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## ORIGINAL RESEARCH

## Intracellular oxygen tension limits muscle contraction-induced change in muscle oxygen consumption under hypoxic conditions during Hb-free perfusion

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### Keywords

Hindlimb perfusion, hypoxia, intracellular oxygen tension, myoglobin.

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## Introduction

Under acute hypoxic conditions, the decrease in O<sub>2</sub> supply reduces muscle oxygen consumption ( $m\dot{V}O_2$ ) during exercise (Calbet et al. 2003; Lundby et al. 2004; Calbet et al. 2009). However, a series of O<sub>2</sub> transport steps (ventilation,

## Abstract

Under acute hypoxic conditions, the muscle oxygen uptake ( $m\dot{V}O_2$ ) during exercise is reduced by the restriction in oxygen-supplied volume to the mitochondria within the peripheral tissue. This suggests the existence of a factor restricting the  $m\dot{V}O_2$  under hypoxic conditions at the peripheral tissue level. Therefore, this study set out to test the hypothesis that the restriction in  $m\dot{V}O_2$  is regulated by the net decrease in intracellular oxygen tension equilibrated with myoglobin oxygen saturation ( $\Delta P_{mb}O_2$ ) during muscle contraction under hypoxic conditions. The hindlimb of male Wistar rats (8 weeks old,  $n = 5$ ) was perfused with hemoglobin-free Krebs–Henseleit buffer equilibrated with three different fractions of O<sub>2</sub> gas: 95.0%O<sub>2</sub>, 71.3%O<sub>2</sub>, and 47.5% O<sub>2</sub>. The deoxygenated myoglobin (Mb) kinetics during muscle contraction were measured under each oxygen condition with a near-infrared spectroscopy. The  $\Delta$ [deoxy-Mb] kinetics were converted to oxygen saturation of myoglobin ( $S_{mb}O_2$ ), and the  $P_{mb}O_2$  was then calculated based on the  $S_{mb}O_2$  and the O<sub>2</sub> dissociation curve of the Mb. The  $S_{mb}O_2$  and  $P_{mb}O_2$  at rest decreased with the decrease in O<sub>2</sub> supply, and the muscle contraction caused a further decrease in  $S_{mb}O_2$  and  $P_{mb}O_2$  under all O<sub>2</sub> conditions. The net increase in  $m\dot{V}O_2$  from the muscle contraction ( $\Delta m\dot{V}O_2$ ) gradually decreased as the  $\Delta P_{mb}O_2$  decreased during muscle contraction. The results of this study suggest that  $\Delta P_{mb}O_2$  is a key determinant of the  $\Delta m\dot{V}O_2$ .

diffusion from the lung to the blood, bulk delivery by the cardiovascular system, and the transfer of O<sub>2</sub> from the blood to the skeletal muscle) control the  $m\dot{V}O_2$  and oxidative ATP generation (Bassett and Howley 2000; Howlett et al. 2009). The way the various steps involved in the determination of the  $\dot{V}O_2$  contribute to the respiration during

exercise under hypoxia conditions remains unclear. Recent research has reported that in hypoxia  $\dot{V}O_2$  might be limited by factors aside from arterial oxygen content (Lundby *et al.* 2004). Taken together, these facts suggest the existence of factors regulating the  $m\dot{V}O_2$  at the peripheral tissue level.

As the value of the  $m\dot{V}O_2$  depends on the  $O_2$  flux – that is, the  $O_2$  diffusion conductance ( $DO_2$ ) and the  $O_2$  gradient between the microvasculature and the myocytes – the decrease in  $m\dot{V}O_2$  under hypoxic conditions may be caused by decreases in both the  $DO_2$  and  $O_2$  gradients across the plasma membrane (Richardson *et al.* 1995; Takakura *et al.* 2010). However, previous studies have not considered the contribution of the  $O_2$  gradient as based on the intracellular oxygen tension equilibrated with myoglobin oxygen saturation ( $P_{mb}O_2$ ) (Gonzalez *et al.* 2006). Currently, only the  $P_{cap}O_2$  is regarded as an adequate measure of the  $O_2$  diffusion between the plasma membrane. The study assumed that the  $P_{mb}O_2$  at rest was close to zero and that it remained unchanged during moderate- to high-intensity exercise (Richardson *et al.* 1995). However, under hypoxic condition, Richardson *et al.* (2006) could not detect any deoxy myoglobin (Mb) signal at rest due to presumably a low signal to noise ratio. Therefore, it remains unclear whether muscle contraction under hypoxic conditions causes a further decrease in  $P_{mb}O_2$ . Other groups have reported that the  $P_{mb}O_2$  decreases with the increase in exercise intensity under normoxic conditions, and that the  $O_2$  gradient from the vasculature to the cell could play a key role in the control of the  $\dot{V}O_2$  (Molé *et al.* 1999; Chung *et al.* 2005). These conflicting results necessitate an examination of the relationship between the  $m\dot{V}O_2$  and the intracellular  $O_2$  environment during muscle contraction under hypoxic conditions.

