Changes in Skeletal Muscle Oxygenation during Dynamic Exercise in Patients with Respiratory Failure

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Abstract. The purpose of this study was to investigate tissue oxygen saturation during a single knee extension exercise in seven chronic respiratory disease patients (CRF) and six age-matched controls. The subjects performed three minutes of dynamic knee-extension exercises at two different intensities, as no weight exercise and 10% maximal voluntary contraction (MVC) exercise. Tissue oxygen saturation ($SO_2$NIRS = oxygenate hemoglobin/total hemoglobin) in the vastus lateralis muscle was measured by continuous-wave NIRS (NIRS: near-infrared spectroscopy). The relative changes in $SO_2$NIRS ($\Delta SO_2$NIRS) was expressed by changes from resting value, and two-way analysis of variance (ANOVA) with repeated measurements used to evaluate the overall comparisons of exercise responses between the CRF and control groups. There was no significant change in quadriceps muscle force between the CRF and control group (208.7 ± 19.6 N; mean ± SE, 234.7 ± 25.9 N, respectively). $\Delta SO_2$NIRS during exercise showed a significant difference between the two groups during no-weight and 10%MVC exercises (p<0.01, p<0.05, respectively), while $SaO_2$ did not show any significant difference. We concluded that CRF subjects demonstrated a lower tissue oxygen saturation during exercise than did healthy older ones, and this difference could be explained by the changes in oxygen supply and/or consumption in the exercised muscle.

Key words: Tissue oxygen saturation, Near-infrared spectroscopy, Chronic respiratory failure

INTRODUCTION

Impaired exercise tolerance is common in pulmonary patients with several pieces of evidence pointing to the fact that there are limits of arterial oxygenation, ventilatory and/or heart action during exercise for such patients. Recently, it has been noted that deterioration of endurance capacity of peripheral muscles also contributes to reduced exercise capacity. Information of skeletal muscle endurance capacity derives from muscle metabolism and oxygenation measurements. To assess muscle metabolism, muscle biopsy during resting, phosphorus magnetic resonance spectroscopy during exercise, and assessing muscle oxygenation by arterial and venous blood sampling are often used. The oxygen consumption of skeletal muscle during exercise has been estimated as the product of muscle blood flow and the arteriovenous $O_2$ difference. However, such measurements of muscle oxygen consumption require invasive techniques that limit application to physiological
and clinical measurements. A noninvasive and reproducible measurement of oxygen consumption in the working muscle is thus needed.

Recently, measurements using NIRS have made it possible to noninvasively measure in vivo changes in the oxygenated hemoglobin, and deoxygenated hemoglobin of tissue. Although this technique has been used to assess changes in blood volume, and the balance between O₂ delivery and O₂ consumption in skeletal muscle, none of the studies have reported changes in tissue saturation during exercise in patients with respiratory insufficiency. The purpose of this study was to compare tissue oxygen saturation during an exercise between patients with chronic respiratory failure and age matched control subjects.

SUBJECTS

A group of seven patients (5 male, 2 female) with chronic respiratory insufficiency; caused by emphysema (4 subjects), post pulmonary tuberculosis and fibroid lung (1 subject), and a group of six age-matched controls were included in this study. Informed consent was obtained from all the subjects. Five of the seven patients were receiving long-term oxygen therapy. All of the control subjects were free of cardiopulmonary diseases and diabetes.

METHODS

Maximal voluntary contraction (MVC) during a knee extension maneuver was measured at the right side by an isometric dynamometer (Combit CB1, MINATO inc.) while seated with the hip in 90° flexion and the knee in 60° flexion. The test was performed three times and the highest value taken. The dynamic knee-extension exercise was performed at two different intensities for three minutes at a frequency of 30 extensions per minute. The subjects extended their right thigh knee joint from 90 to 0 degree. The intensity of exercise corresponded either to a non-weight task or 10%MVC.

Figure 1 shows a schematic of the experimental setup for measurement of the changes in arterial and tissue oxygen saturation during exercise.

Arterial oxygen saturation (SaO₂) was estimated continuously via a pulse oximeter (N-20PA, Nellcor, Co, Ltd.) with measurements every 30 seconds.

A continuous-wave near-infrared spectrometer (BOM-L1TR, Omega Wave Inc.) was used to monitor tissue oxygenation. This instrument used three wavelengths (780, 810 and 830 nm), with the absorption characteristics generally dependent on relative oxygenate hemoglobin (Oxy Hb), deoxygenate hemoglobin (Deoxy Hb). The absorption coefficient of hemoglobin at each wavelength was based on data reported by Matcher et al. and the absorption changes were converted into concentration changes using an algorithm as follows:

\[
\text{OxyHb} = 9.09 \cdot \ln \left( \frac{I_b}{I_{bo}} - \frac{I_c}{I_{co}} \right) - 0.54 \cdot \ln \left( \frac{I_a}{I_{ao}} - \frac{I_b}{I_{bo}} \right)
\]

\[
\text{DeoxyHb} = 5.73 \cdot \ln \left( \frac{I_b}{I_{bo}} - \frac{I_c}{I_{co}} \right) - 3.61 \cdot \ln \left( \frac{I_a}{I_{ao}} - \frac{I_b}{I_{bo}} \right)
\]

Where, \( \ln \) is the natural logarithm, and \( I_a \) and \( I_{ao} \) are the intensity of detected and incident light, respectively, from each of the three-wave lengths.

