

Chapter 21

Muscle, Prefrontal, and Motor Cortex Oxygenation Profiles During Prolonged Fatiguing Exercise

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Abstract This study aimed to compare changes in skeletal muscle, prefrontal (PFC), and motor (MC) cortex hemodynamics during prolonged (i.e., 4-h) fatiguing whole-body exercise using multichannel near-infrared spectroscopy (NIRS). Ten subjects completed three successive 80-min cycling bouts at 45 % of their maximal power output. After the 4-h cycling, maximal voluntary contraction force of the leg was decreased by ~25 %. Muscle exhibited reproductive deoxygenation patterns during each of the three bouts, whereas intra-bout cerebral hemodynamics were different throughout the protocol. Results demonstrate that specific responses to fatiguing exercise are found between tissues but also between cortical sites involved in cycling, as shown by concomitant PFC hyperoxygenation and MC deoxygenation in the first 80 min of exercise. Further insights are needed to understand the consequences of these changes regarding the integrative control of motor output while fatigue develops over several hours.

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21.1 Introduction

Neuromuscular fatigue has been characterized by a decrease in the ability to produce a maximal voluntary contraction force (MVC) or an inability to maintain a certain level of force, potentially originating from multiple sites between the motor planning and the motor production [1]. In the last decade, studies focusing on oxygen transport to tissue with noninvasive techniques have enhanced our understanding of fatigue etiology both at the muscle and brain levels [2, 3].

During progressive maximal cycling, leg muscle tissue saturation index may decrease up to -20% but often present a plateau in the last part of exercise [4] suggesting that metabolic changes in the muscle may not be the ultimate signal leading to exhaustion. Although cerebral oxygenation is increased during submaximal cycling tasks, critical reductions in prefrontal cortex (PFC) oxygenation occur at the end of short (i.e., <20 min) maximal exertion [5, 6]. PFC is known to project to premotor areas and to be responsible for goal-direct behavior, movement planning, pacing strategies, as well as decision-making [7]. Hence, PFC perturbations may contribute to exercise performance limitation by impairing executive functions (e.g., decision to stop exercising) and central motor drive indirectly, potentially because of an imbalance between reduction in regional cerebral blood flow and increased cerebral metabolic rate and O_2 uptake. Only one study [4] addressed the question of whether PFC and MC oxygenation profiles are consistent during whole-body high-intensity exercise. The authors found significant discrepancies between those sites at exhaustion suggesting that O_2 delivery and/or activation pattern may slightly differ.

Tissue-specific (de)oxygenation perturbations that may occur when fatigue develops over several hours of exercise have never been described. The aim of this study was to compare pattern and magnitude of changes in skeletal muscle, PFC, and MC hemodynamics using multichannel near-infrared spectroscopy (NIRS) during prolonged (i.e., 4-h) fatiguing whole-body exercise.

21.2 Methods

21.2.1 Population and Protocol

Ten healthy trained males gave their written informed consent to participate in the study. Their average (\pm SD) age, weight, and height were 37 ± 7 year, 73 ± 7 kg, and 180 ± 5 cm, respectively. Subjects performed a 4-h cycling exercise in laboratory at 45% of their maximal aerobic power output (153 ± 23 W) at a constant pedaling frequency (~ 80 rpm). Exercise was split in three consecutive 80-min bouts (B1, B2, and B3) separated by 25-min periods of neuromuscular function testing including MVC of the leg extensors on a dedicated ergometer to assess fatigue kinetic. Subjects were instructed to drink no alcoholic or caffeinated beverages and to avoid

any physical activity for at least 24 h before testing. The study procedures complied with the Declaration of Helsinki for human experimentation and were approved by the local ethics committee.

21.2.2 Instrumentation

Oxy[HbO₂]-, deoxy[HHb]-, and total[THb]- hemoglobin concentration changes were estimated during exercise over multiple sites using a multichannel continuous wavelengths (780 and 850 nm) NIRS device (Oxymon III, Artinis, the Netherlands). Theoretical and performance details of NIRS have been previously described [8, 9]. Quadriceps muscle oxygenation profiles were assessed from the right *vastus lateralis* using a 4-cm interoptodes distance. Probe holder was secured to the skin using double-sided tape and covered with a black sweatband to shield the optodes from ambient light. PFC oxygenation was assessed between Fp1 and F3 locations according to the international 10–20 EEG system with 3.5-cm interoptodes distance. The probe holder was secured to the skin with double-sided tape and maintained with Velcro headbands. MC hemoglobin concentrations were expressed from the average of a 4-channel square setting (3-cm interoptodes distance) fixed with headbands between Cz and C3 locations.

End-tidal CO₂ (EtCO₂) was measured continuously using a respiratory gas monitor connected to the subject via a face mask (Ohmeda RGM, GE Healthcare, Little Chalfont, UK).

Subjects filled a visual analogue scale of perceived exertion (VAS, ranging from 0 = “no difficulty at all” to 100 mm = “I have to stop immediately”) at the end of each bout to assess subjective fatigue development during the protocol.

