Chapter 10
Changes in Cortical Oxyhaemoglobin Signal During Low-Intensity Cycle Ergometer Activity: A Near-Infrared Spectroscopy Study

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Abstract Near-infrared spectroscopy (NIRS) is a widely used non-invasive method for measuring human brain activation based on the cerebral hemodynamic response during gross motor tasks. However, systemic changes can influence measured NIRS signals. We aimed to determine and compare time-dependent changes in NIRS signal, skin blood flow (SBF), and mean arterial pressure (MAP) during low-intensity, constant, dynamic exercise. Nine healthy volunteers (22.1 ± 1.7 years, 3 women) participated in this study. After a 4-min pre-exercise rest and a 4-min warm-up, they exercised on a bicycle ergometer at workloads corresponding to 30 % VO_2 peak for 20 min. An 8-min rest period followed the exercise. Cortical oxyhaemoglobin signals (O_2Hb) were recorded while subjects performed the exercise, using an NIRS system. Changes in SBF and MAP were also measured during exercise. O_2Hb increased to 0.019 mM cm over 6 min of exercise, decreased slightly from 13 min towards the end of the exercise. SBF continued to increase over 16 min of the exercise period and thereafter decreased till the end of measurement. MAP fluctuated from -1.0 to 7.1 mmHg during the exercise. Pearson's correlation coefficients between SBF and O_2Hb, and MAP and O_2Hb differed in each time phase, from -0.365 to 0.713. During low-intensity, constant, dynamic exercise, the profile of changes in measurements of O_2Hb, SBF, and MAP differed. These results suggested that it is necessary to confirm the relationship between O_2Hb and systemic factors during motor tasks in order to detect cortical activation during gross motor tasks.

Keywords Cortical oxyhaemoglobin • Skin blood flow • Mean arterial pressure • Low-intensity exercise • Near-infrared spectroscopy

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1 Introduction

Functional magnetic resonance imaging [1] and positron emission tomography [2, 3] are used to examine haemodynamic changes related to cortical neural activation during bicycle movement. However, these devices have some measurement constraints. Near-infrared spectroscopy (NIRS) is a good indicator to monitor real-time haemodynamic changes during gross motor tasks, and is widely used.

In NIRS, near-infrared beams are transmitted through the scalp and skull and O_2Hb signals are detected. These signals might indicate task-related cardiovascular responses occurring in the perfusion of extracranial layers. However, blood pressure fluctuations exert confounding effects on brain NIRS [4, 5], and some studies suggest that skin blood flow (SBF) or skin blood volume influences NIRS measurement [6, 7]. Physiological signals arising from cardiac and blood pressure modulations may interfere with the measurement of the haemodynamic response to brain activation.

In particular, blood pressure and scalp blood flow can increase during gross motor tasks. The relationship between NIRS signals and physiological signals must be clarified so that cortical activation can be detected on the basis of changes in O_2Hb concentrations during gross motor tasks.

This study aimed to determine and compare time-dependent changes in O_2Hb, SBF, and mean arterial pressure (MAP) during low-intensity, constant, dynamic exercise.

2 Methods

Nine healthy volunteers ([mean $\pm$ standard deviation] age 22.1 ± 1.7 years; height 167.2 ± 8.9 cm; weight 58.3 ± 7.2 kg; 3 women) participated in this study. All subjects were free from any known neurological, major medical, or cardiovascular diseases and were not taking any medications. Each subject received verbal and written explanations of this study. This study was approved by the Ethics Committee of Niigata University of Health and Welfare (17368-121108) and conformed to the standards set by the Declaration of Helsinki.

To detect exercise workload individually, peak oxygen consumption (VO_2peak) was determined using an incremental protocol on a cycle ergometer (Aerobike 75XLII; Combi, Japan) before the main experiments. Exhaustion was defined based on a previous study [8].

In the main exercise experiment, subjects performed constant exercise on a cycle ergometer. After a 4-min rest and a 4-min warm-up, they exercised at workloads corresponding to 30 % VO_2 peak for 20 min. An 8-min rest followed the exercise. During this experiment, NIRS signals, SBF, and MAP were measured.

A multichannel NIRS imaging system (OMM-3000; Shimadzu Co., Kyoto, Japan) with three wavelengths (780, 805, and 830 nm) was used to detect changes

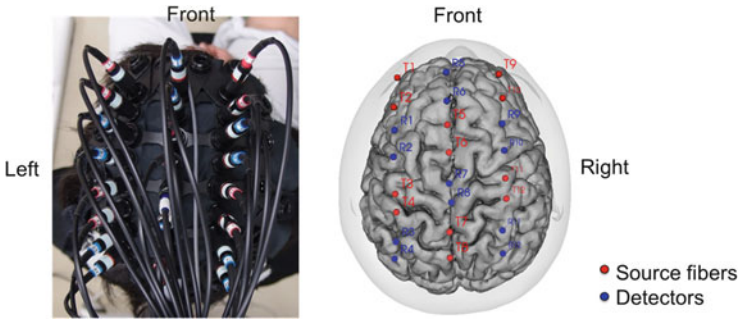

Fig. 10.1 NIRS optode placement and locations of the 12 light-source fibers and 12 detectors

in O_2Hb at a sampling rate of 190 ms. NIRS-determined O_2Hb is a sensitive indicator of changes in cerebral blood flow [9] and is the most sensitive indicator of sensory- and motor-related changes in regional cerebral blood flow [10, 11].

