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EFFECT OF LINEAR POLARIZED NEAR-INFRARED LIGHT IRRADIATION ON MUSCLE FATIGUE RECOVERY AFTER REPEATED HANDGRIP EXERCISE

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Linear polarized near-infrared light (PL) irradiation is considered one of the useful methods for muscle fatigue recovery, because it increases the blood flow and skin temperature of the irradiated part. The purpose of this study was to examine the effect of PL-irradiation on muscle fatigue recovery and physiological response in the upper limbs after maximal repeated rhythmic hand gripping (RRH). Ten males and ten females participated in this study. Subjects performed RRH for 9 min, and then rested for 20 min with PL- or placebo-irradiations. After rest, they again performed RRH for 3 min. As evaluation parameters, we selected the sustained force curve during RRH, subjective muscle-fatigue sensation (Fs), blood lactate concentration (La), muscle oxygenation (Total Hb, Oxy-Hb, and Deoxy-Hb), and skin temperature. The decreasing rate of the integrated area for 30 sec during RRH was significantly smaller in the PL-irradiation than with the placebo. There were no significant differences between irradiation conditions for fatigue sensation and lactate concentration Skin temperature during rest was kept high by PL-irradiation. Muscle oxygenation tended to remain slightly high during the initial phase (1-8 min after the exercise). It is inferred that PL-irradiation maintains a high skin temperature and blood flow, but it may not contribute to recover muscle contraction performance in muscle fatigue.

Key words: linear polarized near-infrared light irradiation; muscle fatigue; blood lactate; muscle oxygenation kinetics.

INTRODUCTION

It is important for athletes to recover quickly from muscle fatigue caused by sustained exhaustion exercise for stable and high performance. Muscle fatigue recovery methods are broadly divided into passive and active methods (Hildebrandt et al., 1992). The former only keeps the body quiet, and the latter actively increases the blood flow and eliminates metabolites such as lactic acid by using some kind of techniques that results from stretching, massage, hot packs, or light exercise. Many researchers have reported that active methods accelerate the recovery of muscle fatigue as compared with passive methods (Hildebrandt et al., 1992; Ishida et al., 1992; Komai et al., 1982; Yamamoto and Yamamoto, 1993).

Linear polarized near-infrared light (PL) irradiation has been used as a laser treatment for pain in clinical settings (Otsuka et al., 1992; Yokoyama and Oku, 1999; Yokoyama and Sugiyama, 2001; Demura et al., 2002a). Ganglions are mainly irradiated using a wavelength with a deep dermal penetration (0.6-1.6 μm). It has been reported that PL-irradiation gives thermal sensation or stimulation and makes the blood flow or the skin temperature increase (Otsuka et al., 1992; Wajima et al., 1996;

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Yokoyama and Oku, 1999; Yokoyama and Sugiyama, 2001; Demura et al., 2002a).

As stated-above, we hypothesize that PL-irradiation is an active method to accelerate muscle fatigue recovery. It is desirable that a specialist performs or instructs on stretching and massage, because special knowledge and techniques are needed and the effect differs considerably by the enforcement method or intensity (Yamamoto and Yamamoto, 1993; Tiidus, 1997). However, there are very few trainers or conditioning coaches with special knowledge and techniques in sports competition settings. In most cases, therefore, the athlete must do it by him/herself. Since PL-irradiation does not need special knowledge and techniques, it is expected to be a simple and useful muscle fatigue recovery method (Demura et al., 2000; Demura et al., 2002b).

Experimental designs must be carefully planned because the extent of muscle fatigue differs considerably by exercise intensity or type. Until now, we examined the effect of PL-irradiation on exhausted isokinetic knee extension/flexion exercises, and determined the recovery effect of the maximal knee extension/flexion with high intensity and subjective muscle fatigue (Demura et al., 2000). We also examined the effect on muscle exertion values, subjective muscle fatigue and physiological responses during sustained isometric handgripping, and reported that short irradiation for 10 min did not contribute to muscle fatigue recovery (Demura et al., 2002b). However, after more intense exercise PL-irradiation tended to recover a blood lactate concentration (La) and to maintain total hemoglobin volume in the tissue, with more of an effect coming from longer irradiations (Demura et al., 2002b). To clarify the effect of PL-irradiation on accelerating muscle fatigue recovery, we planned an experiment considering these reports.