We recently demonstrated that the intracellular Mb dynamics during muscle contraction involved in enhancing the  $O_2$  flux to meet the increased muscle  $O_2$  demand (Masuda *et al.* 2010; Takakura *et al.* 2010). Indeed, the  $P_{mb}O_2$  decreased with increasing exercise intensity under normoxic conditions (Molé *et al.* 1999; Takakura *et al.* 2010). This change in the  $O_2$  gradient as reflected by the decrease in the  $P_{mb}O_2$  can contribute to the muscle  $O_2$  uptake. Therefore, this study considers the effect of hypoxia on the intracellular  $O_2$  environment and assesses whether the vasculature-to-cell  $O_2$  gradient contributes in regulating the  $m\dot{V}O_2$  during muscle contraction.

## Materials and Methods

### Experimental animals and preparation of hindlimb perfusion

Male Wistar rats were employed as subjects. All were housed in a temperature-controlled room at  $23 \pm 2^\circ\text{C}$

with a 12-h light–dark cycle and maintained on a commercial diet with water ad libitum. The procedures conformed to the “Fundamental Guidelines for Proper Conduct of Animal Experiment and Related Activities in Academic Research Institutions” (published by the Ministry of Education, Culture, Sports, Science and Technology, Japan) and was approved by the Ethics Committee for Animal Experimentation of Kanazawa University (Protocol AP-101821).

The hindlimb perfusion was performed to the rats at 8 week of age (body weight at experiment;  $256.0 \pm 8.7$  g). Preparation of isolated rat hindlimb and the perfusion apparatus are described in previous reports (Masuda *et al.* 2010; Takakura *et al.* 2010, 2015). All surgical procedures were performed under pentobarbital sodium anesthesia (64.8 mg/kg intraperitoneal). After finishing a surgical procedure, the rats were killed by injecting 1 mol/L KCl solution directly into the heart and a hemoglobin-free Krebs–Henseleit buffer (NaCl, 118 mmol/L; KCl, 5.9 mmol/L;  $KH_2PO_4$ , 1.2 mmol/L;  $MgSO_4$ , 1.2 mmol/L;  $CaCl_2$ , 1.8 mmol/L;  $NaHCO_3$ , 20 mmol/L; Glucose, 15 mmol/L) equilibrated with 95%  $O_2$  + 5%  $CO_2$  at  $37^\circ\text{C}$  was perfused into the abdominal aorta in flow through mode, at a constant flow rate. In order to adjust the perfusion pressure to approximately 80.0 mmHg, the flow rate was set to  $22.2 \pm 0.5$  mL  $\text{min}^{-1}$  throughout the perfusion period. In this condition, the average perfusion pressures were  $77.5 \pm 3.1$  mmHg, and the perfusion resistance was unchanged throughout the perfusion period. In addition, no sign of edema in the hindlimb was seen at the given flow rate. The effluent was collected from the inferior vena cava in order to measure  $m\dot{V}O_2$  and the lactate and pyruvate concentrations.

During the perfusion period, the oxygen supply was modulated by adjusting the  $O_2$  fraction of the equilibration gas using nitrogen gas, while 5%  $CO_2$  concentration was maintain to keep pH in perfusate. This study set three levels of  $O_2$  concentration: a 95.0%  $O_2$  fraction, a 71.3%  $O_2$  fraction, and a 47.5%  $O_2$  fraction. After establishing a sufficient equilibrium in each oxygen condition, muscle contraction was performed on a rat at the maximal twitch tension in all oxygen conditions. The order of the three oxygen conditions was randomized.

### Measurement parameters

The twitch contraction protocol and measurement of Mb oxygenation and  $m\dot{V}O_2$  followed the previous methods (Masuda *et al.* 2010; Takakura *et al.* 2010). The sciatic nerve of the left hindlimb was then exposed and connected to two parallel stainless steel wire electrodes (Unique Medical, Tokyo, Japan) and the Achilles' tendon

was connected to a sensitive strain gauge with a string (MLT500/D, AD Instrument, Castle Hill, NSW, Australia). The stimulation pulse via the sciatic nerve derived by an electrostimulator system (Model RU-72, Nihon Kodens, Tokyo, Japan) was 1 Hz in frequency (delay, 10  $\mu$ sec; duration, 1 msec) for 120 sec (120 twitch contractions). Target tension was controlled by changing the voltage of stimuli to obtain 100% of peak tension under buffer-perfused conditions (3–8 volts). Twitch tension was calculated as the average of a series of contractions. The muscle also showed no sign of fatigue at the set stimulation intensity.

