Estimation of oxygen extraction in exercising muscle by near infrared spectroscopy

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INTRODUCTION

Pulmonary oxygen uptake (ṾO$_2$) is considered to reflect oxygen consumption of the whole body and give the useful information concerning the integrated respiratory, circulatory and muscular systems. It is well known that pulmonary ṾO$_2$ increases by 15- to - 20-fold from a resting state (about 3.5 ml • min^{-1} • kg^{-1} body mass) to maximal exercise (40-70 ml • min^{-1} • kg^{-1} body mass). On the other hand, it has been indicated that skeletal muscles have a higher capacity to utilize oxygen than is used during whole body exercise (Bangsbo et al., 2000), and during maximal one-legged exercise, muscle oxygen utilization can increase to more than 80-fold from the value at rest (Sahlin, 1991). In fact, Blomstrand et al. (1997) reported that the peak ṾO$_2$ of quadriceps muscle at maximal one-legged knee extension exercise was 353 ml • min^{-1} • kg^{-1} active muscle, whereas the peak pulmonary ṾO$_2$ during the same exercise was 22 ml • min^{-1} • kg^{-1} body mass. Therefore, the data of pulmonary ṾO$_2$ do not always give the amount of oxygen consumed by exercising muscle, since pulmonary ṾO$_2$ includes oxygen consumption in both active and inactive tissues during exercise. This suggests that it is necessary to measure muscle ṾO$_2$ during exercise in order to know precise oxygen utilization in exercising muscle. Presently reliable methods for determining

muscle $\dot{V}O_2$ are invasive and require muscle blood flow measurement such as thermodilution technique, radio-active indicator and Doppler technology (Bangsbo et al., 2000; De Balsi et al., 1993; Rådegran et al., 1999). The muscle $\dot{V}O_2$ can be calculated by multiplying the muscle blood flow ($\dot{Q}$) measurements with arterial and venous difference (a-v O_2 diff) in oxygen content (Fick principle: $\dot{V}O_2 = \text{a-v } O_2 \text{ diff} \times \dot{Q}$). However, these invasive methods for measuring muscle $\dot{V}O_2$ are too difficult to perform repeatedly during exercise owing to the complex procedures including some risks.

Near-infrared spectroscopy (NIRS) has been developed in the last decade to noninvasively monitor oxygenated and deoxygenated hemoglobin (Hb) and myoglobin (Mb) concentrations in brain (Pringle et al., 1998; Firbank et al., 1998) and skeletal muscles (Boushel and Piantadosi, 2000; Chance and Bank, 1995; Van der Zee et al., 1992). NIRS is based on relative ease with which near-infrared (NIR) light (700-1000 nm) passes through biological tissues, including bone, skin and skeletal muscle. Recently NIRS has been used to assess the relative changes in oxygenated Hb ([Oxy-Hb]) and deoxygenated Hb ([Deoxy-Hb]) in skeletal muscle during exercise (Belardinelli et al., 1995; Grassi et al., 1999; Wariar et al., 2000). The [Oxy-Hb] and [Deoxy-Hb] in exercising muscle are expressed in arbitrary units, because the absolute pathlength of NIR light in the tissues is unknown. Consequently, a number of NIRS studies have provided relative estimation (%) in muscle oxygenation by measuring Δ[Oxy-Hb + Deoxy-Hb] in exercising muscle, with a arterial occlusion technique that eliminates oxygen supply to exercising muscle by blood flow. The rate of changes in Δ[Oxy-Hb + Deoxy-Hb] could be determined by the balance in oxygen utilization within and oxygen supply to exercising muscle. According to the occlusion technique, the changes in Δ[Oxy-Hb + Deoxy-Hb] under a condition without oxygen supply to exercising muscle are thought to reflect only relative muscle oxygen utilization. However, this method does not yield absolute level of oxygen utilization and the changes in tissue [Oxy-Hb + Deoxy-Hb] are applied to the only overall change within one subject (Belardinelli et al., 1995).

The present study is focused on the use of NIRS for estimating oxygen extraction in exercising muscle without the vascular occlusion technique. The purpose of this study is to show the possibility for estimating muscle $\dot{V}O_2$ during static and dynamic exercise in upper arm by the NIRS.