The purpose of this study was to examine the effect of PL-irradiation accelerating muscle fatigue recovery and physiological response in the upper limb after maximal repeated rhythmic handgripping (RRH) with high intensity.

METHODS

Subjects

Subjects were 10 healthy males [mean ± SD; age 19.9 ± 1.8 yr, height 174.0 ± 5.0 cm, body mass 64.6 ± 6.1 kg] and 10 females [mean ± SD; age 21.0 ± 1.6 yr, height 160.7 ± 7.7 cm, body mass 54.4 ± 5.4 kg]. Their physical characteristics approximated the standard values for Japanese males and females of the same age stage (Laboratory of Physical Education in Tokyo Metropolitan University, 2000). Written informed consent was obtained from all subjects after a full explanation of the experimental purpose and protocol.

Materials and Measurement parameters

PL-irradiation used a spot irradiation type linear polarized near-infrared light (Super Lizer HA-30, Tokyo Medical Laboratory, Japan; output power: 1800 mW, focus radius: 10 mm, wavelength band: 0.6 μm -1.6 μm). The irradiation unit was the type that stimulated one point on the skin. The irradiation protocol drew upon a previous study (Demura et al., 2002a; Demura et al., 2002b). PL-irradiation was carried out on the flexor muscles of the forearm (flexor digitorum superficialis, flexor carpi radialis, and palmaris longus). The tester illuminated by rotation around a motor unit of each flexor muscle which was defined as the most sensitive point for an electric stimulation. The intensity in PL- and placebo-irradiations was maximal (100%; 1800 mW) and very light (10%), respectively. It is confirmed that the latter irradiation had no effect on increasing the blood flow and skin temperature (Demura et al., 2002b). Both irradiations were carried out for 20 min with a cycle of 5 sec irradiation and 1 sec rest. Grip strength during RRH was measured using a digital hand dynamometer with a load-cell sensor (EG-100, Sakai, Japan). Each signal during RRH was sampled at 20 Hz with an analog-to-digital interface, and then relayed to a personal computer. To increase the subject's motivation during RRH, the recorded digital data was immediately displayed on a screen as a sustained force curve to give feedback.

We selected the sustained force curve during RRH and subjective muscle-fatigue sensation (Fs) as the parameters to evaluate muscle fatigue recovery, and La, muscle oxygenation measured by near infrared spectroscopic (NIR) (Total Hb, Oxy-Hb, and Deoxy-Hb), and skin temperature to evaluate physiological responses. The sustained force parameters during maximal RRH were peak values, and integrated areas for 10, 30, and 60 sec using maximal grip as a target value with a frequency of 30 grips·min^{-1}.

The Fs was estimated by using Borg's CR10 Scale (Borg, 1998). La was measured by gathering blood from the tip of the forefinger by means of measuring equipment (Lactate Pro LT-1710, Arkray, Japan). The equipment was calibrated by the maker (Arkray) before the experiment, and corrected with a reagent lot checkup by the built-in chip input for the calibration data. The measurement was done for a measurement accuracy of ± 0.1% in a measurement range of 0.8-23.3 mmol/l. The above six parameters had a decreasing rate before and after rest, and were calculated by using the following equation.

$$\text{Decreasing rate} = \left(Before\ \ rest - After\ \ rest\right) \Big/ Before\ \ rest \times 100$$

Muscle oxygenation kinetics (oxygenated, deoxygenated and total hemoglobins: Oxy-Hb, Deoxy-Hb, and Total Hb, respectively) during RRH, by NIR (PSA-IIIN, Biomedical Science, Japan), were calculated from the following equations;