An NIRS instrument (NIRO-300 + Detection Fibre Adapter Kit, Hamamatsu Photonics, Shizuoka, Japan) was employed to measure oxygenation of Mb at rest and during muscle contraction. The distance between the photodiode and the LED was fixed at 10 mm. The toe of the foot was secured by a clamp with the rat laid on its back. After that, the NIRS probes were firmly attached to the skin of the gastrocnemius muscle and were fixed by clamps on both sides of the muscle. During the initial period, for at least 30 sec before the start of contraction, the average fluctuation in the NIRS signals was adjusted to a reference value of zero. After the exercise protocol, the anoxic buffer (equilibrated with 95%  $N_2$  + 5%  $CO_2$  gas) was perfused for 30 min to obtain maximal Mb desaturation. The muscle then received electrical stimulation to contract for 2 min. No further increase in change in NIRS signal associated with concentration of deoxygenated Mb ( $\Delta$ [deoxy-Mb]) signal was evident. The final  $\Delta$ [deoxy-Mb] signal intensity served as the normalization constant for 100% Mb deoxygenation.

The value of  $m\dot{V}O_2$  was calculated from the arteriovenous oxygen content difference multiplied by the flow rate, using the equation:

$$m\dot{V}O_2(\mu\text{mol g}^{-1}\text{min}^{-1}) = \text{flow rate} \times [(\text{PO}_{2\text{in}} - \text{PO}_{2\text{out}}) \times O_2 \text{ solubility}] / \text{muscle weight}$$

where flow rate is the flow in milliliters per minute, and  $PO_{2\text{in}}$  and  $PO_{2\text{out}}$  are the arterial and venous oxygen tensions after adjusting for the vapor pressure of water. Inflow  $PO_2$  and outflow  $PO_2$  were measured continuously using two  $O_2$  electrodes (5300A, YSI, Yellow Springs, OH) along tubing before and after perfusion of the hindlimb. The vapor pressure at 37°C was 47.03 mmHg. The solubility of oxygen in the buffer was 0.00135  $\mu\text{mol mL}^{-1}\text{mmHg}^{-1}$  at 37°C (Philip and Dorothy 1971). The  $m\dot{V}O_2$  at rest and during muscle contraction was calculated by using the values of  $PO_{2\text{in}} - PO_{2\text{out}}$  averaged over 15 sec in the steady-state conditions before and during muscle contraction.

The sampling rate for the NIRS data was 1 Hz. The other parameters (tension, perfusion pressure,  $O_2$  content

at the inflow and outflow) were collected using a data acquisition system (PowerLab 8SP, AD Instruments, Australia) at a sampling rate of 1 kHz. All the data were transferred to a personal computer with acquisition software (Chart ver. 5.5.6. AD Instruments).

## Data analysis

The data analysis followed our previous methods (Takakura et al. 2010, 2015). A simple moving average smoothed the  $\Delta$ [deoxy-Mb] NIRS signals using a rolling average of 5 points, which corresponds to a 5 sec time-frame (Box et al. 1978). The  $\Delta$ [deoxy-Mb] signals were calibrated against two different NIRS signal values: one at rest as 10% Mb deoxygenation and the other during steady state with anoxic buffer perfusion as 100% Mb deoxygenation. While the  $S_{\text{mb}O_2}$  at rest could not be determined by NIRS, the value was assumed to be 90% based on previous studies reporting that the  $S_{\text{mb}O_2}$  at rest was greater than 90% (Chung et al. 2005). The % $\Delta$ [deoxy-Mb] plots were converted to  $S_{\text{mb}O_2}$  (%) plots using the following equation:

$$S_{\text{mb}O_2} = 100 - \% \Delta[\text{deoxy} - \text{Mb}]$$

$S_{\text{mb}O_2}$  plots were fitted by the following single-exponential equation to calculate kinetics parameters using an iterative least-squares technique by means of a commercial graphing/analysis package (KaleidaGraph 3.6.1, Synergy Software, Reading, PA):

$$S_{\text{mb}O_2} = \text{BL} + \text{AP} \times [1 - \exp^{-(t-\text{TD})/\tau}]$$

where BL is the baseline value, AP the amplitude between BL and the steady-state value during the exponential component, TD the time delay between onset of contraction and appearance of  $S_{\text{mb}O_2}$  signals, and  $\tau$  the time constant of  $S_{\text{mb}O_2}$  signal kinetics. MRT calculated by  $\text{TD} + \tau$  was used as an effective parameter of the response time for Mb deoxygenation at onset of muscle contraction. Dividing 63% of AP by MRT yields a value for the time-dependent change in Mb deoxygenation. The  $P_{\text{mb}O_2}$  value (mmHg) at rest and steady state during muscle contraction was converted from the  $S_{\text{mb}O_2}$  value using the following equation:

$$P_{\text{mb}O_2} = \frac{S_{\text{mb}O_2} \cdot P_{50}}{(1 - S_{\text{mb}O_2})}$$

where  $P_{50}$  is the partial oxygen pressure required to half-saturate Mb. A  $P_{50}$  of 2.4 mmHg was used for this equation, assuming a muscle temperature of 37°C (Schenkman et al. 1997). The calculated  $P_{\text{mb}O_2}$  plots were evaluated to obtain an MRT of its kinetics using the same single exponential equation as for  $P_{\text{mb}O_2}$ . The  $0.63\text{AP}/\text{MRT}$  for

