Chapter 21
Correlation Between the Cerebral Oxyhaemoglobin Signal and Physiological Signals During Cycling Exercise: A Near-Infrared Spectroscopy Study

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Abstract Near-infrared spectroscopy (NIRS) is a widely used noninvasive method for measuring human brain activation based on the cerebral haemodynamic response. However, systemic changes can influence the signal's parameters. Our study aimed to investigate the relationships between NIRS signals and skin blood flow (SBF) or blood pressure during dynamic movement. Nine healthy volunteers (mean age, 21.3 ± 0.7 years; 6 women) participated in this study. The oxyhaemoglobin (O_2Hb) signal, SBF, and mean arterial pressure (MAP) were measured while the volunteers performed multi-step incremental exercise on a bicycle ergometer, at workloads corresponding to 30, 50, and 70 % of peak oxygen consumption (VO_2peak) for 5 min. The Pearson's correlation coefficients for the O_2Hb signal and SBF at 50 and 70 % VO_2peak were 0.877 ($P<0.01$) and –0.707 ($P<0.01$), respectively. The correlation coefficients for O_2Hb and MAP during warm-up, 30 % VO_2peak, and 50 % VO_2peak were 0.725 ($P<0.01$), 0.472 ($P<0.01$), and 0.939 ($P<0.01$), respectively. Changes in the state of the cardiovascular system influenced O_2Hb signals positively during low and moderate-intensity exercise, whereas a negative relationship was observed during high-intensity exercise. These results suggest that the relationship between the O_2Hb signal and systemic changes is affected by exercise intensity.

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1 Introduction

Near-infrared spectroscopy (NIRS) is widely used to monitor real-time haemodynamic changes related to cortical neural activation during gross motor tasks. Studies have investigated cortical oxygenation during the human gait [1] and cycling exercise [2, 3].

NIRS measures the concentrations of oxyhaemoglobin (O_2Hb) and deoxyhaemoglobin (HHb) in tissues, based on their differential absorption at multiple wavelengths, using the modified Beer-Lambert law [4]. Thus, experimental tasks that induce physiological signals can block the detection of cortical activation by NIRS, as the near-infrared beams are transmitted through the scalp and skull and the resultant O_2Hb signals might represent task-related cardiovascular responses occurring during the perfusion of the extracranial layers.

Our study aimed to determine the relationship between NIRS signals and skin blood flow (SBF) or blood pressure during such gross motor tasks. To investigate the effect of exercise intensity on the relationship between NIRS signals and the cardiovascular control system, an incremental multistep cycle ergometer exercise protocol was used.

2 Methods

Nine healthy volunteers ([mean ± standard deviation] age, 21.3 ± 0.7 years; height, 161.6 ± 9.2 cm; weight, 54.5 ± 8.0 kg; 6 women) participated in this study. The subjects did not exhibit symptoms of neurological, medical, or cardiovascular disease and were not taking any medications. Each subject provided written consent after receiving information regarding the potential risks, study objectives, measurement techniques, and benefits associated with the study. This study was approved by the Ethics Committee of Niigata University of Health and Welfare and conformed to the standards set out by the Declaration of Helsinki.

To detect the exercise workload individually, the 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 as described previously [3].

In the main experiment, subjects performed multi-step incremental exercise on a cycle ergometer. After a 4-min rest and a 4-min warm-up, exercise began at workloads corresponding to 30, 50, and 70 % of the VO_2peak, with each phase lasting 5 min. A 4-min cool-down followed the 70 % VO_2peak workload. During this experiment, the NIRS signals, mean arterial pressure (MAP) and SBF were measured continuously.

A multichannel NIRS imaging system (OMM-3000; Shimadzu Co., Kyoto, Japan) with three wavelengths (780, 805, and 830 nm) was used to detect changes in O_2Hb at a sampling rate of 190 ms. 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, as described in our previous study [5]. The NIRS array map covered the right central, 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), which collected data from the scalp layer within 1 mm from the probe. Analogue data were converted to digital data using an A/D converter (PowerLab; AD Instruments, Australia) at a 1000-Hz sampling rate.

To detect the effect of systemic changes on NIRS signals, the average of the O_2Hb values from all 34 channels was calculated for each subject as the global average of O_2Hb. MAP and SBF were down-sampled by adopting the sampling rate for NIRS monitoring. The global averages of the O_2Hb concentration, MAP, and SBF were expressed as the change from the average rest phase value and were calculated every 10 s. The relationships between O_2Hb and SBF and between O_2Hb and MAP were assessed during rest, warm-up, 30 % VO_2peak, 50 % VO_2peak, 70 % VO_2peak, and cool-down. Pearson's correlation coefficients were calculated, with the significance level set at $P < 0.05$.

