Japanese Journal of Health, Fitness and Nutrition, 18(1), 1 − 5 (2013)

Original Article

Detection of metabolic threshold using near-infrared spectroscopy on the incremental handgrip exercise

Tsuyoshi WADAZUMI[*1], **Hitoshi WATANABE**[*2] **and Kanji WATANABE**[*3]

*1：*Department of Health and well-being, Faculty of Health and well-being, Kansai University*

*2：*Research Center for Urban Health and Sports, Osaka City University*

*3：*Department of Health and Sports Sciences, School of Health and Sports Sciences , Mukogawa Women's University*

Abstract

When tissue oxygenation is detected by near-infrared spectroscopy (NIRS) during ramp load exercise using a bicycle ergometer, there is a linear decrease in oxygenation with increase in exercise intensity during the initial phase of exercise when the intensity is low. However, the decline in muscle oxygen level reaches a NIRS threshold (NT) in the later phase of exercise when the intensity becomes high. Beyond the NT, the level plateaus even as the intensity further increases. We examined the NT phenomenon during an incremental handgrip exercise. To study the physiologic significance of NT, we also examined the relationship of NT with blood lactate concentration and integrated electromyogram (iEMG) values. Twelve healthy male subjects participated in this study. The incremental handgrip exercise was performed with an increment in intensity of 5%/min starting from an intensity equivalent to 5% of the maximum muscle strength, and continued until exhaustion. The pace of exercise was 20 times/min. Blood was collected every minute during exercise to measure the blood lactate concentration. Muscle EMGs were recorded during exercise, and the fatigue threshold (FT) was determined from the iEMG analysis. The tissue oxygenation kinetics of the flexor digitorum muscles during exercise showed changes in tissue oxygenation with increases in exercise intensity during the initial phase of exercise. NT was seen in all subjects. The lactate threshold (LT) and FT were observed at MVC 33.2 ± 6.2% and 34.6 ± 6.2%, respectively. The results confirmed that NT, LT and FT occurred almost simultaneously during exercise. NT is the point at which the rate of increase in deoxyhemoglobin plateaus, suggesting an increase in dependence on anaerobic glycolysis after NT appearance to yield energy. NT was considered to be the point at which the recruitment of type II-b muscle fibers was initiated to yield energy anaerobically as the exercise intensity increased.

Key words： near-infrared spectroscopy (NIRS) (近赤外線分光法), NIRS threshold(NIRS 閾値), lactate(乳酸値), electromyogram(筋電図積分値), incremental handgrip exercise(漸増負荷掌握運動)

Ⅰ. Introduction

Oxygen uptake estimated from the pulmonary gas exchange parameter has been used as an index for oxygenation in working muscles. The oxygen transport and the oxygen use abilities in active muscles during exercise are important factors that determine exercise capacity. In dynamic exercise, it is very difficult technically to measure the continuous blood flow in muscles. Development in optical instruments using near-infrared spectroscopy (NIRS) has made it possible to directly and noninvasively measure the change in relative oxygenated hemoglobin and/or myoglobin in working muscles [1−3].

Studies that have examined intramuscular oxygen dynamics during exercise using NIRS indicated the relationship between the decrease in oxygenation level and the increase in oxygen uptake [4], and significant correlation between the decrease of oxyhemoglobin (oxyHb) level within the active muscle and the lactic acid concentration in blood, and the increase of muscle electric discharge during prolonged exercise [5]. Sympathetic vasoconstriction in peripheral skeletal muscle during certain metabolic states can be evaluated using NIRS [6]. Moreover, it has been reported in studies using NIRS that systemic metabolism changes, such as ventilatory threshold (VT), oxygen uptake, and peripheral muscle oxyHb level, during ramp load exercise using a bicycle ergometer are related [7−10].

When the tissue oxygenation (tissue oxygenation index; TOI) is detected by a NIRS device during ramp load exercise using a bicycle ergometer, there is a linear decrease accompanying the increase in exercise intensity during the initial phase of exercise when the exercise intensity is low. However, the decline in muscle oxyHb level reaches a NIRS threshold (NT) in the later phase of exercise when the exercise intensity becomes high. Beyond the NT, the level plateaus even as the exercise intensity further increases. While the phenomenon of NT has been reported in previous studies [11−13], its mechanism has not been elucidated.

To investigate whether NT occurs during exercises other than the ramp load exercise using a bicycle ergometer, we examined the NT phenomenon in an incremental handgrip exercise. The tissue oxygenation was determined using a NIRS analyzer that provides analyses of three parameters; oxyHb, deoxyhemoglobin (deoxyHb) and total hemoglobin (total Hb). To study the physiologic significance of NT, we also examined the relationship of NT with blood lactate concentration and integrated electromyogram (iEMG) values.