$P_{mb}O_2$  indicates a rate of decrease in  $P_{mb}O_2$  at muscle contraction onset.  $P_{mb}O_2$  at steady state was calculated by using the  $S_{mb}O_2$  value at steady state. Since  $O_2$  partial pressure corresponds to a specific amount of dissolved  $O_2$ , intracellular  $[O_2]$  ( $\mu M$ ) was calculated from the  $P_{mb}O_2$  value at rest and at each  $O_2$  condition using the following equation:

$$\text{Intracellular } [O_2] = P_{mb}O_2 \times O_2 \text{ solubility}$$

with  $P_{mb}O_2$  is in mmHg, and  $O_2$  solubility in buffer is  $0.00135 \mu\text{mol mL}^{-1} \text{mmHg}^{-1}$  at  $37^\circ\text{C}$  (Philip and Dorothy 1971).

The relationship of  $m\dot{V}O_2$  to conductance and  $O_2$  gradient used the following equation:

$$m\dot{V}O_2 = kDO_2 \times (P_{cap}O_2 - P_{mb}O_2)$$

where  $m\dot{V}O_2$  is muscle oxygen consumption,  $k$  is constant,  $D$  is conductance,  $P_{cap}O_2$  is microvascular oxygen tension,  $P_{mb}O_2$  is intracellular oxygen tension equilibrated with myoglobin oxygen saturation as determined from the Mb signal. Because study used a constant flow perfused hindquarter model, the analysis has assumed a proportional relationship between the outflow and capillary  $PO_2$  and has set 30 mmHg as the reference the normoxic  $P_{cap}O_2$  value (Behnke et al. 2001; McCullough et al. 2011; Kano et al. 2014; Ferguson et al. 2015).

## Statistical analyses

All data are expressed as mean  $\pm$  SD. Statistical differences were examined using one-way paired measures analysis of variance (ANOVA) (factor:  $O_2$  fraction). A Turkey–Kramer post hoc test was applied if the ANOVA indicated a significant difference. The level of significance was set at  $P < 0.05$ .

## Results

In this study, the oxygen supply to the hindlimb muscle decreased from  $17.1 \pm 1.3 \mu\text{mol min}^{-1}$  at 95%  $O_2$  saturation to  $12.0 \pm 1.2$  and  $8.8 \pm 0.9 \mu\text{mol min}^{-1}$  in the 71.3% and 47.5%  $O_2$  saturation, respectively. The correspondence between the  $O_2$  saturation and the measured  $O_2$  concentration in the perfusate confirmed the appropriateness of the experimental conditions. As the  $O_2$  supply volume decreased, the  $m\dot{V}O_2$  in resting muscle decreased gradually (Table 1). Even though  $S_{mb}O_2$ , and  $P_{mb}O_2$  also decrease, the measurements could not detect a significant change in the estimated  $O_2$  gradient as reflected in  $(P_{cap}O_2 - P_{mb}O_2)$ , and did not reveal any significant alteration. Under all hypoxia conditions, the lactate to pyruvate ratio (L/P) showed no increase (Table 1).

Relative to the resting  $m\dot{V}O_2$ , muscle contracting at a similar tension (77–83 g) increased  $m\dot{V}O_2$  under all  $O_2$

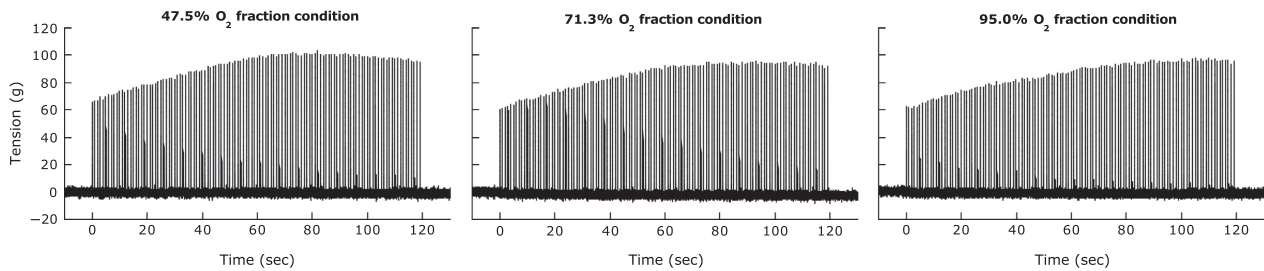
**Table 1.** Muscle oxygen consumption and intracellular  $O_2$  parameter at rest during hindlimb perfusion with different  $O_2$  fraction.