3 Results

During the main experiment, the average O_2Hb began increasing above the baseline value following the 30 % VO_2peak phase. During the 50 % VO_2peak phase, the average O_2Hb increased to 0.029 mM·cm (Fig. 21.1) and subsequently increased to its peak value of 0.045 mM·cm during the first minute of the 70 % VO_2peak phase. From that point, O_2Hb decreased to 0.020 mM·cm at the end of the 70 % VO_2peak phase and decreased even further during the first 30 s of the cool-down phase, with lower values at this point than those detected during the initial rest phase. Finally, O_2Hb rebounded during the cool-down phase to 0.027 mM·cm. HHb increased from the middle part of the 50 % VO_2peak phase to the first 30 s of the cool-down phase, with a peak value of 0.042 mM·cm.

During the warm-up and 30 % VO_2peak phases, SBF remained below the resting value (Fig. 21.2). Following the increase in exercise intensity, SBF increased to 2.74 a.u. at the end of the 50 % VO_2peak phase and to 7.59 a.u. at the end of the 70 % VO_2peak phase. During the 70 % VO_2peak phase, SBF increased from 3.75 to 7.59 a.u. in 5 min. Following the high-intensity exercise, SBF declined gradually during the cool-down phase.

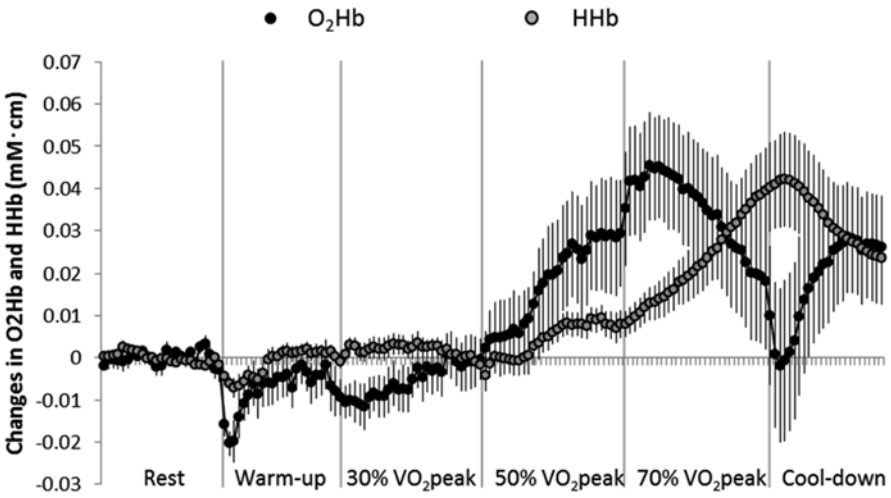

Fig. 21.1 Temporal changes in the average global oxyhaemoglobin (O_2Hb, *black circle*) and deoxyhaemoglobin (HHb, *grey circle*) values. Values are presented as the mean ± standard error of the mean (SEM)

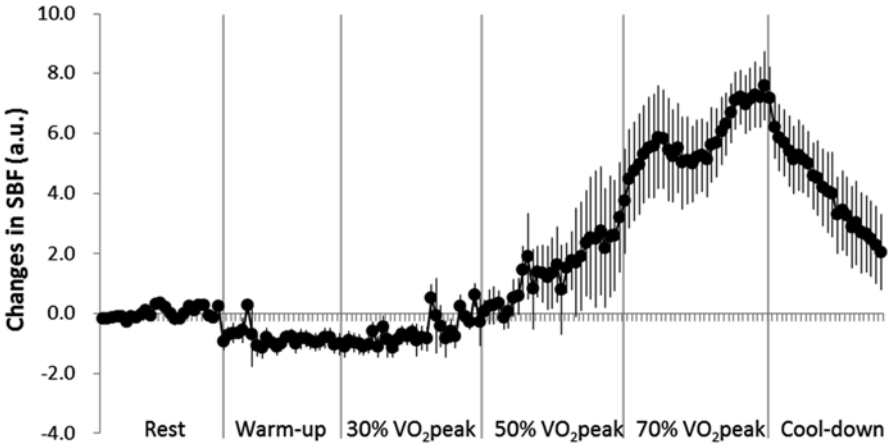

Fig. 21.2 Temporal changes in the average skin blood flow (SBF) value. Values are presented as the mean ± standard error of the mean (SEM)

We observed a slight increase in MAP from the warm-up phase to the end of the 30 % VO_2peak phase (Fig. 21.3). MAP increased gradually to 18.8 mmHg during the 50 % VO_2peak phase and to 30.0 mmHg during the 70 % VO_2peak phase, and then it rapidly returned to resting levels during the cool-down phase.

