Cerebral oxygenation during intermittent supramaximal exercise

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Abstract

This study examined cerebral deoxygenation during intermittent supramaximal exercise in six healthy male subjects (age: 27.2 ± 0.6 years (mean ± S.E.)). The subjects performed seven times exercise at an intensity corresponding to 150% of maximal oxygen uptake ( ˙ V O 2 max ) on cycle ergometer (30 s exercise/15 s rest). Cerebral oxygenation was measured by near-infrared spectroscopy (NIRS). The peak blood lactate concentration after exercise was 15.3 ± 0.2 mmol/l. Cerebral oxygenation increased in first repetition compared with at rest (+5.7 ± 0.6%/H9262M; P< 0.05), but then decreased with time. Thus, in the last repetition cerebral oxygenation was −8.5 ± 0.4%/H9262M (P< 0.05). There was no significant change in arterial oxygen saturation (99.5 ± 0.1% at rest, 98.4 ± 0.2% at the final set of intermittent exercise), and there was no correlated change in end-tidal CO 2 concentration with cerebral oxygenation (P> 0.05). These findings suggest that the fatigue resulting from dynamic severe exercise related to a decrease in the cerebral oxygenation level.

Keywords: Exercise, intermittent supramaximal, exercise; Mammals, humans; Oxygen, cerebral desaturation, exercise

1. Introduction

During intense exercise, subjects exhibit a decrease in cognitive abilities (Brisswalter et al., 1997). Such manifestations could represent a reduction of cerebral blood flow and oxygenation. Nielsen et al. (1999) reported that cerebral oxygenation is reduced when maximal exercise elicits arterial deoxygenation. In their study, not only cerebral deoxygenation but also the arterial oxygen saturation (SaO 2 ) reached 91–93% in normoxia condition. Yet, it is possible that cerebral deoxygenation appears in other exercise patterns without arterial desaturation, e.g. during supramaximal intermittent exercise.

Cerebral oxygenation changes reflect cerebral functional activation (Colier et al., 1997, 1999; Kleinschmidt et al., 1996; Obrig et al., 1996), and can be measured with several techniques. Near-infrared spectroscopy (NIRS) and functional magnetic resonance imaging allow for non-invasive monitoring of regional changes in cortical tissue oxygenation in response to various stimuli (Colier et al., 1999; Kleinschmidt et al., 1996; Mehnagol-Schipper et al., 2000; Obrig et al., 1996, 2000).

NIRS permits monitoring of changes in oxyhemoglobin ([HbO 2 ]); deoxyhemoglobin ([Hb]); and total hemoglobin ([HbT]) with a high temporal resolution.
resistance. The NIRS method is based on absorption changes that depend on concentration changes of [HbO₂] and [Hb] in the tissue under investigation. In addition, NIRS can monitor changes in cerebral oxygenation during dynamic exercises. Muscle fatigue results from not only peripheral fatigue but also central neural system (Miles, 1987; Loscher and Nordlund, 2002; Pitcher and Miles, 2002) and de-
crease of maximal oxygen uptake (\( \dot{V}_\text{O}_2 \text{max} \)) to investigate the effect on cerebral cortex oxygenation changes.

2. Methods

2.1. Subjects

Six male healthy volunteers were studied (age: 27.2 ± 0.6 years; body weight: 66.3 ± 1.2 kg; height: 174.3 ± 0.9 cm; \( \dot{V}_\text{O}_2 \text{max} \): 43.0 ± 1.5 ml/(kg min) (mean ± S.E.)). All subjects gave written informed consent. The criteria for the subjects were a medical history free of cardiovascular, pulmonary, renal, endocrinological and neurological disorders. The sub-
jects were told not to train hard on the previous day of testing and not to exercise on the day. Also, they were asked to refrain from consuming food or beverages containing caffeine before test.