METHODS

Subjects. Four healthy male subjects (aged 20 to 43 yr) volunteered to participate in this study. Before the subjects gave their informed consent, they were fully explained the purpose and procedures of this experiment.

Procedures. Before starting a series of exercise tests, the subjects were asked to rest in sitting position for approximately 10 min to obtain a stable baseline from the NIRS measurements. All subjects performed two types of muscle contractions (static exercise: ST-5 and ST-8 and dynamic exercise: DY-5 and DY-8) using two weights of 5 and 8 kg. In the two static exercises with 5 and 8 kg, the subjects maintained isometric muscle contractions in the right upper arm until volitional fatigue, at a fixed angle of 90 degree between forearm and elbow joint. The dynamic exercise test was executed by lifting up and down the weights from a vertical position to a horizontal position at a constant frequency: one contraction every 2 s (0.5 Hz). Four exercise

tests were separated by approximately 15-min recovery period.

The NIRS measurements were made using a continuous light source triple-wavelength spectrophotometer (model BOM-L1 TR, OMEGAWAVE INC.). The probe unit consists of silicon photodiode as a photodetector and three light-emitting diodes (peak wavelengths 780, 810 and 830 nm). The probe was attached over the biceps muscle of the right upper arm (~5-7 cm above elbow joint). The distance between each light source and the photodiode was 3 cm. The NIRS data were collected via an analog-to-digital converter (PowerLab/8S) every second. Spectra were analyzed according to a modified Lambert-Beer Law (Delpy et al. 1988) with a constant pathlength factor of 4.0 to obtain quantification of [Oxy-Hb], [Deoxy-Hb] and [Total Hb] in muscle tissue during the exercise tests. The results were converted to micromoles per 100 ml of muscle tissue volume, assuming a molecular mass of 64,458 for Hb. The oxygen content in muscle tissue was calculated by taking the molecular ratio between Hb and O_2 [1:4]. In the exercise model used in this study, it is postulated that oxygen supply to exercising muscle would remain unchanged during exercise. This allows a better estimation of oxygen extraction in exercising muscle without vascular occlusion. Muscle oxygen extraction ($[O_2\text{-extrac}]_m$) was assessed as the difference of the oxygen content between the baseline (resting value) and exercising values with respect to time. The integral ($=\int[O_2\text{-extrac}]_m$ with respect to time) of $[O_2\text{-extrac}]_m$ from the onset of exercise to the end of exercise was converted into $ml \cdot min^{-1} \cdot 100\ ml^{-1}$ muscle tissue volume and has been abbreviated as muscle $\dot{V}O_2$.

RESULTS AND DISCUSSION

Muscle contraction times of the static exercises with two weights (5 and 8 kg) were 81.3 ± 29.5 s (mean ± SD) for ST-5 and 64.5 ± 33.8 s for ST-8, respectively, whereas in the dynamic exercise with two weights they were ranged from 43 to 83 s (65.3 ± 15.0 s) for DY-5 and from 31 to 47 s (40.5 ± 5.9 s) for DY-8.

A typical illustration of [Oxy-Hb], [Deoxy-Hb] and [Total Hb (=Oxy-Hb + Deoxy-Hb)] changes during the static and dynamic exercise test is shown in Figure 1. The [Total Hb] revealed a constant value throughout the two static exercises. During the static (isometric) exercise, an elevated intramuscular pressure within the contracting muscle would be sustained until the end of exercise. In contrast, the slight decreases and increases of [Total Hb] occurred alternatively during the two dynamic exercises. Cyclical changes were observed during each contraction-relaxation cycle. This fluctuation of [Total Hb] could be directly attributable to the changes in intramuscular pressure due to contraction and relaxation in the exercising muscle. The [Total Hb] change has been indicated to reflect change in muscle blood volume (Firbank et al., 1998). The [Total Hb] change was more pronounced in dynamic exercise than in static exercise. The difference is probably due to the changes of intramuscular pressure, which can occur in dynamic exercise but not during isometric contraction. From this contention, it might be expected that muscle blood flow (oxygen supply to muscle) was kept almost constant throughout the exercise tests used in this study.