Parameter	Unit	$O_2$ fraction in perfusate		
		47.5%	71.3%	95.0%
Inflow $PO_2$	mmHg	$291.1 \pm 37.4^{12}$	$399.1 \pm 48.0^1$	$566.9 \pm 53.7$
$[O_2]$ in perfusate	$\mu\text{mol/L}$	$18.0 \pm 2.1^{12}$	$24.5 \pm 2.7^1$	$35.1 \pm 3.0$
Outflow $PO_2$	mmHg	$112.3 \pm 20.7^{12}$	$170.5 \pm 31.8^1$	$291.1 \pm 37.4$
Relative outflow $PO_2$		$0.41 \pm 0.08^{12}$	$0.63 \pm 0.12^1$	$1.00 \pm 0.15$
Estimated $P_{cap}O_2$	mmHg	$12.4 \pm 2.3^{12}$	$18.8 \pm 3.5^1$	$30.0 \pm 4.6$
$m\dot{V}O_2$	$\mu\text{mol g}^{-1} \text{min}^{-1}$	$0.34 \pm 0.05^{12}$	$0.43 \pm 0.07^1$	$0.55 \pm 0.12$
$S_{mb}O_2$	%	$55.0 \pm 7.9^{12}$	$74.1 \pm 11.7^1$	$90.0 \pm 0.1$
$P_{mb}O_2$	mmHg	$3.1 \pm 0.9^{12}$	$8.5 \pm 4.6^1$	$21.7 \pm 0.2$
Intracellular $[O_2]$	$\mu\text{mol/L}$	$4.1 \pm 1.2^{12}$	$11.5 \pm 6.2^1$	$29.3 \pm 0.3$
$P_{cap}O_2 - P_{mb}O_2$	mmHg	$9.3 \pm 3.0$	$10.3 \pm 5.2$	$8.3 \pm 4.5$
L/P		$19.6 \pm 3.0$	$17.8 \pm 2.3$	$18.3 \pm 2.0$

Values are mean  $\pm$  SD ( $n = 5$  in each condition). Inflow  $PO_2$ , oxygen tension before perfusion of the hindlimb;  $[O_2]$  in perfusate,  $O_2$  concentration in perfusate; Outflow  $PO_2$ , oxygen tension after perfusion of the hindlimb; Relative outflow  $PO_2$ , relative value of outflow  $PO_2$  based on the outflow  $PO_2$  value at 95.0%  $O_2$  fraction; Estimated  $P_{cap}O_2$ , estimated microvasucular oxygen tension based on 30 mmHg of  $P_{cap}O_2$  at 95.0%  $O_2$  fraction.  $m\dot{V}O_2$ , muscle oxygen consumption;  $S_{mb}O_2$ , intracellular  $O_2$  myoglobin saturation;  $P_{mb}O_2$ : intracellular  $O_2$  tension equilibrated with myoglobin  $O_2$  saturation; Intracellular  $[O_2]$ , intracellular  $O_2$  concentration;  $P_{cap}O_2 - P_{mb}O_2$ , the difference in oxygen tension between  $P_{cap}O_2 - P_{mb}O_2$ ; L/P, lactate to pyruvate ratio measured in effluent perfusate.

<sup>1</sup> $P < 0.05$  versus 95.0% condition

<sup>2</sup> $P < 0.05$  versus 71.3% condition.



**Figure 1.** Representative muscle tension generation during muscle contraction for 120 sec under each  $O_2$  fraction conditions. Maximal twitch muscle contractions were elicited every 1 sec (1 Hz) by stimulating sciatic nerve. The time courses of the change in twitch tension at each  $O_2$  fraction condition are shown. No sign of fatigue was observed during muscle contraction regardless of the  $O_2$  fraction conditions.

supply conditions. The representative time course of the change in twitch tension at each  $O_2$  fraction condition was shown in Figure 1. However, the largest increase occurred at 95%  $O_2$ , where the  $\Delta m\dot{V}O_2$  rose by  $0.28 \mu\text{mol g}^{-1} \text{min}^{-1}$ . At 47.5% and 71.3%  $O_2$  saturation,  $\Delta m\dot{V}O_2$  rose only by 0.11 and  $0.16 \mu\text{mol}$

$\text{g}^{-1} \text{min}^{-1}$ , respectively. Even though  $m\dot{V}O_2$  increased under hypoxia conditions, it increased much less than muscle under normoxic condition (Table 2).

In contrast, L/P increased with declining  $O_2$  supply. L/P increased significantly higher at 47.5%  $O_2$  ( $3.6 \pm 3.4$ ) than at 95.0%  $O_2$  ( $1.8 \pm 1.0$ ). At 95.0%  $O_2$  the muscle

**Table 2.** Muscle oxygen consumption and intracellular  $O_2$  parameter during muscle contraction during hindlimb perfusion with different  $O_2$  fraction.

