our research.

2. Materials and Method

Subjects

Twenty-three athletes (13 females and 10 males) in the national fin-swimming team were recruited in the experimental research. The age of female subjects were 19.5±2.4 years and the age of male subjects were 20.0±1.5 years. The heights of female subjects were 172.5±3.7cm and those of males were 181±2.8cm. The weights of female subjects were 66.6±5 kg and those of males were 82±6.3 kg.

Equipments

The equipments used in this research included a portable three-wavelength NIRS which was developed by Huazhong University of Science and Technology. a MAX-II cardio-pulmonary function monitoring system made in the U.S, a MONARK（829）power bicycle made in Sweden, a P-Lar heart rate watch made in Finand and a BLA monitor made in Japan.

Experimental paradigm

Incremental exercise on power bicycle was adopted in this research. The initial power of the exercise for female subjects was 40 w and that for male subjects was 100 w. During the exercise, the power of exercise increased by 30 w per 3 min until the exercise limit of the subjects [19].

Data collection

The probe of NIRS was tied to the surface skin on the right quadriceps femora's muscle. The bottom edge of the probe is 10 cm upper to the crevice of the knee-joint. The separation between light source and detectors was 3 cm. the simplified demonstration of detection principle of NIRS was shown by the

light transport in layered tissue with muscle (see Fig. 1). The variation of $\triangle HBO2$ was recorded by NIRS during the experiment. The MAX-II cardio-pulmonary function monitoring system was used to record oxygen uptake, VO_2 and carbon dioxide output (VCO_2), which were also related with oxygen metabolism in the body and thus would be used in supplemental analysis to the relationship between $\triangle HBO2$ and BLA. During the rest phase right before the exercise, BLA was recorded as a contrast. Then, when starting the exercise, increasing the exercise load and ending the exercise, at 1.5 min, 3.0 min, 6 min, 9 min just after the exercise, the values of BLA were recorded accordingly.
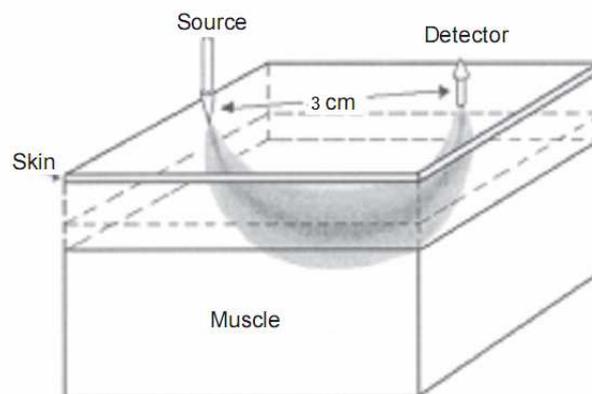

Fig. 1   Schematic of NIR light transport in the tissue with muscle.

Data analysis

Except NIRS, other used equipment belonged to commercial systems which provided the measurement of correspondent parameters without need of additional computing. The prototype NIRS instrument provided the measurements of the reflected light intensities of all used wavelengths during the experiment. A translation algorithm, which was based on the modified Beer-Lambert law, was used initially to change the data on the reflected light intensities to the data on the relative concentration change of $\triangle HBO_2$, $\triangle Hb$ and blood volume. The algorithm had been validated by a serial of published reports. In this research, we mainly analyze the data of $\triangle HBO_2$.

Time course analysis was carried out to compare the variations of $\triangle HBO_2$ and BLA, with intense attention on both turning points, that were, the BLT and the turning point of $\triangle HBO_2$ which were called as oxygen dissociation point.

3. Results

Fig. 2 showed typical primary result curves from a single subject. Compared among $\triangle$HBO2, BLA, VO_2 and VCO_2, we can easily see that the turning point of $\triangle HbO_2$ occurred concurrently with BLT at about 900 s and that the crossing point between VO_2 and VCO_2 occurred at the same time to BLT and oxygen dissociation point. This finding kept consistent in other subjects' results. The crossing point between VO_2 and VCO_2 were generally known as respiratory exchange ratio turning point (RERT). The concurrence of the oxygen dissociation point by $\triangle HbO_2$, BLT and RERT marked the conversion of the sportsmen body from the status of aerobic metabolism to the status of anaerobic metabolism.