2.2. Protocol

The subjects performed two trials. The first trial in-
volved the measurement of steady-state \( \dot{V}_\text{O}_2 \) at a sub-
maximal power and the determination of the \( \dot{V}_\text{O}_2 \text{max} \) reached during cycling. The second trial was a supra-
maximal exercise test conducted for the determination of \( \dot{V}_\text{O}_2 \text{max} \) at 90 rate per minute cycling. Each subject performed a preliminary progressive exercise test on a Monark cycle ergometer (Stockholm, Sweden). Data collected from submaximal exercise bouts were used to establish \( \dot{V}_\text{O}_2 \)-power relationship used to calcu-
late the power corresponding to 150% of \( \dot{V}_\text{O}_2 \text{max} \). The calculated power was used in the subsequent supra-
maximal exercise test (Medbo et al., 1977).

After this preliminary test, subjects preformed seven times intermittent cycling at 150% \( \dot{V}_\text{O}_2 \text{max} \) (30 s exercise/15 s rest). Blood lactate concentration was measured at 3, 5, 7, and 10 min after the last repeti-
tion, and analyzed by enzymatic method (Lactate Pro LT-1710; ARKRAY Inc., Japan). Arterial oxygen satu-
ration (\( \text{SaO}_2 \)) was recorded every 30 s using a pulse oximeter (8500 M; Nonin Medical Inc., USA) of the second finger. The laboratory was air-conditioned and the temperature was kept constant at 19–22°C.

2.2.1. Near-infrared spectroscopy

NIRS techniques have been described elsewhere (Elwell et al., 1994). We used continuous wave NIRS (BOM-L1 TR, Omegawave, Japan). Light with wave-
lengths of 780, 810, and 830nm was guided on the subjects’ heads through glass fiber bundles. The trans-
mitter and receiver optodes were positioned over the forehead assessing higher brain function with an in-
teroptode distance of 5 cm. Before the testing, the oxy-
genation response to a 20 s/2 Hz finger-opposition task was checked (Colier et al., 1997). If no increase in oxy-
genation could be detected, the optodes were moved (less than 1 cm) until a response could be found. Cere-
bral oxygenation in frontal areas according to blood volume increases in response to finger tapping, cy-
cling, and auditory-evoked (Chen et al., 2002; Colier et al., 1999; Nielsen et al., 1999). For quantification of changes in [HbO₂], [Hb] (Delpy et al., 1988), and total hemoglobin concentrations ([Hb] = [HbO₂] + [Hb]), a modified Lambert–Beer law was used, which describes optical attenuation in a highly scattering medium:

\[
\text{attenuation (OD)} = \log \frac{I_{0\text{det}}}{I_{\text{det}}} = \alpha L B + G
\]

where OD is the optical density, \( I_{0\text{det}} \) the incident light intensity, \( I_{\text{det}} \) the detected light intensity, \( \alpha \) the absorp-
tion coefficient of chromophores in mmol/l, \( L \) the in-
teroptode distance in cm, and \( B \) the differential optical pathlength factor that takes into account the scatter-
ing of light in tissue. \( G \) is a factor related to the tissue geometry.

We used an age-dependent pathlength factor as described by Duncan et al. (1996). The NIRS data were collected with a sample frequency of 2 Hz. The
hemoglobin difference ($[\text{Hb} \text{diff}] = [\text{HbO}_2] - [\text{Hb}]$) was calculated for evaluating oxygenation.

2.2.2. Pulmonary oxygen uptake

The subjects breathed through a facemask connected to a hot wire flowmeter (RM-300; Minato Medical Sciences, Japan) for the measurement of respiratory flow and calibrated using a 2 l syringe. A small sample (1 ml/s) of expired gas was withdrawn continuously from the mask and analyzed for $\text{O}_2$ and $\text{CO}_2$ with a mass spectrometer (WSMR-1400; Westron, Japan). The mass spectrometer was calibrated with fresh air and precision gas ($\text{O}_2 15.04\%$, $\text{CO}_2 4.957\%$). The time delay between the flow and gas concentration signals were calculated to obtain breath-by-breath data. Pulmonary gas exchange data were collected every 30 s. Heart rate (HR) was measured by use of leads with an electrocardiogram monitor (OEC-6201; Nihon-Kohden, Japan).

2.2.3. Statistics

All parameters were described by mean ± S.E. NIRS time trends were analyzed by repeated measures ANOVA, with the Bonferroni correction for post-hoc tests. Other parameters were analyzed by Student’s paired $t$-test. A $P$-value of 0.05 was considered statistically significant.