Parameter	Unit	$O_2$ fraction in perfusate		
		47.5%	71.3%	95.0%
Muscle tension	g	$76.7 \pm 15.2$	$81.5 \pm 8.9$	$82.8 \pm 12.9$
$m\dot{V}O_2$	$\mu\text{mol g}^{-1} \text{min}^{-1}$	$0.45 \pm 0.08^{1\ddagger}$	$0.60 \pm 0.07^1$	$0.87 \pm 0.15$
$\Delta m\dot{V}O_2$	$\mu\text{mol g}^{-1} \text{min}^{-1}$	$0.11 \pm 0.04^{12}$	$0.16 \pm 0.07^1$	$0.28 \pm 0.05$
Outflow $PO_2$	mmHg	$104.9 \pm 20.6^{1\ddagger}$	$158.7 \pm 30.1^1$	$252.2 \pm 41.1$
Relative outflow $PO_2$		$0.42 \pm 0.08^{12}$	$0.63 \pm 0.12^1$	$1.00 \pm 0.15$
Estimated $P_{\text{cap}O_2}$	mmHg	$12.5 \pm 2.4^{12}$	$18.9 \pm 3.6^1$	$30.0 \pm 4.9$
$S_{\text{mb}O_2}$ kinetics				
Steady-state value	%	$12.3 \pm 8.0^{12}$	$42.0 \pm 16.6^1$	$68.7 \pm 3.0$
AP	%	$-42.7 \pm 7.5^1$	$-32.1 \pm 8.8$	$-21.4 \pm 3.0$
MRT	s	$39.4 \pm 7.8$	$37.3 \pm 8.0$	$42.4 \pm 11.8$
$_{0.63}AP/MRT$	$\% \text{ s}^{-1}$	$-0.69 \pm 0.10^1$	$-0.57 \pm 0.23^1$	$-0.34 \pm 0.11$
$P_{\text{mb}O_2}$ kinetics				
Steady-state Value	mmHg	$0.4 \pm 0.3^{12}$	$2.1 \pm 1.2^1$	$5.5 \pm 0.9$
AP	mmHg	$-2.7 \pm 0.8^1$	$-6.5 \pm 3.8^1$	$-16.2 \pm 0.9$
MRT	sec	$30.6 \pm 5.4$	$35.3 \pm 8.2$	$33.4 \pm 11.7$
$_{0.63}AP/MRT$	$\text{mmHg sec}^{-1}$	$-0.03 \pm 0.07^1$	$-0.13 \pm 0.18^1$	$-0.41 \pm 0.14$
Intracellular $[O_2]$	$\mu\text{mol/L}$	$0.5 \pm 0.4^{12}$	$2.8 \pm 1.7^1$	$7.4 \pm 1.2$
$P_{\text{cap}O_2} - P_{\text{mb}O_2}$	mmHg	$12.1 \pm 2.5^{12}$	$16.8 \pm 3.8^1$	$24.5 \pm 2.5$
$\Delta L/P$		$3.6 \pm 3.4^1$	$2.5 \pm 1.7$	$1.8 \pm 1.0$

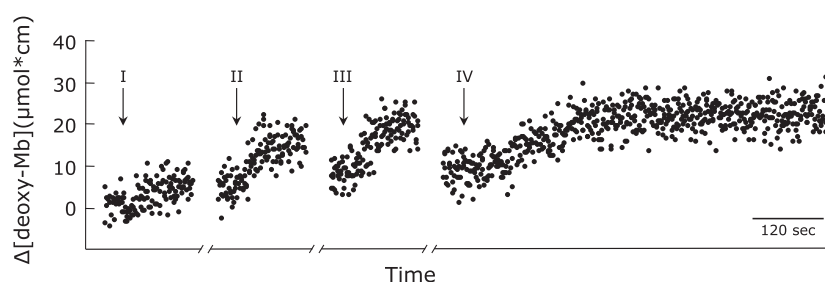
Values are mean  $\pm$  SD ( $n = 5$  in each condition).  $m\dot{V}O_2$ , muscle oxygen consumption;  $\Delta m\dot{V}O_2$ , the net increase in  $m\dot{V}O_2$  due to muscle contraction; Outflow  $PO_2$ : oxygen tension after perfusion of the hindlimb, Relative outflow  $PO_2$ , relative value of outflow  $PO_2$  based on the outflow  $PO_2$  value at 95.0%  $O_2$  fraction; Estimated  $P_{\text{cap}O_2}$ , estimated microvascular oxygen tension based on 30 mmHg of  $P_{\text{cap}O_2}$  at 95.0%  $O_2$  fraction;  $S_{\text{mb}O_2}$ , intracellular  $O_2$  myoglobin saturation; AP is the amplitude between BL (baseline) and the steady-state value during the exponential component; MRT is the time required to reach 63% of AP from the onset of muscle contraction.  $_{0.63}AP/MRT$  is calculated by dividing  $_{0.63}AP$  by MRT;  $P_{\text{mb}O_2}$ , intracellular  $O_2$  tension equilibrated with myoglobin  $O_2$  saturation; Intracellular  $[O_2]$ , intracellular  $O_2$  concentration;  $P_{\text{cap}O_2} - P_{\text{mb}O_2}$ , the difference in oxygen tension between  $P_{\text{cap}O_2} - P_{\text{mb}O_2}$ ;  $\Delta L/P$ , the net increase in lactate to pyruvate ratio measured in effluent perfusate.

<sup>1</sup> $P < 0.05$  versus 95.0% condition.