During the incremental exercise, $\triangle HbO_2$ decreased slowly and step-shapely before the time point of BLT and then decreased intensely and linearly. On the contrary, BLA increased slowly before the occurrence of BLT and then increase sharply and linearly. Except for the tendency of increase or decrease, there is another difference between $\triangle HbO_2$ and BLA, that is, the step-shaped variation of $\triangle HbO_2$ before BLT but no obvious step-shaped variation of BLA. Considering that it was hard to measure BLA in real time and thus it was almost unrealistic to improve the sampling rate of BLA, it is unreasonable to expect that the curve of BLA before BLT might form the similar step-shape of $\triangle HbO_2$.
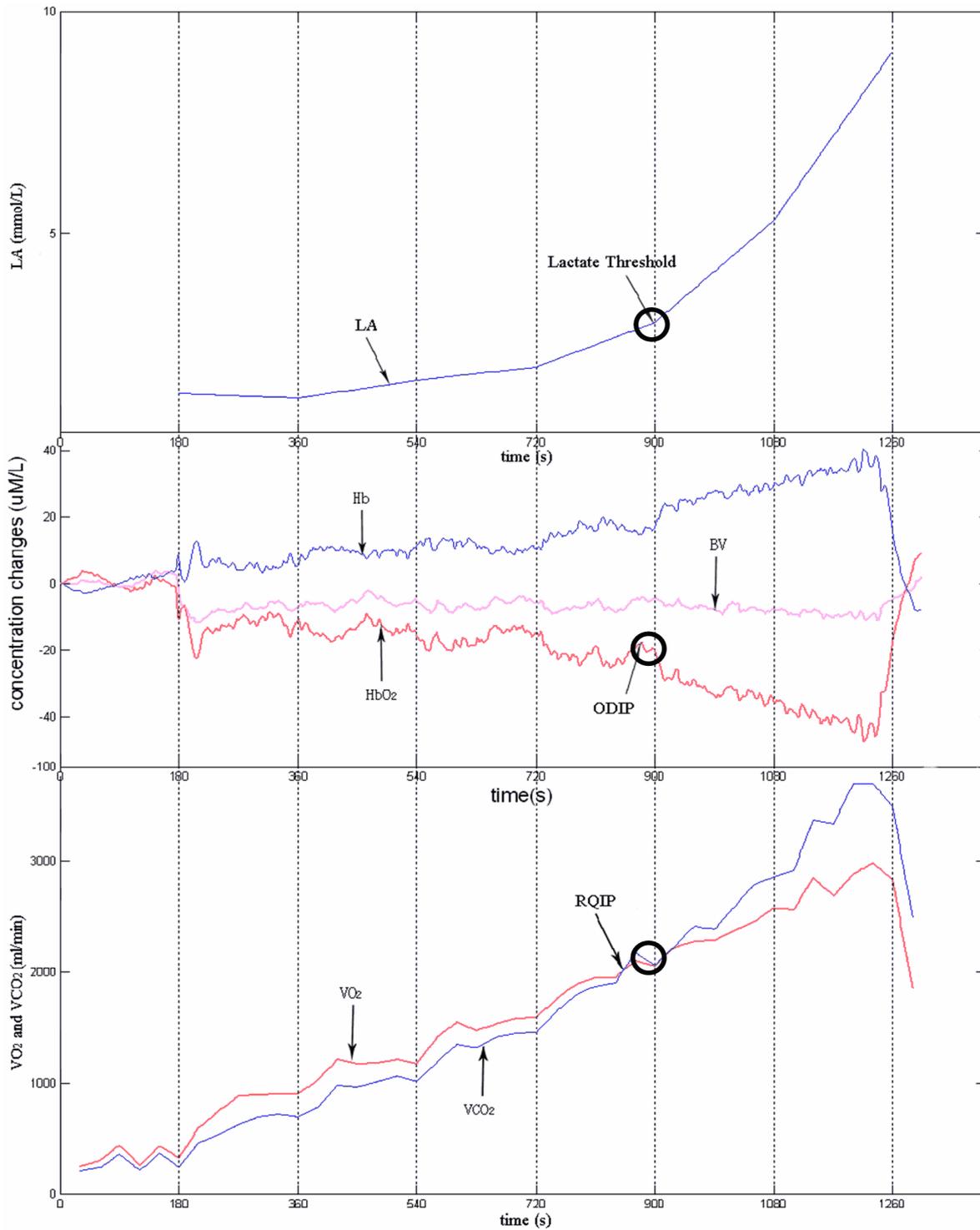
Fig. 2.   Time courses of BLA, $\triangle HBO_2$, and VO_2/VCO_2. The occurring time point of BLT, the turning point of $\triangle HBO_2$, and the crossing between curves VO_2 and VCO_2 were marked with circles.