$$\text{Oxy-Hb} = \text{Total Hb x StO}_2 \qquad (\%)$$

$$\text{Deoxy-Hb} = \text{Total Hb - Oxy-Hb} \qquad (\%)$$

NIR spectroscopic measurements evaluated muscle oxygenation by the forearm during RRH. The NIR instrument (PSA-IIIN, Biomedical Science, Japan) consisted of a probe and a computerized control system. The probe contained a light source that was filtered at 700, 750 and 830 nm, and two optical detectors were placed 15 mm and 25 mm, respectively, from the light source. Transmitted light from the probe was then either absorbed or scattered within the tissue. Scattered light was delivered via two fiber-optic light detectors to a photomultiplier every 0.1 sec. The optical path length of the NIR light in tissue was assumed by the direct method or using a Monte Carlo simulation (Hiraoka et al., 1993). The mean depth of measurement in the tissue has been confirmed to be half of the distance between the light source and the detector (Yokoyama and Sugiyama, 2001). According to this hypothesis, the average measurement depth of PSA-IIIN was approximately 7 – 12.5 mm. We measured a thickness of subcutaneous fat on the region with the NIR probe (forearm) using an ultrasound B-mode imaging device (EUB-200, Hitachi Medical Corp., Japan) in a prior experiment. All subject's thicknesses ranged within 2 – 4 mm. PSA-IIIN will, therefore, measure the oxygenation kinetics of tissue deeper than the subcutaneous fat layer. The PSA-IIIN used three-wavelengths and two optical detectors analyzed absorbance of three-wavelengths based on the Lambert-Beer law, and measured tissue oxygen saturation (StO$_2$) and total tissue haemoglobin (Total Hb). Total absorbance of a light incident to the tissue is explained by the sum of the absorbance by oxygenated haemoglobin (Oxy-Hb) and deoxygenated haemoglobin (Deoxy-Hb) in the blood, and tissue except the blood. Moreover, it is assumed that the difference of the absorbance of tissue except the blood is very small and can be neglected, because three-wavelengths (700-830 nm) on a NIR spectroscopic correspond to a very narrow range. The following equation comes from this assumption, and StO$_2$ is measurable even if the mean optical path length cannot be calculated (Yokoyama and Sugiyama, 2001; Sakai and Saito, 1995).

$$StO_2 = Ca \cdot \bar{d} \Big/ (Ca + Cb) \cdot \bar{d} \cdot 100 = Ca \Big/ Hb \cdot 100$$

Ca: mass of Oxy-Hb, Cb: mass of Deoxy-Hb, $\bar{d}$: mean optical path length, Hb: Total Hb volume

The principle of PSA-IIIN was discussed in detail in a previous paper by Sakai and Saito (1995). Data obtained by NIR was converted to relative values based on the resting value before the experiment.

Skin temperature was measured with a thermal sensor (Thermal sensor, Biomedical Science, Japan).