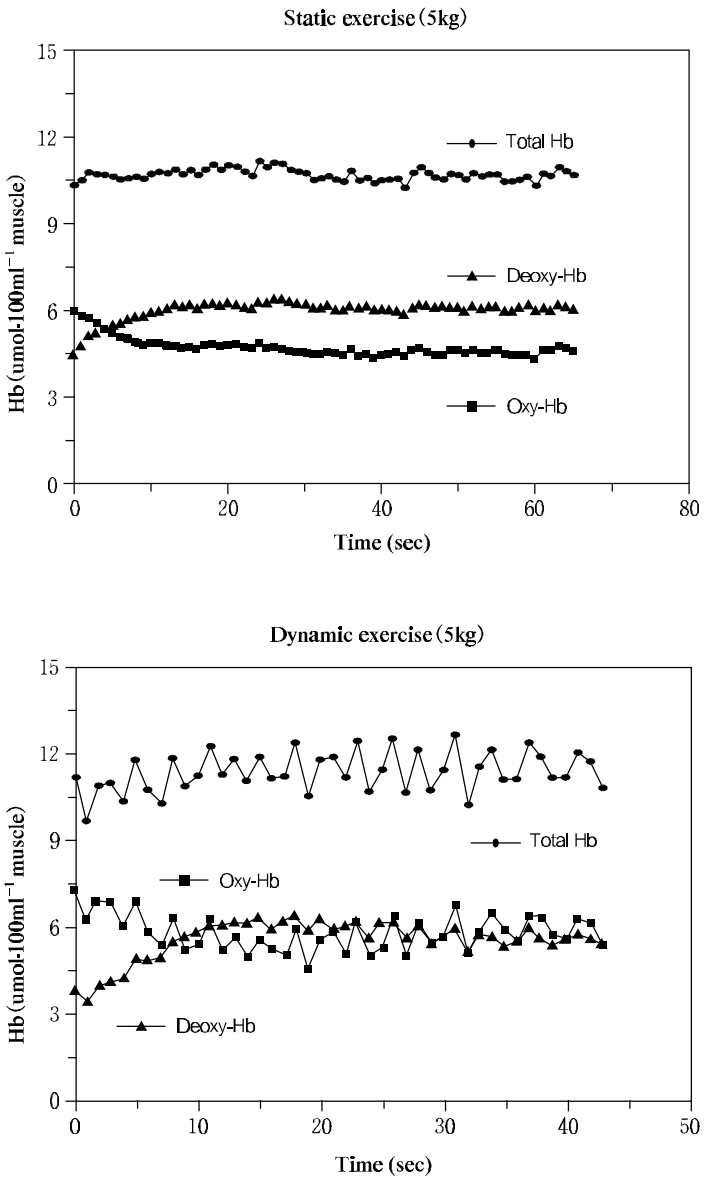

Figure 1. Changes in oxygenated, deoxygenated and total hemoglobin in biceps muscle during static (upper panel) and dynamic exercise (lower panel).

Consequently, it seems likely that [Oxy-Hb] decreases and [Deoxy-Hb] increases in exercising muscle could give an evidence for the increased oxygen utilization in exercising muscle (Hampson and Piantadosi, 1988). In addition, Grassi et al. (1999) have indicated that [Oxy-Hb] and [Deoxy-Hb] changes can be considered a reliable oxygenation index only if [Total Hb] is constant. As given in Figure 1, a large part of the changes in [Oxy-Hb] and [Deoxy-Hb] were found within the first 10 s of both types of exercises, which would imply that oxygen utilization in exercising muscle was accelerated immediately after the onset of exercise.

Figure 2 shows the changes in oxygen content and oxygen extraction in exercising muscle with the time course of the two static exercises (ST-5 and ST-8). The rate of decline of oxygen content in the exercising muscle for ST-8 was greater than that for ST-5. This trend was found in the two dynamic exercises of DY-5 and DY-8. These findings were associated with the faster acceleration in $[O_2\text{-extrac}]_m$ within a few seconds of the onset of exercise, which suggests that oxygen utilization of the exercising muscle is much faster than previously reported (Grassi et al., 1996). Bangsbo et al. (2000) showed that muscle oxygen extraction (measured from the muscle blood flow measurements with dyedilution technique) was elevated after a few seconds (<6 s) of exercise, which is consistent with the present results of muscle deoxygenation at the initial phase of exercise (figures 1 and 2). The faster oxygen extraction by the exercising muscle in the early phase of exercise could be caused by muscle oxygen stores and/or oxygen bound to myoglobin (MbO_2) as a source of oxygen, rather than the faster oxygen supply to the muscle, in particular during the static exercise (Bangsbo et al., 2000).