In order to test the above expectation and further analyzing the relationship between $\triangle HbO2$ and

BLA, we increased the sampling rate and redraw the variation curve of BLA, which was shown in blue color in Fig. 3. It was quite clear that the step-shape of $\triangle HbO_2$ was almost repeated by the new curve of BLA. In addition, it was found that the earlier occurred step shape of $\triangle HbO_2$ showed a faster and shorter increase phase and a slower and longer decrease phase. However, following with the increment of the exercise load, the $\triangle HbO_2$ trended to be flat, which was obvious during the fourth increment of the exercise. This variation could not be significantly observed by the data of BLA, but we could found the time points linking the increasing phase and the decreasing or flat phase under all increment of the exercise loads kept consistent between $\triangle HbO_2$ and BLA. Moreover, it should be emphasized that, the expectation on the step-shape of BLA variation in the aerobic status of metabolism could also be supported by the theory analysis.
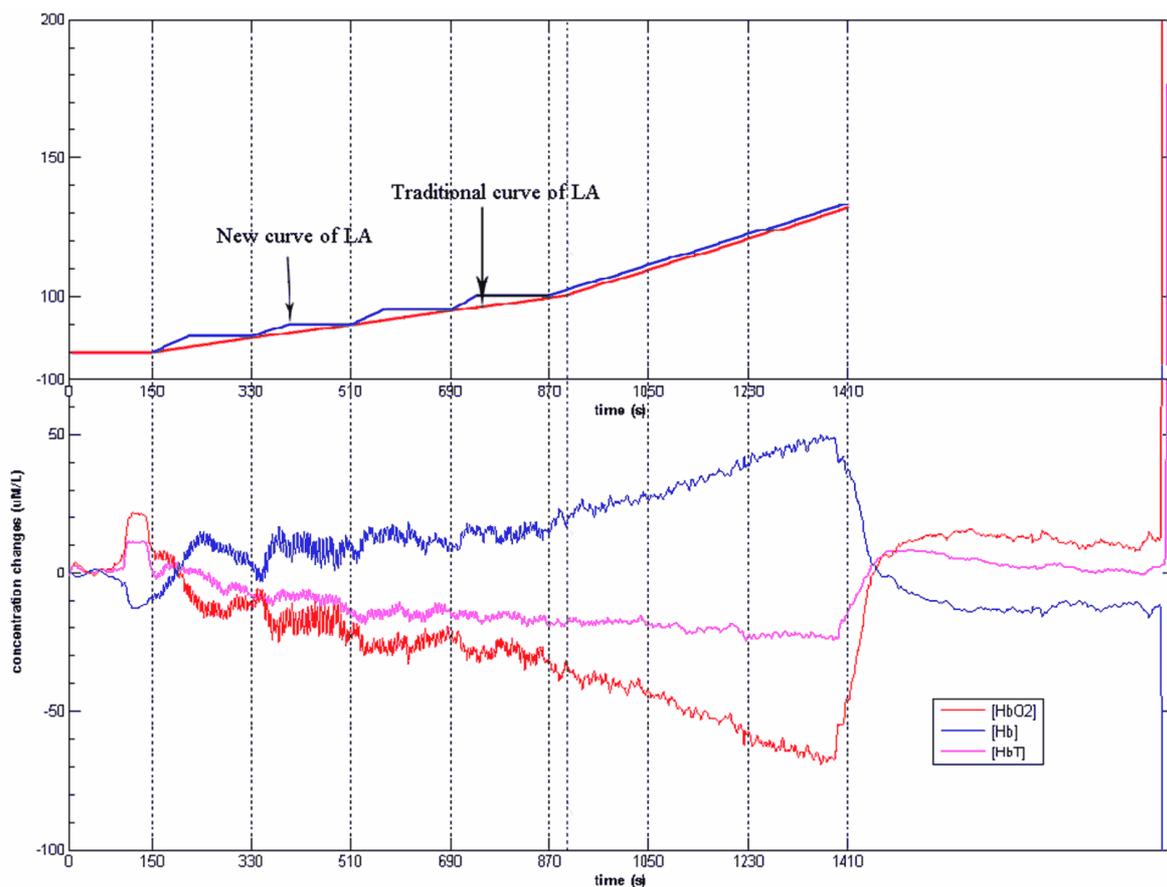