Ⅱ. Methods

1. Subjects

Twelve healthy male subjects (age, 28.3 ± 9.7 years) participated in this study. The mean (± SD) values for height, weight and BMI were 171.5 ± 6.5 cm, 65.9 ± 6.5 kg, 16.9 ± 4.0 kg/m^2, respectively. Written informed consent was obtained after informing all subjects of the purpose of the experiment, the procedure, and possible risks. The study was approved by the Kansai University Faculty of Health and Well-being Ethics Committee.

2. Exercise mode

A handgrip exercise was adopted as the exercise mode employing a manufactured handgrip device (comprised of a TKK-5001 handgrip, Takei, Japan; a TU-8 transducer, Kyowa, Japan; and a strain amplifier, Kyowa, Japan).

3. Physiological measurements

The muscle oxygenation level was measured using a NIRS analyzer (NIRO-300/Hamamatsu Photonics, Japan) that provides analyses of three parameters; oxyHb, deoxyHb and total Hb. The device consisted of two optical probes and a computerized control system. Each optical probe consisted of one emitter and one detector. Four different wavelength laser diodes (775, 810, 850, and 910 nm) in the emitter provided the light source. The optodes were housed in an optically dense plastic holder. The NIRS probe was fixed to the skin over the right flexor digitorum muscle.

Blood was collected from the antebrachial vein every minute during exercise in order to measure the blood lactate concentration in the contracting muscle.

Continuous surface electromyograms (EMGs) were recorded using bipolar electrodes. The electrodes were attached to the skin over the flexor digitorum muscle. Prior to EMG electrode application, the measurement site was prepared by gentle abrasion with abrasive cream to remove dead skin. The interelectrode impedance was kept below 10 kΩ . The EMG signals were amplified with a gain of 2000. (EEG1A94, Nihondenki Sanei, Japan).

4. Experimental procedure

The maximum voluntary contraction (MVC) of a handgrip for each subject was measured in advance of the experiment. With the subject in a sitting position, the NIRS probe and EMG electrodes were attached to the skin over the right flexor digitorum muscle. A catheter was inserted in the right antebrachial vein in order to collect blood samples. Incremental handgrip exercises were performed with a load increment of 5%/min starting from an exercise intensity equivalent to 5% of the maximum muscle strength, and the exercise was continued until exhaustion. The pace (tempo) of exercise was 20 times/min, and the relaxation ratio of the active muscle was 1:1.

Subjects observed the intensity value of their handgrip on an oscilloscope (DS-8812, IWATSU, Japan). Subjects performed the handgrip exercise at a constant tempo according to the incremental exercise intensity. Identification of handgrip strength was made using intensity feedback with the oscilloscope through a transducer.

5. Data analysis

All data were recorded at 1000 Hz by a computer through an A/D converter. The changes in oxygen kinetics of oxyHb, deoxyHb and total Hb accompanying the incremental increase of exercise intensity were detected. The NT point at which an increase stagnates from a change in the deoxyHb concentration was determined. The increase in deoxyHb denotes an increase in oxygen consumption without any influence from the blood flow. The lactate threshold (LT) in which the concentration changes in lactate increases steeply was detected. EMGs of the muscle during exercise were also recorded, and the fatigue threshold (FT) was determined from the iEMG analysis.

6. Statistical analysis

The results are expressed as mean ± SD. LT, FT and NT are calculated from log-log model [14].