21.2.3 Processing and Statistical Analyses

NIRS parameters were recorded at 25 Hz, filtered with a 2-s width moving Gaussian smoothing algorithm and average over 3-min periods at 20, 40, 60, and 80 min in each bout. Tissues hemodynamics were expressed as relative changes from a stabilized baseline (BL) preceding each exercise bout to assess inter- and intra-bout kinetics throughout the protocol. Single ANOVA with repeated measures was performed to compare MVC and VAS values across the protocol and two-way (bout × time epoch) ANOVA with repeated measures was performed for EtCO₂ and each NIRS dependent variable. Post hoc Fisher’s LSD tests were applied when appropriate to determine a difference between two mean values. Relationships between changes in tissue oxygenation parameters, between sites and with EtCO₂ variations, were determined by Pearson’s product correlations. Values are presented as means ± SD in the text and means ± SE in Fig. 21.1. An alpha level of 0.05 was used as the cutoff for significance.

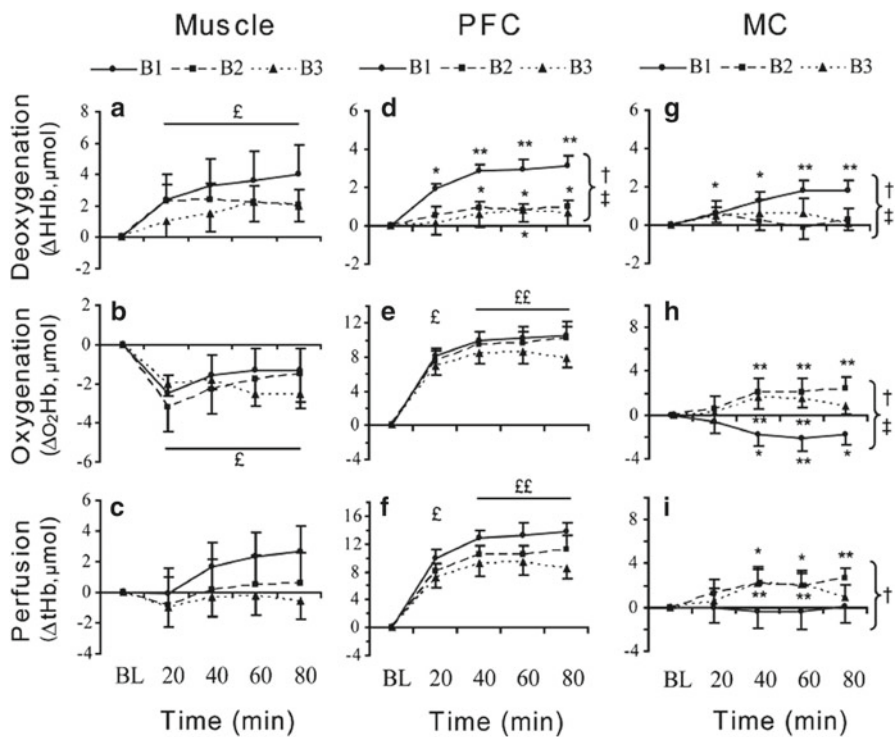


Fig. 21.1 Changes in oxy-([HbO₂]), deoxy-([HHb]), and total hemoglobin ([THb]) from BL during each of the first (B1), second (B2), and third (B3) exercise bouts. Results are shown for the *vastus lateralis* muscle (*left panels*), for the prefrontal cortex (PFC, *middle panels*), and for the motor cortex (MC, *right panels*). Values are mean \pm SE. Significant main effect of time: £ versus BL, ££ versus +20 min. Significant main effect of bout: † B2 versus B1, ‡ B3 versus B1. Significant main interaction effect: * versus BL, ** versus +20 min

21.3 Results

21.3.1 Exercise-Induced Fatigue and EtCO₂ Changes

MVC was reduced after B1 and further decreased after B2 and B3 (-11% , -19% , and -25% compared to pre-exercise, respectively, $P < 0.001$). VAS of perceived exertion increased to 30 ± 16 after B1 and further to 52 ± 22 and 67 ± 25 mm after B2 and B3, respectively ($P < 0.001$). EtCO₂ increased significantly in each bout between BL and +20 min ($+7.1 \pm 1.6$ mmHg on average) before decreasing until the end of the bouts. Besides, a progressive hypocapnia was seen throughout the protocol as mean bout EtCO₂ decreased from 37.4 ± 0.7 mmHg in B1 to 33.3 ± 0.7 and 29.5 ± 0.6 mmHg in B2 and B3, respectively ($P < 0.001$).

21.3.2 Exercise-Induced Tissue Oxygenation Profiles

21.3.2.1 Muscle

Muscle did not show any significant bout effect during the protocol, whatever the chromophore (Fig. 21.1a–c). Reproductive typical bout kinetics consisted of a progressive increase in $\Delta[\text{HHb}]$ and a decrease in $\Delta[\text{HbO}_2]$, reaching a plateau after ~20 min, without any significant change in $\Delta[\text{THb}]$ throughout the 80 min.