Fig. 3.   Comparison between BLA and hemodynamic changes on each step-shape segment corresponding to the increment of the exercise loads. The blue curve for BLA was redrawn by increasing the sampling rate of the primary curve of BLA.

In order to compare the total tendency of $\triangle HbO_2$ and BLA during the whole experiment, we decreased the sampling rate of $\triangle HbO_2$ to be the same as BLA. After the operation of $\triangle HbO_2$ data, the curve of $\triangle HbO_2$ was updated as shown in black color in Fig.4. It was clear that the opposite $\triangle HbO_2$ curve would be same to BLA in variation in the complete duration of the experiment. Specifically, in the status of aerobic metabolism, $\triangle HbO_2$ presented the similar slower increasing variation to the BLA; in the status of anaerobic metabolism, $\triangle HbO_2$ presented nearly the same sharp increasing variation to the BLA. In detail, there is only a small difference between the reduced curve of $\triangle HbO_2$ and the primary curve of BLA, which is that, $\triangle HbO_2$ in the status of aerobic metabolism showed a nonlinear increment but BLA showed linear increment.

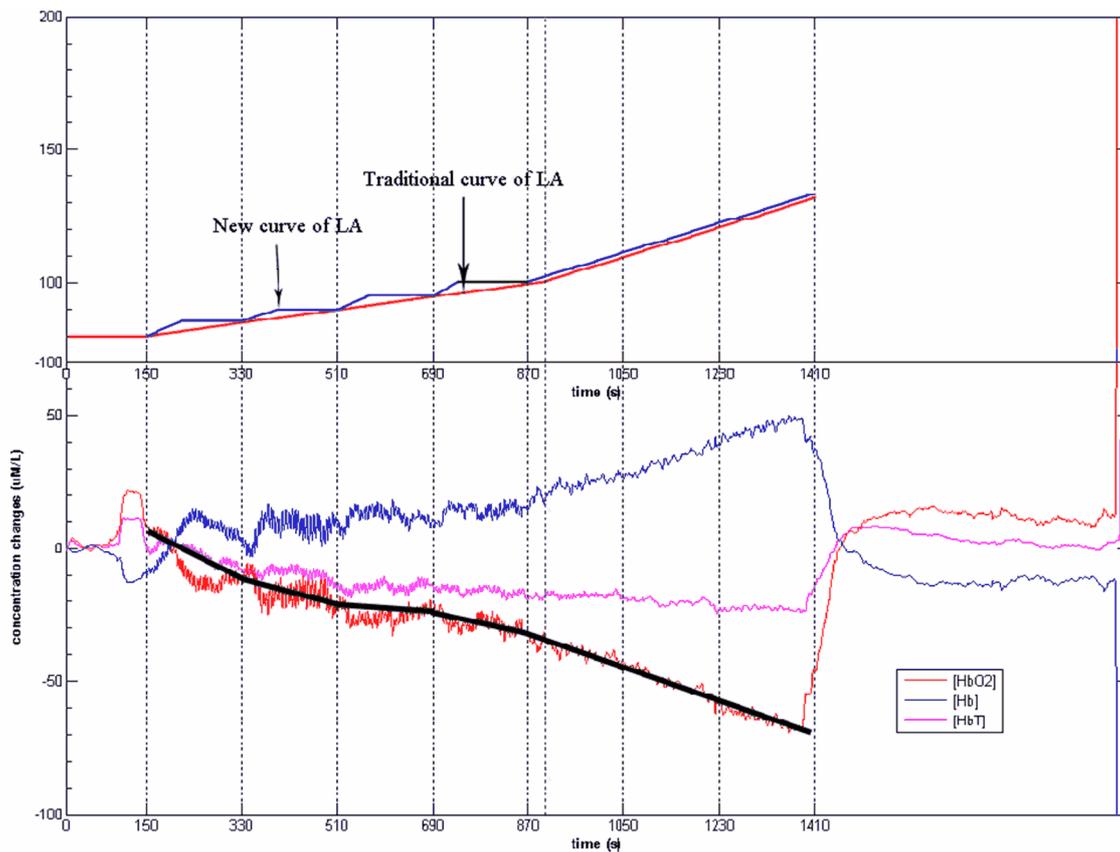Fig. 4   Comparison between BLA variation and hemodynamic changes. To be noted, the black curve displayed the variation of $\triangle HbO_2$ at the same sampling rate with BLA.

It is worth noting thta, the parameter $\triangle Hb$ also showed the nearly the same turning point and the variation tendency to BLA. To mention, the curve of $\triangle Hb$ was almost parallel to the updated curve of

BLA when it was smoothed in Figs. 2 - 4, no matter in the status of aerobic metabolism or in the status of anaerobic metabolism. On the contrary, the blood volume did not exhibit obvious consistence with BLA.