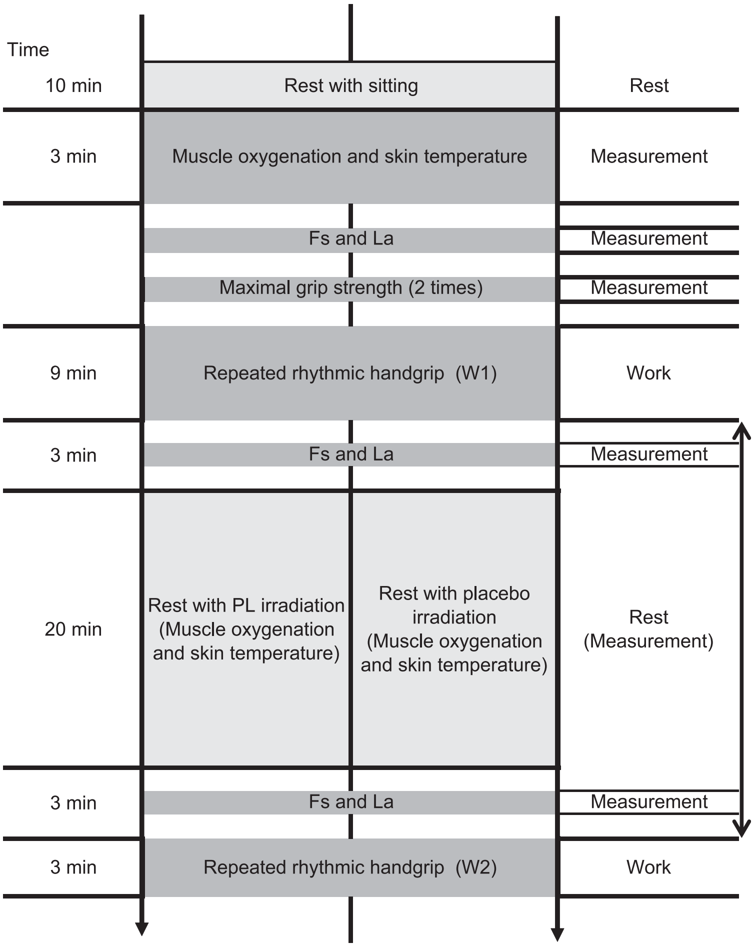

Fig. 1. Experimental procedure in this study.

Experimental procedure

Figure 1 shows the experimental procedure in this study. The experimental design set conditions for both PL- and placebo-irradiations, and was a cross over design in which all subjects participated in both conditions. The PL- and placebo-irradiations were performed on different days in a random measurement order, by considering the effect of the irradiation. The double blind method was used to eliminate the psychological effect of the tester and the subjects. After resting for 10 min, the NIR probe and the skin temperature sensor were positioned over the center of the flexor digitorum superficialis, i.e. one-third points above the medial epicondyle of the humerus and the styloid process of radius. Direct PL-irradiation of this position was avoided. All subjects performed the RRH with the dominant hand, and grip width was individually adjusted to achieve a 90-degree angle with the proximal-middle phalanges. Each subject performed the RRH while seated in an adjustable ergometric chair. The arm, supported by an armrest, was in a sagittal and horizontal position, with the forearm vertical with the hand in a semi-prone position. After measuring maximal grip strength, each subject performed the RRH test (using maximal grip strength with a target frequency of 30 grips·min^{-1} for 9 min (Work 1: W1)). No verbal encouragement was given during the test. Fs, blood La, muscle oxygenation (Total Hb, Oxy-Hb, and Deoxy-Hb), and skin temperature were measured before W1. Subjects rested for 26 min, and then carried out RRH for 3 min (Work 2: W2) after W1. During rest, subjects quietly laid their dominant arm on the table, and PL- or placebo- irradiations for 20 min took place. The Fs and La were measured when just finishing W1 and just before W2 (before/after rest). During rest, muscle oxygenation and skin temperature were measured continuously. The experiment room was set at 24°C and 30-40% humidity, and there was very little breeze. Subjects wore the same clothes (cotton short-sleeved shirts, knit pants, and socks) in both experimental sessions.

Data analysis

Two-way ANOVA was used to examine the mean difference between the conditions (PL-/placebo-irradiation) and the measurement point of time (before/after W1 and after rest) for Fs and La, and between the conditions and work (W1 and W2) for sustained force parameters. A paired t test was used to examine the difference in the decreasing rate of these parameters between the conditions. Two-way ANOVA (conditions and the irradiation time every 1 min) was used to examine the mean differences for muscle oxygenation (Total Hb, Oxy-Hb, and Deoxy-Hb) and skin temperature. Multiple comparisons used Tukey's HSD method. The probability level of 0.05 was indicative of statistical significance.

RESULTS

Table 1 shows the results of two-way ANOVA for sustained force parameters, and Table 2 shows those for Fs and La. There was a significant main factor of work or measurement point of time for all parameters. Sustained force parameters in both irradiation conditions for W1 were higher than those for W2. The Fs and La in both conditions after W1 were higher than those before W1 and after rest.

Table 3 shows the results of the t-test between irradiation conditions for the decreasing rate before and after rest of the sustained force parameters, Fs, and La. The decreasing rate of integrated area for 30 sec in the PL-irradiation was significantly lower than that in the placebo-irradiation.

Table 1. Results of two-way ANOVA (conditions × work) for force-time parameters.