The relationship between O_2Hb and SBF varied according to the exercise phase (Figs. 21.4 and 21.5). A moderate positive correlation was observed during the 30 % VO_2peak phase, and a strong positive correlation was observed during the 50 %

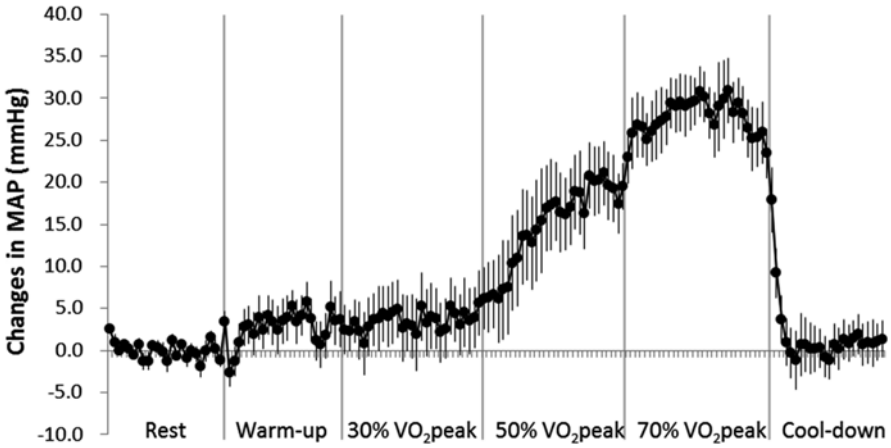

Fig. 21.3 Temporal changes in the average mean arterial pressure (MAP). Values are presented as the mean ± standard error of the mean (SEM)

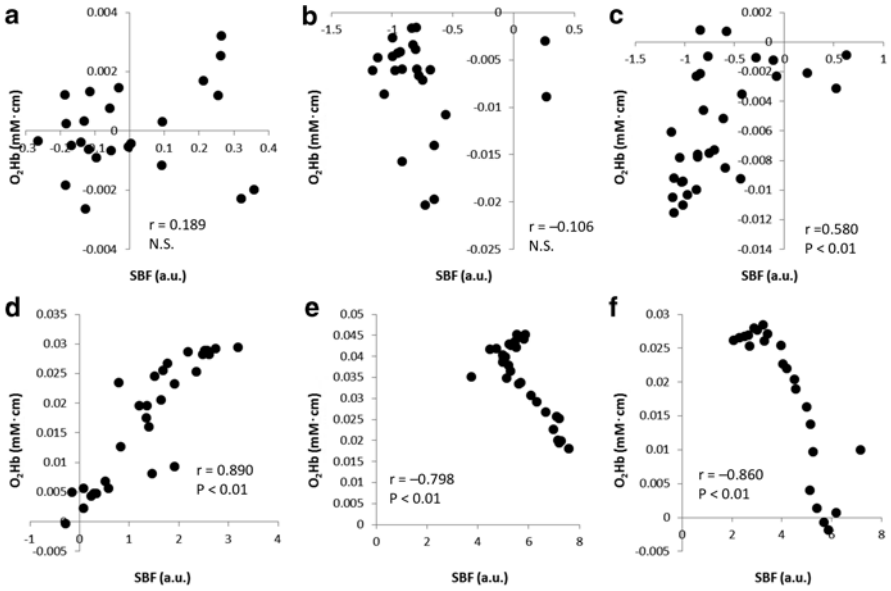

Fig. 21.4 Scatter plots for the skin blood flow (SBF) and O_2Hb during the rest (**a**), warm-up (**b**), 30 % VO_2peak (**c**), 50 % VO_2peak (**d**), 70 % VO_2peak (**e**) and cool-down (**f**) phases

VO_2peak phase. In contrast, a strong negative correlation was observed during the 70 % VO_2peak and cool-down phases. A moderate positive correlation was observed between O_2Hb and MAP during the warm-up and 30 % VO_2peak phases, and a strong positive correlation was observed during the 50 % VO_2peak phase.