Last but not least, the oxygen dissociation point is not the precise time point but a small time segment, which was the same either in BLT or in the crossing point between the curves of VCO_2 and VO_2. In theory, it should take a while for the body turned into the anaerobic status of metabolism from the aerobic status of metabolism. In the practical test, it was common to observe that the curve of RER fluctuated around the crossing point between VCO_2 and VO_2. In the measurement of BLA, we found the time point of BLT but considering that sampling rate of BLT was quite low, the actual BLT should be within the sampling interval around BLT and we could not conclude BLT was a point but not a segment. As for the whole body, all skeletal muscles could not turn into the anaerobic status of metabolism simultaneously. Actually, the transferring time of each muscle between those statuses was dependent on its sustainability to the exercise load. Consistent with the physiology theory, the curve of $\triangle HbO_2$ also showed a fluctuation period around the analyzed oxygen dissociation point. Rightly in this fluctuation period, the metabolism status of the body changed. Among all the subjects, the time range (870 ~ 900 s) of the oxygen dissociation period (See Fig. 4) was quite small and showed coincidence with BLT and RERT.

4. Discussion and Conclusion

This study investigated the relationship of muscle oxygenation in term of oxy-hemoglobin concentration change ($\triangle HbO_2$) and blood lactate (BLA) in local skeletal muscle. Twenty-three athletes in the national fin-swimming team were recruited to take the increasing load training on the power bicycle. The variation of $\triangle HbO_2$, BLA, and other oxygen metabolism related physiological parameters (VO_2/VCO_2) were simultaneously recorded. The time courses among hemodynamic changes (especially $\triangle HbO_2$), BLA, and VO_2/VCO_2 were compared and analyzed. The consistence between the variation of $\triangle HbO_2$ and BLA were revealed and were supported by the observation on VO_2/VCO_2.Our study showed that the traditional important parameter used in sports training, BLA, which owned the drawbacks including invasive approaches and non real-time measurement, could be

possibly predicted by $\triangle HbO_2$ and $\triangle Hb$ by NIRS, which is noninvasive and real-time in measure.