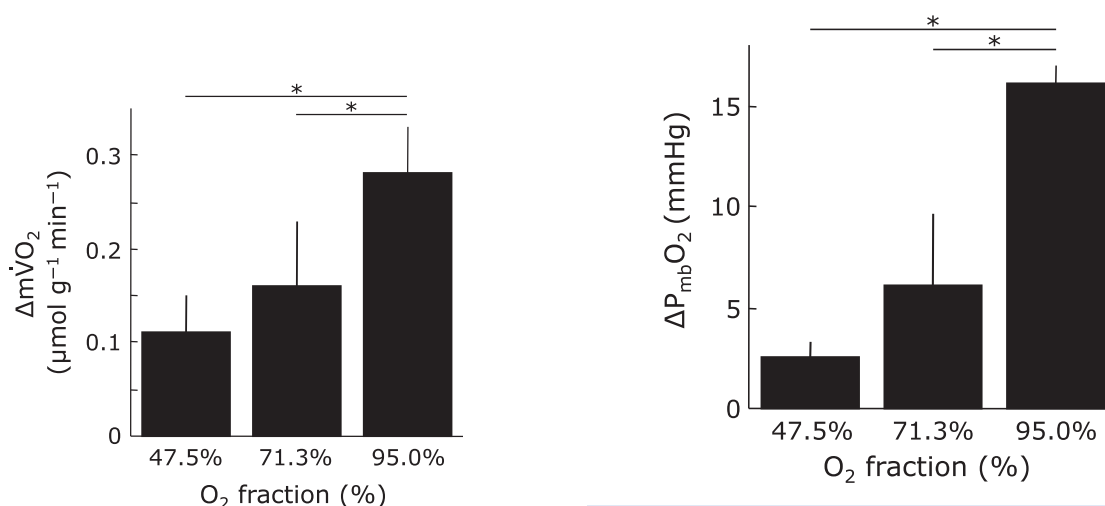
<sup>2</sup> $P < 0.05$  versus 71.3% condition.

contraction causes no significant change in the L/P ratio, consistent with previous observations (Takakura et al. 2010).

During muscle contraction, the steady  $S_{mb}O_2$  and  $P_{mb}O_2$  still decreased with decreasing oxygen supply. However, the  $S_{mb}O_2$  and  $P_{mb}O_2$  kinetics did not show a significant difference (Table 2). Figure 2 shows representative  $\Delta[\text{deoxy-Mb}]$  kinetics during different levels of  $O_2$  delivery conditions and during anoxic perfusion, as assessed by NIRS. The roman numerals I, II and III represent the NIRS signal response to 1 Hz maximal twitch contractions at 95.0%, 71.3% and 47.5%  $O_2$  fraction condition, respectively. In protocol IV, the noncontracting muscle received a perfusate equilibrated with 95%  $N_2 + 5\% CO_2$ .



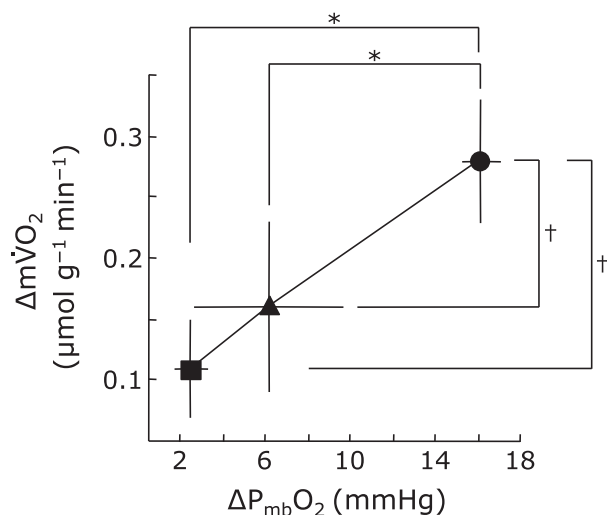
**Figure 2.** Representative time courses of the  $\Delta[\text{deoxy-Mb}]$  NIRS signals during muscle contraction under different  $O_2$  fraction conditions (I–III) and during anoxia perfusion (IV). The arrows indicate the onset of muscle contraction (I–III) and anoxic perfusion (95% $N_2 + 5\%CO_2$ ; IV). Protocols I, II and III show the  $\Delta[\text{deoxy-Mb}]$  signals during maximal twitch contraction under 95.0%, 71.3% and 47.5%  $O_2$  fraction conditions in the Hb-free perfusion model. The  $\Delta[\text{deoxy-Mb}]$  signals changed immediately at the onset of contraction and reached the steady state. As protocol IV was conducted after finishing protocol III, desaturated Mb already existed at a certain level at rest before perfusing anoxia buffer.



**Figure 3.** Change in net increase in muscle  $O_2$  consumption ( $\Delta m\dot{V}O_2$ ) due to muscle contraction for each  $O_2$  fraction. The  $\Delta m\dot{V}O_2$  due to muscle contraction decreased with the decrease in the  $O_2$  supply volume.  $\Delta m\dot{V}O_2$ : net increase in muscle oxygen consumption due to contraction. Values are expressed as means  $\pm$  SD ( $n = 5$ ). \* $P < 0.05$  vs. 95.0%  $O_2$  fraction.