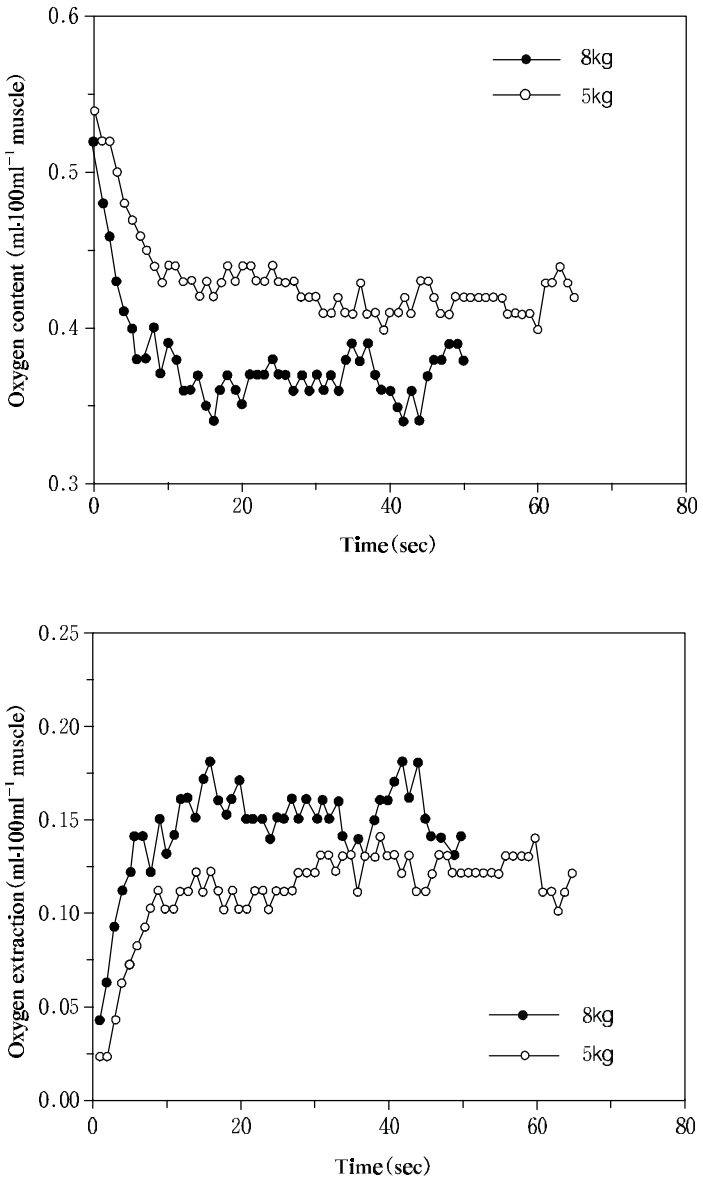

Figure 2. Changes in oxygen content (upper panel) and oxygen extraction (lower panel) in biceps muscle during static exercise.

The data of oxygen uptake in exercising muscles previously reported (Brechue and Stainsby, 1994; Brechue et al., 1991; Blomstrand et al., 1997; Catcheside and Scroop, 1993; Hartling et al., 1989; Hogan et al., 1995; Richardson et al., 1999) are listed in Table 1. Muscle $\dot{V}O_2$ in these studies was assessed by the Fick principle (see INTRODUCTION). It is to be noted that oxygen uptake in exercising muscle is much higher than expected from pulmonary $\dot{V}O_2$ (peak pulmonary $\dot{V}O_2$=60-80 ml • min^{-1} • kg^{-1} body mass in endurance athletes). When comparing muscle $\dot{V}O_2$ between the static and dynamic exercise at the same workload, mean values of muscle $\dot{V}O_2$ in the static exercise (4.72 ± 1.58 for ST-5, 8.55 ± 1.09 ml • min^{-1} • 100 ml^{-1} muscle volume for ST-8) were found to be lower than in dynamic exercise (7.32 ± 1.52 ml • min^{-1} • 100 ml^{-1} muscle volume for DY-5 and 9.77±1.48 ml • min^{-1}•

Table 1. Oxygen uptake of exercising muscles calculated by the Fick principle from muscle blood flow measurements in the previous studies.