	Unit		W1		W2		ANOVA			Tukey's HSD
			mean	(SD)	mean	(SD)	works	irradiations	interaction	
Peak grip force	(%)	Placebo	96.8	(5.7)	87.5	(8.5)	*	ns	ns	W1>W2
		PL	96.3	(5.2)	90.5	(6.5)				
Integrated area										
10 sec	(%)	Placebo	366.6	(35.7)	334.1	(33.4)	*	ns	ns	W1>W2
		PL	366.7	(22.2)	347.0	(24.7)				
30 sec	(%)	Placebo	1207	(111.2)	1079.6	(109.4)	*	ns	ns	W1>W2
		PL	1215	(81.4)	1135.4	(94.5)				
60 sec	(%)	Placebo	2302	(248.0)	2055.6	(209.8)	*	ns	ns	W1>W2
		PL	2343	(201.5)	2157.8	(223.6)				

*: P < 0.05, ns: no significant difference.

Table 2. Results of two-way ANOVA (conditions × before/after W1 and after rest) for Fs and La.

	Unit	Conditions	Before W1 mean	(SD)	After W1 mean	(SD)	After rest mean	(SD)	ANOVA time	conditions	interaction	Tukey's HSD
Fs		Placebo	0.1	(0.2)	7.1	(2.3)	0.8	(1.2)	*	ns	ns	A(W) > B(W), A®
		PL	0.1	(0.2)	7.0	(2.6)	0.8	(0.9)				
La	mmol/l	Placebo	1.4	(0.4)	2.1	(0.8)	1.3	(0.3)	*	ns	ns	A(W) > B(W), A®
		PL	1.4	(0.4)	2.0	(0.8)	1.4	(0.3)				

* P < 0.05, ns: no significant difference. A(W): After W1, B(W): Before W1, A®: After rest.

Table 3. Results of t-test between irradiation conditions of the decreasing rate for force-time parameters, Fs, and La.

Parameters	Placebo Mean (SD)	PL Mean (SD)	t	
Peak grip force	9.6 (7.9)	5.9 (6.9)	1.70	
Integrated area				
10 sec	8.0 (14.0)	5.1 (8.1)	0.81	
30 sec	10.3 (8.0)	6.5 (5.3)	2.20	*
60 sec	10.3 (7.7)	7.9 (4.4)	1.61	
Fs	88.9 (14.1)	88.3 (13.6)	0.20	
La	29.9 (22.6)	23.2 (25.1)	1.49	

*: P < 0.05, peak grip force: peak grip force during W1 and W2.
Decreasing rate (%) = (W1-W2)/(W1)×100.