During the incremental exercise, all the sportsmen showed the consistence between the variation of hemodynamic changes mainly revealed by $\triangle HbO_2$ and BLA, which specifically included below. Firstly, the oxygen dissociation point revealed by $\triangle HbO2$ and $\triangle Hb$ appeared concurrently with BLT and RER, which is the crossing point between VCO_2 and VO_2. This point means for the body's transition from the status of aerobic metabolism to the status of anaerobic metabolism. More importantly, the oxygen dissociation points revealed by $\triangle HbO_2$ and $\triangle Hb$ in all subjects were actually a time segment ranged from 870 s to 900 s in practical test, which was also in coincidence with BLT and RER crossing point. Secondly, the complete variation tendency of $\triangle HbO_2$ and $\triangle Hb$ were consistent to BLA. During the aerobic status of metabolism, they both exhibited a slow increasing phase; while during the anaerobic status of metabolism, they both exhibited a fast and linear increasing phase. In addition, they both showed step-shaped increase during the aerobic status of metabolism and interestingly, the time point connecting the sharp increasing phase and the slow decreasing or flat phase in each step-shaped segment showed up nearly at the same time among $\triangle HbO_2$, $\triangle Hb$ and BLA. Accordingly, although the value of each point in the BLA curve could not be predicted by $\triangle HbO2$ or $\triangle Hb$, the variation of BLA in the whole time sequence and some critical point for further physical analysis could be likely to predict by $\triangle HbO2$ or $\triangle Hb$. There seems to be a proportional ratio between the measured values of $\triangle HbO2/\triangle Hb$ and BLA. In this situation, the invasive and non real-time approach to measure BLA is potentially substituted by noninvasive and real-time method, NIRS.

Here, it might be questioned that why $\triangle HbO_2$ changed as BLA in a similar linear way? A possible explanation would be as follows: the association and dissociation of $\triangle Hb$ and O_2 could be affected by the PH value. As demonstrated by the Bohr effect [20, 21], when the PH value in the blood decreased, the association between $\triangle Hb$ and O_2 would be suppressed and the dissociation between $\triangle Hb$ and O_2 would increase [22]. In this case, the concentration of $\triangle HbO_2$ would decrease and the concentration of $\triangle Hb$ would increase. During the initial state of increasing the exercise load, strong glycolysis activity exploded which caused the in vivo accumulation of blood lactic acid and accordingly decreased the PH value in the blood. Therefore, the concentration of $\triangle HbO_2$ and $\triangle Hb$ would change

correspondingly respond to the variation of BLA. Such process benefited the supply of O_2 to the body in exercise. However, further study was required to test this explanation and explore the quantitative relationship between $\triangle HbO_2 / \triangle Hb$ and BLA, by which we could predict the value of BLA with NIRS measured $\triangle HbO_2 / \triangle Hb$.

In summary, our study attempted to apply NIRS in sports training and found that the concentration change of $\triangle HbO_2$ and $\triangle Hb$ measured by NIRS showed the same variation tendency and critical turning point as BLA. In addition, the oxygen dissociation point revealed by both $\triangle HbO2$ and $\triangle Hb$ was proved by the crossing point between VCO_2 and VO_2. This study presented the strong capability of NIRS in sports training and proposed the strong potential of predicting BLA variation tendency with the data of $\triangle HbO_2$ or $\triangle Hb$ by NIRS. Considering that the BLA was one of the crucial parameter used in sports training and its measuring approach is invasive and non real-time and that NIRS is noninvasive and real-time, our finding on the relationship between $\triangle HbO_2 / \triangle Hb$ and BLA would be likely to enlighten a novel way to measure BLA.

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