For measurements, the distance between the incident point and the detected point in this condition, required a penetration of about 15 mm. The NIRS probe was placed over the right vastus lateralis muscle 10–12 cm above the knee and was protected by adhesive tape and a rubber sheet.

NIRS data were input to a Macintosh personal computer at a sampling frequency of 10 Hz via an A/D transducer (Mac Lab 8s, AD Instrument Inc.). Tissue oxygen saturation (SO₂NIRS) was calculated...
from the ratio of Oxy Hb to Total Hb (the sum of Oxy Hb and Deoxy Hb) values, which were expressed by changes from resting values ($\Delta SO_2$NIRS).

**Statistical analysis**

The data were expressed as means ± SE. The maximal quadriceps force and $\Delta SO_2$NIRS at the end of exercise was compared between the CRF and control groups using an unpaired t-test. Two-way analysis of variance (ANOVA) with repeated measurements was used to evaluate the overall comparisons of exercise response between the groups. The statistical analyses were performed using StatView 5.0J software and the level of statistical significance for all tests was set at p<0.05.

### RESULTS

Table 1 shows the anthropometric and clinical data for the two groups. There were insignificant differences in age, weight and body mass index, but a significant difference in heights (p<0.05). Group mean values for the strength of the quadriceps muscle was 234.7 ± 25.9 N versus 208.7 ± 19.6 N, for the control and CRF groups, respectively. The strength of the quadriceps muscle was not significantly different between the two groups.

$\Delta SO_2$NIRS at the same exercise times was significantly different between the two groups with exercise intensities of both no-weight and 10%MVC (ANOVA p<0.01, p<0.05, respectively). However SaO$_2$ during no-weight and 10%MVC exercises saw no significant changes in the two groups (Fig. 2).

$\Delta SO_2$NIRS values at the end of exercise were significantly difference between the two groups with exercise intensity of no-weight (control: 1.28 ± 1.0%, CRF: −6.4 ± 1.9%, p<0.01), and 10%MVC (control: −1.29 ± 2.4%, CRF: −9.99 ± 2.4%, p<0.05).

### DISCUSSION

Peripheral muscle weakness is common in patients with COPD$^6,7)$. In a large study, Hamilton et al.$^7)$ found that approximately 70% of patients with chronic lung disease, some of them with restrictive disorders, had lower quadriceps strength than the mean value obtained in normal subjects of similar ages. The reduction in muscle mass certainly contributes to peripheral muscle weakness in patients with COPD$^8)$, but it is still unclear if muscle weakness can be attributed entirely to muscle atrophy$^9)$. Compared with normal subjects of similar ages, the reduction in quadriceps strength averaged 20 to 30% in patients with severe to moderate disease$^6,7,10)$. The present study showed that respiratory patients did not have significantly lower quadriceps muscle strength than a similar-aged healthy group. This result may have been caused by the gender difference between the respiratory group (5 male and 2 female) and healthy one (1 male and 5 female), because Frontera et al.$^{11}$) reported that absolute strength of women ranged from 42.2 to 62.8% of that of men. Tissue oxygen saturation does not represent that in a single vessel, but rather in a weighted average of the saturation in arterial, capillary and venous oxy-hemoglobin and oxy-myoglobin. The NIRS signals, however, reflect oxygenation of hemoglobin and myoglobin at the level of the capillaries and veins$^{12})$. We have shown in the CRF group that $\Delta SO_2$NIRS decreased during the no-weight and 10%MVC exercises compared with the age-matched controls. Furthermore, a lower level of $\Delta SO_2$NIRS presented at the end of exercise. This suggests that the rate of muscle desaturation during a lower intensity of exercise differed between the groups. SO$_2$NIRS

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<th>Table 1. Subject characteristics</th>
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Values are expressed as mean ± SE. Definition of abbreviations: M/F = male/female; BMI = body mass index; Hb = hemoglobin concentration; VC = vital capacity; FEV$_1$ = forced expiratory volume in 1s; FVC = forced vital capacity; PaO$_2$ = partial pressure of oxygen in arterial blood; PaCO$_2$ = partial pressure of carbon dioxide in arterial blood; NA = not available.
Changes should be taken into account consideration oxygen supply, which is determined by the blood flow into the exercising muscles. Andersen\(^{13}\) reported that blood flow in the leg during knee extension exercises increased with exercise intensity, and suggested that hyperemia at low work intensities was due to vasodilation. Vollestadet al.\(^{14}\) reported that blood flow in the leg increased gradually with increasing leg oxygen consumption during submaximal knee-extension exercise. In the present study, blood flows to individual muscles of the thigh were not measured, and remain to be determined in a further study.

In conclusion, \(\Delta SO_2\) during exercise was shown to have significant differences between the two groups during no-weight and 10\%MVC exercise. The results indicate that skeletal muscle oxygenation response to the knee-extension exercise differed between patients with chronic respiratory failure and the control subjects.

**REFERENCES**

4) Takaishi T, Sugiura T, Katayama K, et al.: Changes in blood volume and oxygenation level in a working

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**Fig. 2.** Changes in \(SaO_2\) and \(\Delta SO_2\) during exercise (■: control group; ●: CRF group).