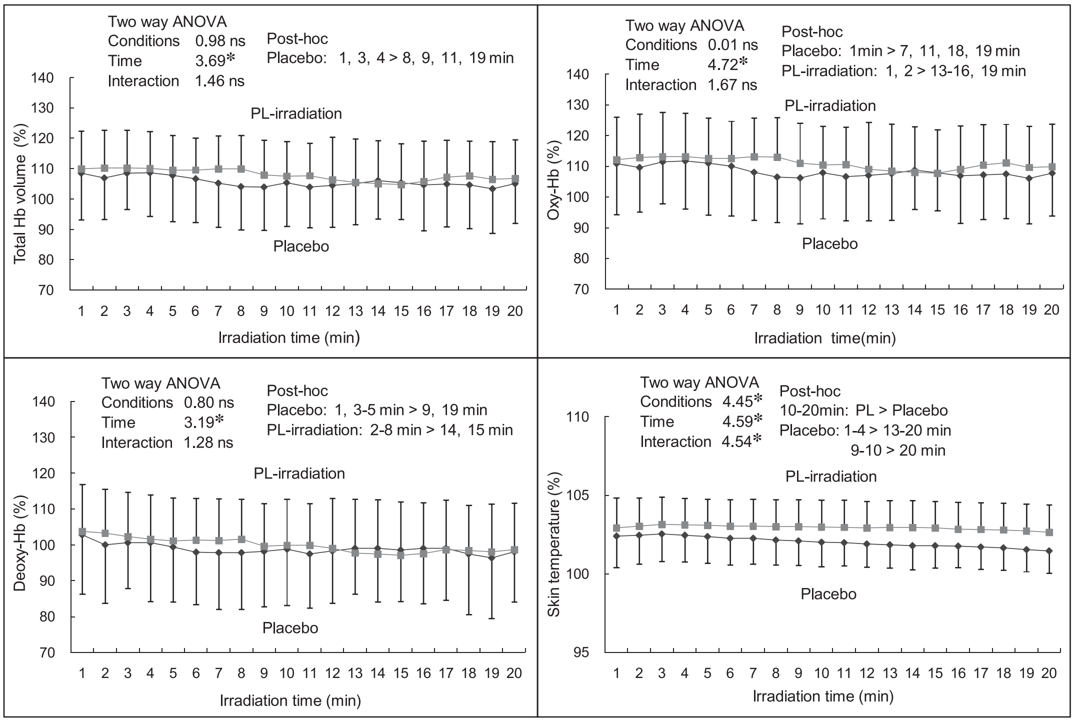

Fig.2. Change of Total-Hb volume (upper left diagram), Oxy-Hb volume (upper right diagram), Deoxy-Hb volume (lower left diagram), and skin temperature (lower right diagram) during PL-/Placebo irradiation. ns: not significant. Vertical bars indicate standard deviations. *: P<0.05

Moreover, the other sustained force parameters, Fs and La, in the PL-irradiation tended to be lower, but there were no significant differences between irradiation conditions.

Figure 2 shows the average time-series change for all subjects during rest in both irradiation conditions and the results of two-way ANOVA for muscle oxygenation (Total Hb, Oxy-Hb, and Deoxy-Hb) and skin temperature. There were significant main factors of irradiation time in Total Hb and Oxy-Hb. Total Hb showed a significantly low value at 8, 9, 11, and 19 min in a placebo-irradiation and at 14 and 15 min in PL-irradiation. Oxy-Hb showed a significantly low value at 7, 11, 18 and 19 min with a placebo-irradiation and at 13-16 and 19 min with PL-irradiation. Deoxy-Hb showed a significantly low value at 9 and 19 min with a placebo-irradiation and at 14 and 15 min with PL-irradiation. Significant interaction factors were found in skin temperature. Skin temperature showed a significantly higher value from 13 min to 20 min in PL-irradiation as compared with that in the placebo-irradiation. Skin temperatures in PL- and placebo-irradiation before W1 were 32.4±0.4°C and 32.2±0.6°C respectively, and after W1 were 32.8±0.5°C and 33.0±0.6°C, respectively. There were no significant differences between both irradiation conditions. During rest with the irradiation period, skin temperature in PL-irradiation increased to 33.4±0.5°C (4 min after onset of irradiation), but in placebo-irradiation it decreased gently.

DISCUSSION

The gripping force during RRH for 9 min (W1) markedly decreased until about 60-120 sec after the onset of RRH, slowly decreased to about 180-240 sec, and then reached an almost steady state. This decreasing tendency was similar to that in previous studies (Caffier et al., 1992; Clarke et al., 1992). Accordingly, gripping force is considered to reach a critical force, which does not decrease more even if a subject continues RRH (Caffier et al., 1992). Because Fs corresponded to "very strong" and La increased over 40% as compared with that before the W1, the subject's forearm after W1 is considered to have reached the muscle fatigue state.

The physiological mechanism of active recovery of muscle fatigue after strenuous exercise eliminates metabolites such as lactic acid produced in the activated muscle by an increase of the blood flow (Hildebrandt et al., 1992; Yamamoto and Yamamoto, 1993). Yamamoto and Yamamoto (1993) reported that stretching and massage after strenuous cycle exercise allows for quick recovery, and light exercise contributes to the elimination of lactic acid. Moreover, Ishida et al. (1992) reported that light exercise allowed for the quick recovery of the force exertion value and La, and massage recovered the force exertion value. On the other hand, they reported that hot packs and warm water showers resulting in passive increases in skin temperature can hardly conduct heat stimuli to deeper tissues in a short time and did not contribute to recovery of muscle fatigue. PL-irradiation thermally sensitizes deeper tissues (muscle) and increases the skin temperature and the blood flow around the irradiation region, because it has a high output and uses a wavelength with a deep dermal penetration (Otsuka et al., 1992; Wajima et al., 1996). The PL-irradiation method may provide effective and active recovery from muscle fatigue.

We pooled both sexes in this study because there was no tendency for a sex difference in any parameter (La, Fs, muscle oxygenation, and skin temperature) after PL-irradiation. The decreasing rate of sustained force parameters before and after rest in PL-irradiation tended to be lower than that in placebo-irradiation, and there was a significant difference in the integrated area for 30 sec.