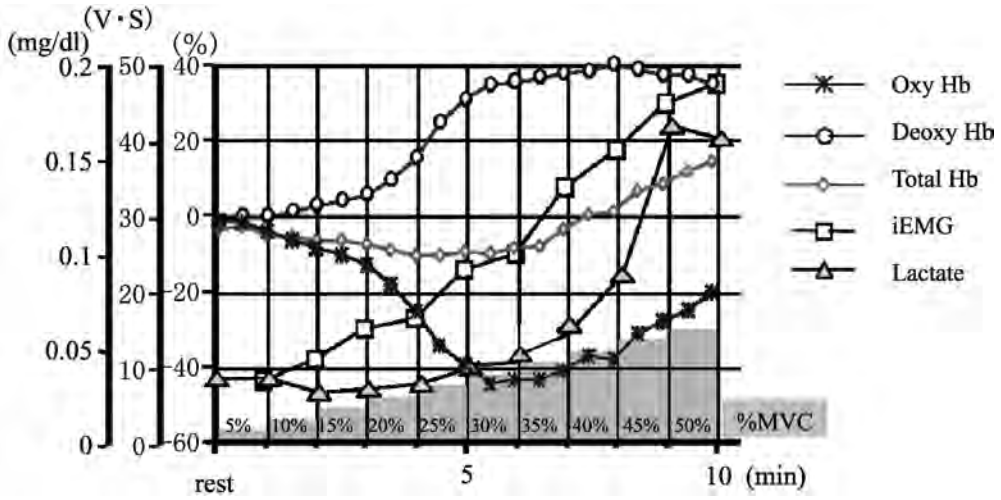

Fig 1. Typical changes in oxyhemoglobin, deoxyhemoglobin, total hemoglobin, blood lactate concentration and integrated electromyogram (iEMG) during incremental handgrip exercise in one subject.

Ⅲ. Results

Fig. 1 shows a typical example of changes in oxyHb, deoxyHb, total Hb, lactate concentration and iEMG during the incremental handgrip exercise for one subject. The oxy-gen kinetics after the start of the incremental handgrip exercise changed with the increase in exercise intensity, and NT appeared in the latter half of the exercise. The appearance of NT in all 12 all subjects was confirmed (34.2 ± 5.6% MVC). LT and FT were 33.2 ± 6.2% of MVC and 34.6 ± 6.2% of MVC, respectively. NT, LT and FT occurred almost simultaneously during the incremental handgrip exercise (Fig.1, 2, 3, 4, Table.1). In addition, the kinetics of the deoxyHb plateaued, although the oxyHb increased slowly with the increase of exercise intensity after NT appeared (Fig. 1, 3).

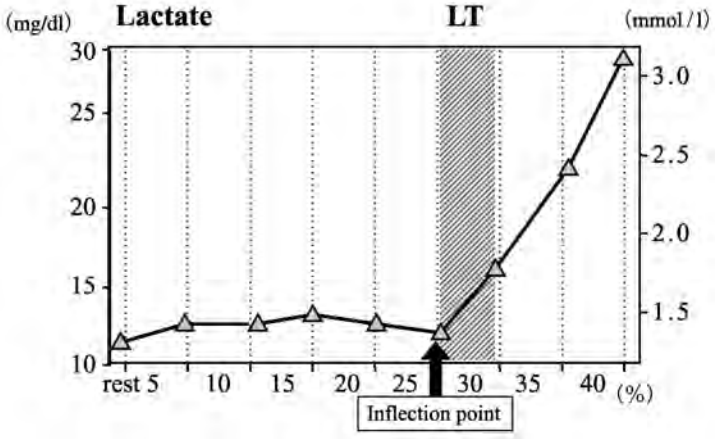

Fig 2. Typical changes in blood lactate concentration during incremental handgrip exercise in one subject.

Ⅳ. Discussion

There is a linear increase in deoxyHb that accompanies the increase in exercise intensity during the initial phase of exercise when the exercise intensity is low. However, the deoxyHb level plateaus in the later phase of exercise when the exercise intensity becomes high (Fig.1, 4). It was confirmed that NT appeared during the incremental handgrip exercise. NT corresponded to exercise intensity during which the increase in deoxyHb and the decrease in oxyHb stagnated. Moreover, the deoxyHb plateaued although the oxyHb increased slowly with the increase of exercise intensity after NT appeared (Fig. 4). Miura et al. [5] examined the change in oxyHb, iEMG and blood lactate concentration with bicycle exercises at five different intensities. They reported that

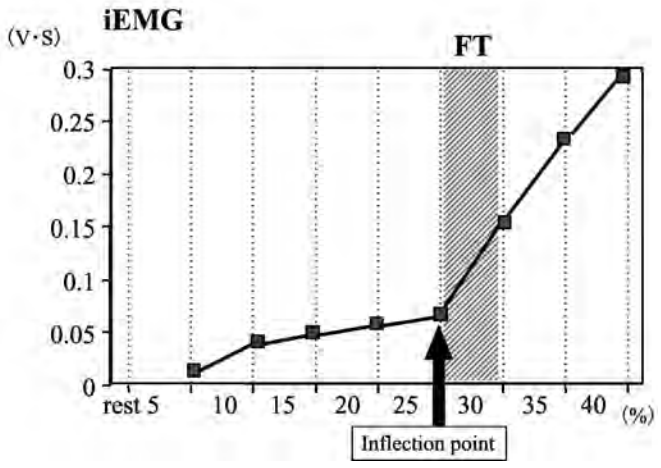

Fig 3. Typical changes in integrated electromyogram (iEMG) during incremental handgrip exercise in one subject.