NIRS optodes, consisting of 12 light-source fibres and 12 detectors providing 34-channel simultaneous recording, were set in a 3×8 multichannel probe holder (Fig. 10.1). A 30-mm interoptode distance was used to measure cortical tissue oxygenation. We used a double-density probe holder [12, 13], consisting of two sets, one of which was shifted to half the optode distance from the origin. The Cz position of the international 10–20 system was used to ensure consistent optode placement among all subjects. The NIRS array map covered the right and left central and parietal areas of the scalp to measure cortical tissue oxygenation in motor-related areas.

Beat-to-beat MAP was recorded by volume clamping the finger pulse with a finger photoplethysmograph (Finometer; Finapres Medical Systems, Amsterdam, The Netherlands) on the left middle finger. Changes in SBF were measured at the forehead using a laser Doppler blood flow meter (Omegaflow FLO-CI; Omegawave Inc., Osaka, Japan). Analogue data were converted to digital data using an A/D converter (PowerLab; AD Instruments, Australia) at a 1000-Hz sampling rate.

To observe the effect of systemic changes on O_2Hb, the mean of all 34-channel O_2Hb values was calculated for each subject. O_2Hb concentration, SBF, and MAP were expressed as changes from the rest phase mean, and were calculated every 10 s. These values were compared by performing one-way analysis of variance (ANOVA) with time as an independent variable using the Statistical Package for Social Sciences (SPSS) ver. 21 (IBM Japan, Tokyo, Japan). The relationship between O_2Hb and SBF, and between O_2Hb and MAP were assessed using Pearson's correlation coefficients, with significance set at $p < 0.05$ during the pre-exercise rest period, warm-up period, main exercise period, and post-exercise rest period. The main exercise period and post-exercise rest period were divided into 4-min segments for analysis.

3 Results

One-way ANOVA showed a significant main effect of time on O_2Hb level ($F = 1.69$, $p < 0.05$), SBF ($F = 2.47$, $p < 0.05$), and MAP ($F = 1.27$, $p < 0.05$). O_2Hb increased to 0.019 mM cm over 6 min of exercise, decreased slightly from 13 min towards the end of the exercise, and continued to decrease during the first 20 s of the post-exercise rest phase. O_2Hb increased again, to 0.008 mM cm, over 2 min of the post-exercise rest and decreased again towards the end of measurement (Fig. 10.2). SBF continued to increase over 16 min of the exercise period, and thereafter decreased until the end of measurement (Fig. 10.3). MAP fluctuated between −1.0 and 7.1 mmHg during exercise (Fig. 10.4).

The correlation coefficients between SBF and O_2Hb, and MAP and O_2Hb differed in each time phase (Table 10.1). During the 30 % VO_2 peak cycling

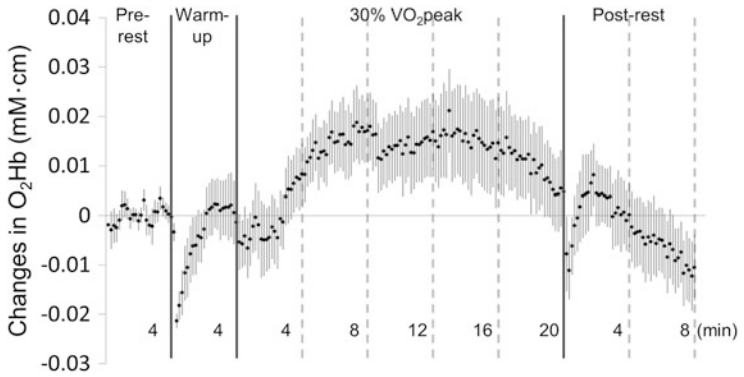

Fig. 10.2 Temporal changes in the averaged oxyhaemoglobin (O_2Hb) level. Values are presented as mean ± standard error of the mean (SEM)

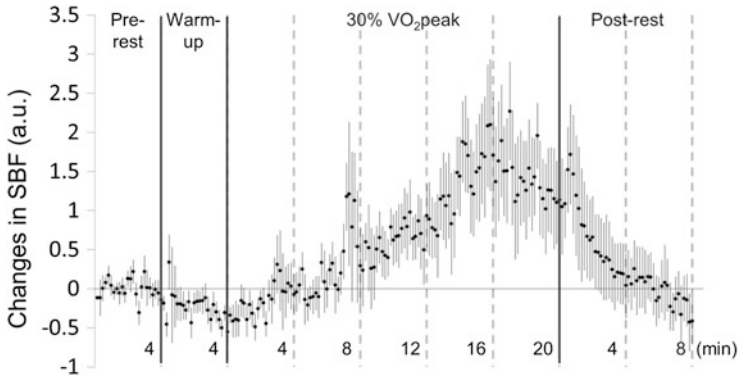

Fig. 10.3 Temporal changes in the averaged skin blood flow (SBF). Values are presented as mean ± standard error of the mean (SEM)