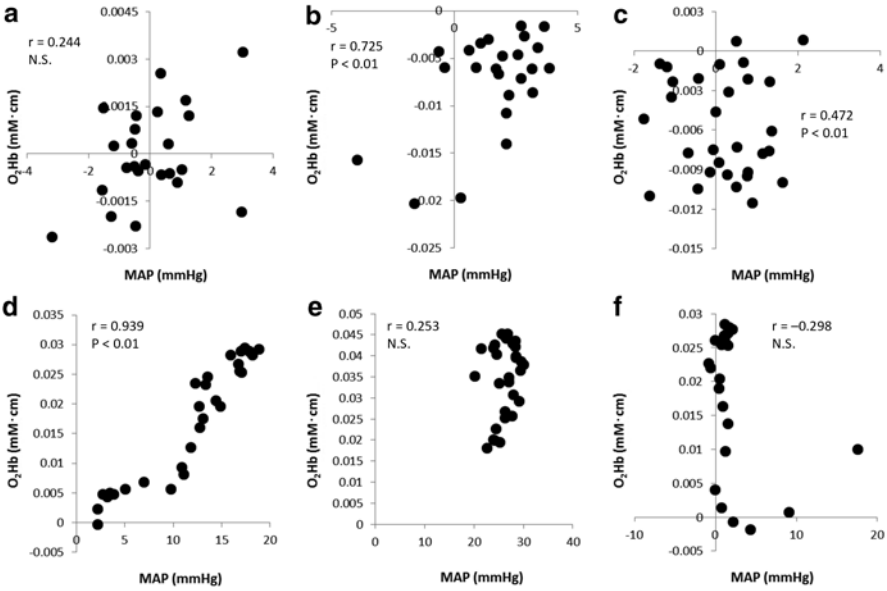

Fig. 21.5 Scatter plots for the mean arterial pressure (MAP) and O_2Hb during the rest (**a**), warm-up (**b**), 30 % VO_2peak (**c**), 50 % VO_2peak (**d**), 70 % VO_2peak (**e**) and cool-down (**f**) phases

4 Discussion

In the present study, the relationships between O_2Hb and MAP and between O_2Hb and SBF varied by exercise intensity. O_2Hb was moderately positively correlated with both SBF and MAP during the 30 % VO_2peak phase and strongly correlated during the 50 % VO_2peak phase. A strong negative correlation between O_2Hb and SBF was observed during the 70 % VO_2peak and cool-down phases.

NIRS can be used to measure changes in cerebral haemodynamics and metabolism, thus allowing for the use of multichannel NIRS recording for functional optical imaging of human brain activity [6]. Many studies have reported that changes in O_2Hb reflect changes in cortical neural activation [1, 7, 8], although none have discussed the relationship between O_2Hb changes and systemic circulatory changes during gross motor tasks. Our results indicate that brain activation can be monitored during motor tasks, such as cycling on an ergometer.

SBF, MAP, and O_2Hb all increased between 30 % VO_2peak and 50 % VO_2peak and were strongly correlated during the 50 % VO_2peak phase. These results suggest that cortical neural activation, blood pressure changes, and SBF changes affected the changes in O_2Hb during low and moderate-intensity exercise. Some studies have reported that an increase in cerebral oxygenation occurs with increased exercise intensity [2, 3], which is consistent with our results. The reason for the strong positive relationship between SBF and O_2Hb is because SBF affects the O_2Hb concentration, and these parameters have been found to be closely correlated ($R^2 = 0.94$) in

the frontal cortex [9]. Another study has shown that O_2Hb and forehead SBF were significantly increased during exercise, and the correlation between O_2Hb and forehead SBF was strong (R = 0.71–0.99) [10]. The strong positive relationship between MAP and O_2Hb is likely due to the effect of blood pressure on O_2Hb. Minati et al. [11] reported correlation coefficients of 0.93–0.95 between O_2Hb and MAP during visual stimulation combined with motor activity.

During the 70 % VO_2peak phase, SBF increased from 3.75 to 7.59 a.u. over 5 min, while O_2Hb decreased from 0.045 to 0.020 mM·cm, resulting in a strong negative correlation. Following exhaustive exercise, decreases in O_2Hb have also been observed in the prefrontal cortex [3, 12] and in the prefrontal and motor cortices [13]. Cortical oxygenation, measured using NIRS in healthy subjects, has shown a quadratic response to incremental exercise, increasing during moderate and high intensities, then falling at very high intensities [14]. In contrast, SBF increases during exhaustive exercise, and these contrasting phenomena create a strong negative correlation during the 70 % VO_2peak phase, suggesting that O_2Hb accurately reflects cortical haemodynamic changes during cycle ergometer exercise.

This study has some limitations. First, the measurement locations differed for SBF and O_2Hb. SBF was recorded at the forehead to prevent interference from the near-infrared and laser light emitted from the laser Doppler flow meter. Second, we could not clarify the relationship between O_2Hb and exercise duration; our results only examined changes in O_2Hb during 15 min of continuous exercise. Thus, future studies are needed to clarify the relationship between O_2Hb and exercise time.

In conclusion, we found that the relationships between O_2Hb and SBF and between O_2Hb and MAP varied according to exercise intensity during cycling. The relationships during the 70 % VO_2peak and cool-down phases suggest that O_2Hb signals reflect cortical haemodynamic changes other than SBF or MAP. The relationship between O_2Hb and systemic factors during motor tasks must be confirmed in order to detect cortical activation during gross motor tasks, and the findings of the present study serve as the basis for further investigation.

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