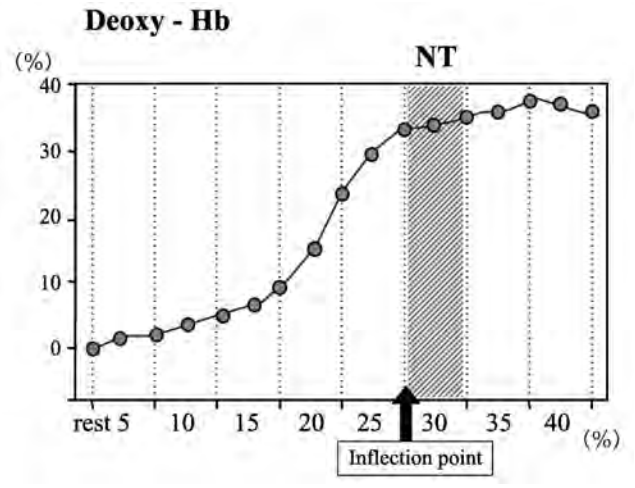

Fig 4. Typical changes in deoxyhemoglobin concentration during incremental handgrip exercise in one subject.

the kinetics of the oxyHb related to the muscle activity and the change in the blood lactate concentration, and VT was 61% of $V\dot{O}_2$max. In this report, although the oxyHb decreased during high-intensity exercise that exceeded VT, it augmented gradually exceeding NT in the present study.

We considered that the differences in these results are due to differences in the measurement method. We fixed the forearm to prevent muscle recruitment.

Mimura et al. [15] reported that oxyHb increased during constant cycling at an intensity that was 80% of aerobic threshold (AT), while $V\dot{O}_2$ was not changed. They reported that the change in the blood lactate concentration, the catecholamine concentration and the oxygen uptake reflects an increase in the blood flow of the active muscle. It is necessary to examine these phenomena in future studies to clarify this mechanism, such as the exercise mode and exercise load strength, etc. The results of the present study suggest that the change in the energy metabolism occur at the point that exceeds NT.

The evaluation of muscle activity by EMG has been used as an index of exercise intensity and muscle fatigue [16−19]. It is known that the increase in iEMG reflects greater motor unit recruitment to maintain the required force level [20]. The blood lactate concentration by the increase of exercise intensity reflect in energy-yielding by anaerobic glycolysis [21]. Stringer et al. [22] reported that the acidosis produced by lactic acid formation influences oxyHb dissociation. Viitasalo et al. [18] reported that the iEMG of the vastus lateralis muscle increases sharply during bicycle exercise, which corresponds to changes in metabolism. NIRS measures muscle oxygenation in small blood vessels and capillaries. Therefore, the skeletal muscle oxygenation evaluated with NIRS might indicate peripheral

Table 1 Individual appearance phases of NT, LT and FT in all subjects

Case NO. (MVC%)	NT (MVC%)	LT (MVC%)	FT (MVC%)
1	40	35	35
2	35	35	35
3	30	30	30
4	40	35	45
5	30	20	25
6	40	45	45
7	30	35	35
8	30	35	30
9	40	30	30
10	30	30	35
11	40	30	40
12	25	40	30
Mean	34.2	33.3	34.6
S.D	5.6	6.2	6.2

muscle activity, which could then be compared with whole-body metabolism, such as oxygen uptake. This suggests that the contribution of anaerobic glycolysis augments the energy yield after NT appearance. In other words, aerobic exercise using type I muscle fibers occurs during the initial phase of exercise when the exercise intensity is low, and the kinetics of deoxyHb concentration, LT, and FT change linearly with increases in exercise intensity.

In the present study, changes of oxygenation level, muscle activity (EMG) and the blood lactate concentrations in muscles during a handgrip exercising were simultaneously examined. NT, LT and FT, which reflect the metabolic state in peripheral small muscles, appeared simultaneously. NT reflects the point at which the deoxyHb increase plateaus; therefore, it was considered to be the point at which the recruitment of type II-b muscle fibers was initiated to yield energy anaerobically as the exercise intensity increases.

In summary, it was confirmed that NT occur during the incremental handgrip exercise. NT could be an index reflecting the metabolic state of muscles during exercise. Our findings suggested that NT reflects the recruitment of type II-b muscle fibers to yield energy.