Demura et al. (2000) reported that PL-irradiation after sustained and hard isokinetic exercise accelerated the recovery of force exertion and Fs in knee extension and flexion. On the other hand, they reported that PL-irradiation after sustained isometric handgripping for 3 min did not accelerate recovery (Demura et al., 2002b). This inconsistency may relate to work intensity and rest time rather than the irradiation point or exercise type. Although the rest time in both studies was the same (10 min), the former performed exhaustive isokinetic exercise for 5-10 min to get the state to an "absolute maximum (highest possible)". The latter did the sustained static handgrip for 3 min to get the state as "strong" or "very strong". In the case of low exercise intensity, PL-irradiation may not effect force exertion.

The increasing rate of Fs and La from the work before rest (W1) was higher in this study as compared with the report of Demura et al. (2002b). The present work intensity was, therefore, almost the same or somewhat higher. PL-irradiation for 20 min may accelerate recovery of subjective muscle-fatigue sensation after the exhausting RRH for 9 min. However, the recovery effect was not enough to reflect force output.

Moreover, the present PL-irradiation was carried out for 20 min and was longer than 10 min in the previous study (Demura et al., 2002b). Demura et al. (2002b) suggested that the effect of PL-irradiation on muscle fatigue recovery becomes clearer by extending the irradiation period, because Total Hb tended to change in the latter period of rest. The present findings may support this suggestion.

On the other hand, after rest, Fs and La in both conditions recovered to the level before W1 (Table 2) because of the long rest. We cannot judge from only the present results that PL-irradiation accelerated muscle fatigue recovery, because we did not measure the above parameters during rest. Yamamoto and Yamamoto (1993) stated the necessity for active recovery from muscle fatigue to make muscle groups contract actively or passively. However, Demura et al. (2002b) reported that even PL-irradiation during rest without contracting the muscle group after sustained static gripping would contribute to recovering the La level. La recovery relates closely to muscle blood flow.

La produced by the glycolytic cycle during exercise moves to other muscles to reuse for energy metabolism. Ishimaru et al. (1992) examined the irradiation effect of a semiconductor low energy laser (Ga-Al-As, wavelength: 780 nm, output: 10 mW) on peripheral circulation for 15 min using acupuncture points, and reported that finger blood flow significantly increased from 20.6 ± 6.3 ml/min/100 g to 31.3 ± 6.0ml/min/100 g. Because there is no occlusion in the centralis blood vessel and no obstruction of the perfusion of blood, we can deduce the change of blood flow roughly from the change of Total Hb, Oxy-Hb, and Deoxy-Hb measured by NIR (Homma et al., 1996).

Moreover, muscle oxygen consumption during rest without muscle contraction is considered to be constant. Therefore, the changing tendency of Total Hb during rest was similar to that of Oxy-Hb and Deoxy-Hb, and the similarities were confirmed in this study. As the blood flow after the exercise markedly increases by post exercise hyperemia (Kagaya and Homma, 1997), it may become higher in both conditions. Total Hb in PL-irradiation tended to maintain high levels during the early rest period (1-8 min after the exercise).

The skin temperature in placebo-irradiation decreased with the time lapse, but in PL-irradiation it maintained a high level. This result was consistent with that in previous studies (Demura et al., 2002b). This may be the effect of thermal stimulation by PL-irradiation. However, the absolute difference of Total Hb between PL- and placebo irradiation was very small. It is yet to clarify how increase of Total Hb (blood flow) reflects in the increase of skin temperature and muscle fatigue recovery. Although PL-irradiation makes Total Hb (blood flow) and skin temperature increase slightly, it has no effect on muscle fatigue recovery.

In this study, the immediate effect of muscle fatigue recovery by PL-irradiation could not be confirmed. However, because PL-irradiation increases skin temperature and blood flow, it may inhibit delayed onset of muscle soreness or fatigue. This is an issue for further study.

In conclusion, PL-irradiation during rest increases or maintains skin temperature and blood flow and may accelerate the disposal of La. However, the recovery effect is not enough to reflect La and force output recovery. PL-irradiation may not contribute to the recovery of grip force in muscle fatigue.

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