3. Results

The mean work rate in supramaximal intermittent exercise was $260.6 ± 30.4$ W. Peak blood lactate concentrations ($15.3 ± 0.2$ mmol/l) were found from 3 to 10 min after the end of exercise. $\dot{\text{V}}_{\text{O}_2}$, $\dot{\text{V}}_\text{E}$, $\dot{\text{V}}_{\text{CO}_2}$, and HR gradually increased with the repetition time increased, but did not increased during last three repetition (Table 1 and Fig. 1). There was no significant change in $\text{Sa}_\text{O}_2$. The end-tidal carbon dioxide concentration increased at the times of second, third, and fourth repetitions compared with baseline value ($P < 0.05$). However, there was no changes from baseline during other repetitions. At the first set of intermittent exercise, $[\text{Hb}]$, $[\text{HbO}_2]$, and $[\text{Hbdiff}]$ increased compared with resting values ($P < 0.05$) (Table 2). $[\text{Hb}]$ increased at the last two sets of intermittent exercise, while $[\text{HbO}_2]$ and $[\text{Hbdiff}]$ decreased ($P < 0.05$). $[\text{Hb}]$ and $[\text{HbO}_2]$ reached baseline values during the 15 s of recovery between each trial. There was no correlated change in end-tidal $\text{CO}_2$ concentration with cerebral oxygenation ($P > 0.05$).

4. Discussion

We investigated the effects of human cortex oxygenation changes induced intermittent supramaximal exercise that induced physical fatigue. To the best of our knowledge, there have been few reports about oxygenation changes in response to physical fatigue. Previous studies, which monitored cortical activation during exercise using NIRS, reported that cerebral oxygenation during submaximal, maximal, and supramaximal cycling exercise increased from the resting values (Ide et al., 1999; Nielsen et al., 1999). However, in our previous studies, blood volume (cerebral total hemoglobin concentration) and oxygenation gradually decreased with the time passage during supramaximal exercise (Shibuya et al., in press). In the present study, using supramaximal intermittent exercise, significant increases of blood volume and oxygenation at the early phase of exercise were observed (Fig. 2). However, blood volume and oxygenation gradually decreased with the repetition time increased. Nielsen et al. (1999) reported that cerebral oxygenation decreased only when maximal exercise elicits an arterial desaturation. However, we did not find any decrease of arterial desaturation. Arterial desaturation might not be a major factor for cerebral deoxygenation. The difference between the results of Nielsen et al. and the present study might cause from the difference of exercise-induced increase in cerebral perfusion by a Valsalva-like maneuvers (Clifford et al., 1994). In general, the cerebral oxygenation increases from resting levels during a task that is not a severe task, such as a finger tapping task (Clifford et al., 1994). In confirmation of the evaluation based on the regional oxygen utilization and cerebral blood flow in response to cerebral activation, the increase in flow is larger than the oxygen demand (Mehagnol-Schipper et al., 2000). However, we found a decrease in $[\text{HbO}_2]$ and oxygenation during the task even in cycling exercise. It is well established that blood flow to the brain and cerebral oxygenation are elevated with an increase in arterial $\text{CO}_2$ pressure (Harris et al., 1994; Madsen et al., 1995). However, a recent study reported that
Table 1