21.3.2.2 Prefrontal Cortex

As shown in Fig. 21.1e, f, $\Delta[\text{HbO}_2]$ and $\Delta[\text{THb}]$ significantly increased during B1 reaching a plateau after ~40 min. No significant main effect of bout was observed throughout the protocol for those chromophores. $\Delta[\text{HHb}]$ was progressively increased during B1 (Fig. 21.1d, $P < 0.05$) from 20 to 80 min and showed a significant main effect of bout throughout the protocol, $\Delta[\text{HHb}]$ increase during B2 and B3 being significantly reduced compared to B1 ($P < 0.05$).

21.3.2.3 Motor Cortex

During B1, MC $\Delta[\text{HbO}_2]$ was significantly reduced from 20 to 80 min compared to BL (Fig. 21.1h), while $\Delta[\text{HHb}]$ increased simultaneously (Fig. 21.1g). $\Delta[\text{THb}]$ was unchanged in B1 compared to BL (Fig. 21.1i). $\Delta[\text{HbO}_2]$, $\Delta[\text{HHb}]$, and $\Delta[\text{THb}]$ showed significant main effect of bout over time as B2 and B3 were different from B1 ($P < 0.05$). Both $\Delta[\text{HbO}_2]$ and $\Delta[\text{THb}]$ increased from 20 to 80 min in B2 and from 20 to 60 min in B3, while $\Delta[\text{HHb}]$ did not present any change from BL during B2 and B3. Cerebral and muscle hemodynamics were not correlated during exercise. MC $\Delta[\text{THb}]$ were not correlated to EtCO_2 , while CPF $\Delta[\text{THb}]$ was correlated to EtCO_2 changes only at +20 min in B2 ($R^2 = 0.48$, $P < 0.05$) and +20 min in B3 ($R^2 = 0.45$, $P < 0.05$).

21.4 Discussion

MVC and VAS of perceived exertion kinetics indicated increasing levels of objective and subjective neuromuscular fatigue across the 4-h exercise, respectively. Despite progressive fatigue and a tendency towards lower muscle $\Delta[\text{THb}]$, intra-bout muscle deoxygenation kinetics were reproducible when comparing the three successive bouts. This suggests that the balance between O_2 delivery and O_2 consumption over the repetitive long-duration submaximal exercises was well preserved.

In response to repetitive prolonged submaximal exercise, we observed large increases in PFC $\Delta[\text{THb}]$ ($+11.2 \pm 5.8 \mu\text{Mol}$ on average) and $\Delta[\text{O}_2\text{Hb}]$ ($+9.6 \pm 4.7 \mu\text{Mol}$ on average) compared to what has been described previously in shorter (i.e., 10–20-min) maximal exercises [3–6]. Also, the three- to fourfold increase in $\Delta[\text{O}_2\text{Hb}]$ compared to the $\Delta[\text{HHb}]$ in PFC argues in favor of an efficient neurovascular coupling throughout the three fatiguing exercise bouts, with no sign of potential mismatch between O_2 utilization and availability for the cortical region.

Very different responses were observed in the MC, in particular during the first 80 min where $\Delta[\text{THb}]$ did not change and $\Delta[\text{O}_2\text{Hb}]$ significantly decreased in response to exercise. This is the first time that such a different tissue oxygenation pattern between PFC and MC is described during whole-body fatiguing (but non-exhausting) exercise. Our results confirm the relatively specific O_2 delivery and activation pattern of motor-related cortical areas, which has been suggested by others during short maximal exercise [4]. Accordingly, using only PFC location to speculate on potential cerebral limitation of motor performance should be done with caution. Otherwise, differential cortical sensitivity to exercise/fatigue may lead to misinterpretations.

21.4.1 Limitations

To better assess intra-bout kinetics we chose to express data in relation to the respective bout baseline. Unfortunately, it excludes any interpretation on the continuous time course in tissue oxygenation during the 4-h exercise. Besides, even if exercise-induced EtCO_2 changes were not correlated with MC oxygenation kinetics and only poorly correlated with PFC profiles, it remains difficult from the NIRS signal to determine how far exercise-induced systemic changes (e.g., in arterial CO_2 , cardiac output) may interfere with the underlying activation-related hemodynamic changes [6]. Our data also raise the question of the exact somatotopic correspondence and function of the investigated areas.

To conclude, our results demonstrate that specific responses to fatiguing exercise are found between tissues and between cortical sites implicated in cycling, as shown by concomitant PFC hyperoxygenation and MC deoxygenation in the first 80 min of exercise. Hence, the pattern and magnitude of hemodynamics perturbations are distinct between muscle, prefrontal, and motor regions throughout a prolonged intermittent exercise. Further insights are needed to understand the consequences of these changes, regarding the integrative control of motor output while fatigue develops over several hours.

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