Experiment	Muscle O_2 uptake (ml•min^{-1}• 100 g^{-1} muscle)	Reference
Dog Gastrocnemius muscle Isometric contraction (30% of peak $\dot{V}O_2$)	5.1 ($\dot{V}O_2$ peak=17)	Hogan et al. 1995
Dog Gastrocnemius muscle Maximal repetitive contraction 30 s isometric contraction	20.2 7.8	Brechue & Stainsby 1991 1994
Human Maximal knee-extensor exercise (q. femoris)	35.3	Blomstrand et al. 1997
Human Maximal knee-extensor exercise (q. femoris)	43.2	Richardson et al. 1999
Human Static forearm exercise 15% MVC	3.4	Catcheside & Scroop 1993
Human Dynamic forearm exercise 45% MVC 90% MVC	2.3 3.4	Hartling et al. 1989

MVC, maximal voluntary contraction.

100 ml^{-1} muscle volume for DY-8) as shown in Figure 3. This result supports that dynamic exercise causes higher oxygen demand compared to a prolonged isometric contraction (De Blasi et al., 1993). The muscle $\dot{V}O_2$ obtained in this study was higher than Hartling et al. (1989) measured during forearm repetitive contractions at 90% of MVC. It is difficult to compare muscle $\dot{V}O_2$ among studies, since it depends on muscle mobilized in exercise, exercise intensity and type of exercise (see Table 1). On the other hand, a large variability of muscle $\dot{V}O_2$ was observed even at the same workload (2.59-6.05 for ST-5, 7.40-10.25 for ST-8, 4.70-8.40 for DY-5 and 8.18-11.29 $ml \cdot min^{-1} \cdot 100\ ml^{-1}$ muscle volume for DY-8). This inter-individual variability could be accounted for by inter-individual differences in pathlenghth factor and fat/

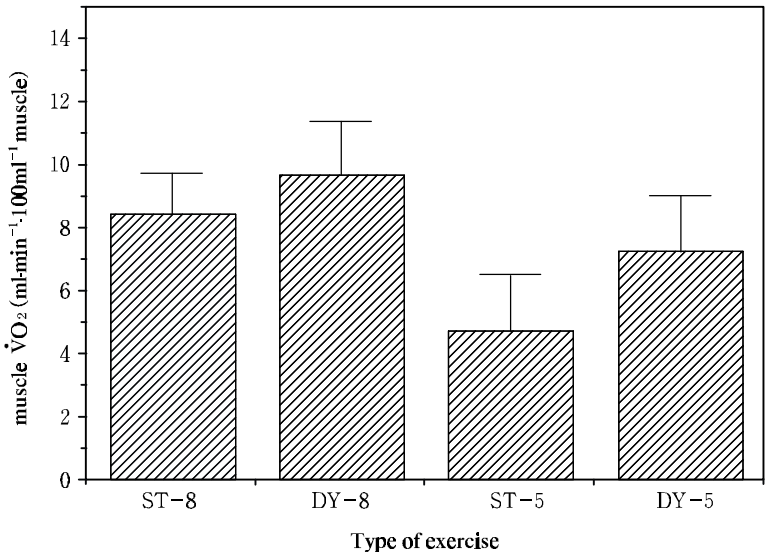

Figure 3. Comparison of oxygen uptake in biceps muscle during static and dynamic exercise. Values shown are means±SD for 4 subjects.

muscle ratio. In this study, a constant pathlength factor (4.0) was used for quantification of the NIRS signal. In addition, subcutaneous fat thickness is expected to be different among subjects. It has been indicated that the pathelength factor is different between subjects and subcutaneous fat has a large impact on the NIRS signal (Colier et al., 1993; McCully and Hamaoka, 2000).

In summary, the NIRS appears to be a reliable and simple method for the noninvasive assessment of muscle oxygen extraction during exercise, especially in isometric contraction with constant blood volume within the exercising muscle. However, useful calibrations of the NIRS signal based on the heterogeneous mediums (skin, fat and muscle) are needed to obtain more reliable absolute data from the NIRS measurements. This could contribute to resolution of the main problems on the NIRS studies.

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