<table>
<thead>
<tr>
<th>Variable</th>
<th>Rest</th>
<th>Exercise</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>First</td>
<td>Second</td>
<td>Third</td>
<td>Fourth</td>
<td>Fifth</td>
<td>Sixth</td>
<td>Seventh</td>
</tr>
<tr>
<td>$\dot{V}O_2$ (ml/min)</td>
<td>349.9 ± 10.3</td>
<td>1337.8 ± 45.3</td>
<td>2220.0 ± 35.3</td>
<td>2374.8 ± 43.3</td>
<td>2492.2 ± 41.2</td>
<td>2504.0 ± 34.0</td>
<td>2492.8 ± 41.5</td>
</tr>
<tr>
<td>$V_E$ (l/min)</td>
<td>13.0 ± 0.4</td>
<td>41.0 ± 1.4</td>
<td>79.2 ± 1.9</td>
<td>103.4 ± 1.8</td>
<td>118.0 ± 2.2</td>
<td>123.8 ± 2.4</td>
<td>129.3 ± 3.9</td>
</tr>
<tr>
<td>$\dot{V}CO_2$ (ml/min)</td>
<td>2325.5 ± 16.8</td>
<td>1152.0 ± 43.8</td>
<td>2538.2 ± 38.7</td>
<td>3195.2 ± 60.8</td>
<td>3399.4 ± 71.0</td>
<td>3320.0 ± 71.0</td>
<td>3392.6 ± 69.4</td>
</tr>
<tr>
<td>HR (beats/min)</td>
<td>76.3 ± 5.5</td>
<td>130.0 ± 1.3</td>
<td>152.4 ± 1.0</td>
<td>157.5 ± 1.1</td>
<td>161.7 ± 1.0</td>
<td>163.9 ± 0.6</td>
<td>173.9 ± 0.9</td>
</tr>
<tr>
<td>$SaO_2$ (%)</td>
<td>99.6 ± 0.1</td>
<td>98.8 ± 0.1</td>
<td>98.4 ± 0.2</td>
<td>98.0 ± 0.2</td>
<td>97.8 ± 0.3</td>
<td>98.6 ± 0.2</td>
<td>98.4 ± 0.2</td>
</tr>
<tr>
<td>ETCO$_2$ (%)</td>
<td>3.05 ± 0.08</td>
<td>3.44 ± 0.04</td>
<td>3.82 ± 0.05</td>
<td>3.80 ± 0.04</td>
<td>3.53 ± 0.03</td>
<td>3.32 ± 0.04</td>
<td>3.03 ± 0.04</td>
</tr>
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</table>

Values are mean ± S.E. at rest and during exercise. $\dot{V}O_2$: pulmonary O$_2$ uptake; $V_E$: pulmonary ventilation; $\dot{V}CO_2$: expired CO$_2$; HR: heart rate; $SaO_2$: saturation of arterial hemoglobin.

* $P < 0.05$, different from resting values.
end-tidal CO₂ concentration did not affect cerebral blood flow (Vovk et al., 2002). In the present study, we did not find a positive significant relationship between end-tidal CO₂ concentration and cerebral blood volume and oxygenation. The decreases of cerebral blood volume and oxygenation observed in this study would not result from arterial CO₂ tension. Consequently, decreases in cerebral blood volume

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**Fig. 1.** Pulmonary oxygen uptake ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), minute ventilation ($V_E$), heart rate (HR), and arterial saturation ($SaO_2$) during supramaximal intermittent cycling. Values are mean ± S.E. *P < 0.05, different from resting values.
Fig. 2. The values of changes from resting values in total hemoglobin concentration ([tHb]), oxyhemoglobin concentration ([HbO₂]), deoxyhemoglobin concentration ([Hb]), hemoglobin difference ([Hbdiff] = [HbO₂] − [Hb]), end-tidal CO₂ concentration (P_{ETCO₂}) during supramaximal intermittent cycling. Values are mean ± S.E.
and oxygenation might be caused by cerebral fatigue. However, we did not measure he arterial CO₂ tension or O₂ tension. It cannot be known as the relationship the arterial CO₂ tension and end-tidal CO₂ tension remains unclear.

Since we did not measure cerebral metabolism and motor–cortex oxygenation changes, whether cerebral oxygenation changes result from the changes of cerebral metabolism, and/or motor–cortex activation remains unclear. The meaning of data obtained from near-infrared spectroscopy is still under discussion; in particular whether the NIRS signals reflect the intracranial blood volume of pial and/or, probably, also of more superficial circulation. For example hyper-ventilation at rest induces a reduction of [HbO₂] and of [Hb] not for a less cerebral oxygenation but because blood volume reduces due to peripheral vaso-constriction. Doppler transcranial monitoring should be performed in order to have more information about intracranial circulation. In conclusion, we found a decrease of cerebral oxygenation during dynamic inter-mittent supramaximal exercise. These findings suggest that the decrease of cerebral activity occurs with the decrease of muscular functions.

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