References

1) Chance B, Dait MT, Zhang CM, Hamaoka T, Hagerman F: Recovery from exercise-induced desaturation in the quadriceps muscles of elite competitive rowers. Am J

Physiol. 262, 766-778, 1992.
2) Hamaoka T, Iwane H, Shimomitsu T, Katsumura T, Murase N, Nishio S, Osada T, Kurosawa Y, Chance B: Noninvasive measures of oxidative metabolism on working human muscles by near-infrared spectroscopy. J Appl Physiol. **81**, 1410-1417, 1996.
3) Homma S, Eda H, Ogasawara S, Kagaya A: Near-infrared estimation of O_2 supply and consumption in forearm muscles working at varying intensity. J Appl Physiol. **80**, 1279-1284, 1996.
4) Belardinelli R, Barstow TJ, Porszasz J, Wasserman K: Skeletal muscle oxygenation during constant work rate exercise. Med Sci Sports Exerc. **27**, 512-519, 1995.
5) Miura H, Araki H, Matoba H.Kitagawa K: Relationship among oxygenation, myoelectric activity, and lactic acid accumulation in vastus lateralis muscle during exercise with constant work rate. Int J Sports Med. **21**, 180-184, 2000.
6) Fadel PJ, Keller DM, Watanabe H, Raven PB, Thomas GD: Noninvasive assessment of sympathetic vasoconstriction in human and rodent skeletal muscle using near-infrared spectroscopy and Doppker ultrasound. J Appl Physiol. **96**, 1323-1330, 2004.
7) Belardinelli R, Barstow TJ, Porszasz J, Wasserman K: Changes in skeletal muscle oxygenation during incremental exercise measured with near infrared spectroscopy. Eur J Appl Physiol. **70**, 487-492, 1995.
8) Bhambhani YH, Buckley SM, Susaki T: Detection of ventilator threshold using near infrared spectroscopy in men and women. Med Sci Sports Exerc. **29**, 402-409, 1997.
9) Bruno G, Quaresima V, Marconi C, Ferrari M, Cerretelli P: Blood lactate accumulation and muscle deoxygenation during incremental exercise. J Appl Physiol. **87**, 348-355, 1999.
10) Kawaguchi K, Tabusadani M, Sekikawa K, Hayashi Y, Onari K: Do the kinetics of peripheral muscle oxygenation reflect system oxygen intake?. Eur J Appl Physiol. **84**, 158-161, 2001.
11) Hamaoka T, Iwane H: Noninvasive evaluation of systemic and localized working muscle oxidative metabolism during exercise in normal people. Jpn Circ J. **58**, 487, 1994.
12) Wadazumi T, Kimura M, Oshima Y, Miyamoto T, Tanaka S, Fujimoto S: Differences in breakpoint patterns in the muscle oxygenation curve measured by NIAS during RAMP exercise. Therapeutic Research. **17**, 55-59, 1996.
13) Wadazumi T, Kimura M, Oshima Y, Miyamoto T, Tanaka S, Fujimoto S: Evaluation of the muscle oxygenation curve by near-infrared spectroscopy (NIAS) during ramp exercise －A new methpod of evaluation and its relationship to physical fiteness-. Jpn J Phys Fitness Sports Med. **48**, 125-136, 1999. (in Japanese).
14) Beaver W, Wasserman K, Whipp B: Improved detection of lactate threshold during exercise using a log-log transformation. J Appl Physiol. **59**, 6, 1936-1940, 1985.
15) Mimura T, Tanaka S, Ishihara K, Wadazumi T, Fujiwara H, Fujimoto S: Significance of muscle oxygenation measured by NIRS during prolonged exercise Jpn Soc Edu Health Sci. **49**, 222-229, 2003. (in Japanese).
16) Moritani T, Nagata A, Muro M: Electromyographic manifestations of muscular fatigue. Med Sci Sports Exercise. **14**, 198-202, 1982.
17) Petrofsky JS: Frequency and amplitude analysis of the EMG during exercise on the bicycle ergpmeter. Eur J Appl Physiol. **41**, 1-15, 1979.
18) Viitasalo JT: Luhtanen P, Rahkila P: Electromyographic activity related to aerobic and anaerobic threshold in ergometer bicycling. Act Physiol Scand. **124**, 287-293, 1985.
19) Hanon C, Thpaut-Mathieu C, Hausswirth C, Le Chevalier JM.: Electromyogram as an indicator of neuromuscular fatigue during incremental exercise. Eur J Appl Physiol. **78**, 315-323, 1998.
20) Enoka RM, Stuart DG: Neurobiology of muscle fatigue. J Appl Physiol. **72**, 1631-1648, 1992.
21) Schneider DA, McLeean TM, Gass GC: Plasma catecholamine and blood lactate responses to incremental arm and leg exercise. Med Sci Sports Exerc. **32**, 608-613, 2000.
22) Stringer W, Wasserman K, Casaburi R, Porszasz J, Maehara K, French W: Lactic acidosis as a facilitator of oxyhemoglobin dissociation during exercise. J Appl Physiol. **76**, 1462-1467, 1994.