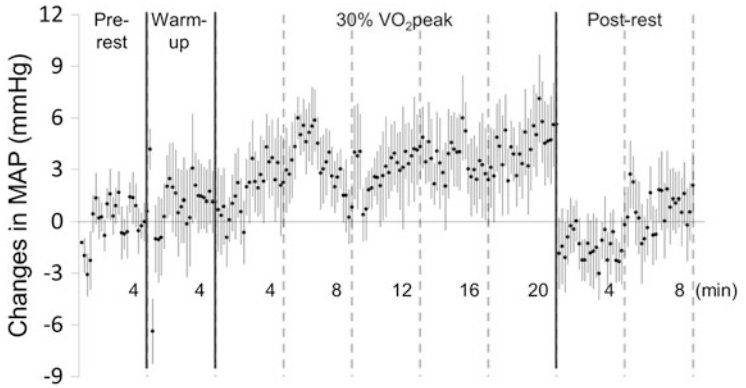

Fig. 10.4 Temporal changes in the averaged mean arterial pressure (MAP). Values are presented as mean ± standard error of the mean (SEM)

Table 10.1 Pearson's correlation coefficients between O_2Hb and SBF and between O_2Hb and MAP

	Pre-rest	Warm-up	30 % VO_2peak					Post-rest	
			(a)	(b)	(c)	(d)	(e)	(a)	(b)
SBF	0.250	−0.365	0.713*	0.671*	0.054	−0.365	0.589*	−0.439*	0.795*
MAP	0.760*	0.685*	0.652*	−0.296	0.760*	0.143	−0.437*	0.022	0.008

O_2Hb oxyheamoglobin, *SBF* skin blood flow, *MAP* mean arterial pressure; (a), from start to 4 min; (b), after (a) to 8 min; (c), after (b) to 12 min; (d), after (c) to 16 min; (e), after (d) to 20 min
*$p < 0.05$

exercise, positive and moderate to strong correlations between O_2Hb and SBF were observed in the first, second, and last 4-min segments. These were also observed between O_2Hb and MAP in the first and third 4-min segments.

4 Discussion

This study is the first to report the relationship between the O_2Hb signal, measured by NIRS, and systemic factors during low-intensity, constant, dynamic exercise. The main findings were as follows: (1) the profile of changes in O_2Hb, SBF, and MAP differed, (2) the strength of the relationships between O_2Hb and SBF, and O_2Hb and MAP differed in each time phase.

In the present study, it was observed that O_2Hb changes were not constant despite subjects performing constant load cycle ergometer exercise. This result suggests that cerebral activation in the motor related area changes during the 20-min exercise. Changes in O_2Hb reflect changes in cortical neural activation [11, 14, 15] and depend on exercise intensity [16]. Habituation decreases activity in

the ipsilateral motor cortex during a repetitive handgrip exercise [17]. The habituation of this motor task might cause the O_2Hb decline.

The correlation coefficients between O_2Hb and SBF were positive in the first, second, and last 4-min segments of the cycling exercise. O_2Hb concentration is correlated closely ($R^2 = 0.94$) with the integrated Doppler SBF signal in the frontal cortex [6]. Hirasawa et al. [18] showed that changes in O_2Hb and SBF are positively correlated during superficial temporal artery compression. O_2Hb changes in this study might be affected by SBF in the exercise phase.

Positive correlations were also observed between O_2Hb and MAP in the first and third 4-min segments of the cycling exercise. It was reported that blood pressure changes fluctuate brain NIRS signals in the visual cortex during visual stimulation [4]. Gross motor tasks produce systemic circulatory changes, including blood pressure changes. It is suggested that this blood pressure change leads to O_2Hb changes in this study.

During the 20-min of 30 % VO_2 peak cycling exercise, there were weak correlations between O_2Hb and SBF, and O_2Hb and MAP in the fourth 4-min segment. Therefore, we could measure the cerebral activation of the motor-related area with less SBF and/or MAP effects in this segment.

There were some limitations in this study. First, we measured the SBF on the forehead, not over the motor-related area, in order to prevent interference from near-infrared and laser light emitted from the laser Doppler flow meter. Second, we did not measure systemic blood flow changes during low-intensity, constant, dynamic exercise. Finally, although we could clarify the relationships between variables, the experimental design did not enable an assessment of the causality between variables.

In conclusion, O_2Hb changes were not constant during low-intensity, constant, dynamic exercise, and the correlation coefficients between both SBF and MAP, and O_2Hb differed in each time phase. It is necessary to confirm the relationship between O_2Hb and systemic factors during motor tasks in order to detect cortical activation during gross motor tasks, and the findings of the present study will assist with further analysis.

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