Figure 3 shows the net increase in  $m\dot{V}O_2$  ( $\Delta m\dot{V}O_2$ ) relative to its resting value during muscle contraction in each  $O_2$  fraction condition. The  $\Delta m\dot{V}O_2$  due to muscle contraction ( $0.11 \pm 0.04$ ,  $0.16 \pm 0.07$ , and  $0.28 \pm 0.05 \mu\text{mol g}^{-1} \text{min}^{-1}$  at 47.5%, 71.3%, and 95%  $O_2$  fraction) decreased progressively with hypoxia. Under resting conditions, the measurements indicate  $P_{mb}O_2$  values of 3.1, 8.5, and 21.7 mmHg at 47.5, 71.3, and 95%  $O_2$ . With muscle contraction, the  $P_{mb}O_2$  values decrease correspondingly to 0.4, 2.1, and 5.5 mmHg. Figure 4 shows then net decrease in  $P_{mb}O_2$  ( $\Delta P_{mb}O_2$ ) due to muscle contraction ( $2.50 \pm 0.81$ ,  $6.12 \pm 3.52$ , and  $16.10 \pm 0.87$  mmHg in 47.5, 71.3, and 95%  $O_2$  fraction conditions, respectively). Even though  $P_{mb}O_2$  decreases under all

**Figure 4.** Net decrease in intracellular oxygen tension ( $\Delta P_{mb}O_2$ ) due to muscle contraction for each  $O_2$  fraction. The  $\Delta m\dot{V}O_2$  due to muscle contraction decreased with the decrease in the  $O_2$  supply volume.  $P_{mb}O_2$  during contraction, hatched bars: net decrease in  $P_{mb}O_2$ .  $\Delta P_{mb}O_2$ : net decrease in intracellular oxygen tension equilibrated with  $O_2$  saturation myoglobin. Values are expressed as means  $\pm$  SD ( $n = 5$ ). \* $P < 0.05$  vs. 95.0%  $O_2$  fraction.



**Figure 5.** Relationship between net decrease in intracellular oxygen tension ( $\Delta P_{mb}O_2$ ) and net increase in muscle oxygen consumption ( $\Delta m\dot{V}O_2$ ) during muscle contraction. The  $\Delta P_{mb}O_2$  and  $\Delta m\dot{V}O_2$  gradually decreased as the  $O_2$  supply volume decreased. The relationship between the  $\Delta P_{mb}O_2$  and the  $\Delta m\dot{V}O_2$  was represented with a line graph.  $\Delta m\dot{V}O_2$ : net increase in muscle oxygen consumption due to contraction.  $\Delta P_{mb}O_2$ : net decrease in intracellular oxygen tension equilibrated with  $O_2$  saturation myoglobin. Each data point represents a mean  $\pm$  SD.  $n = 5 \times 3$  points. \* $P < 0.05$  for  $\Delta m\dot{V}O_2$  parameter. † $P < 0.05$  for  $\Delta P_{mb}O_2$  parameter.

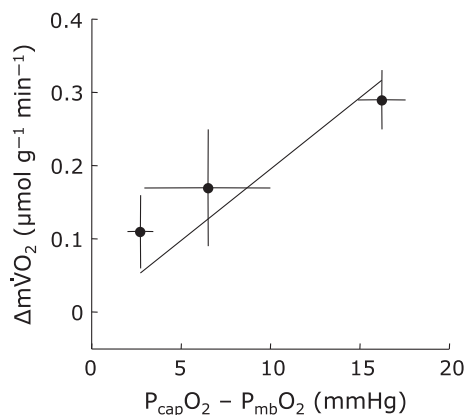
exercise conditions, the value changes the most at 95%  $O_2$ . Figure 5 shows the relationship between the  $\Delta m\dot{V}O_2$  and the  $\Delta P_{mb}O_2$  in each  $O_2$  fraction condition. During muscle contraction, the decrease in oxygen supply caused a decrease in the  $\Delta P_{mb}O_2$ , which led to a decrease in the  $\Delta m\dot{V}O_2$ .

The linear relationship between  $\Delta m\dot{V}O_2$  and  $\Delta P_{mb}O_2$  suggests that the  $O_2$  gradient as reflected in ( $P_{cap}O_2 - P_{mb}O_2$ ) has changed. Using an estimate  $P_{cap}O_2$ , the analysis shows that indeed  $\Delta m\dot{V}O_2$  changes linearly with ( $P_{cap}O_2 - P_{mb}O_2$ ) (Fig. 6).

## Discussion

### Intracellular $O_2$ environment under hypoxic conditions

As oxygen delivery decreases, the  $P_{mb}O_2$  at rest decreased correspondingly from 21.7 to 8.5 to 3.1 mmHg. The  $m\dot{V}O_2$  decreases correspondingly from 0.55 to 0.43 to 0.34  $\mu\text{mol g}^{-1} \text{min}^{-1}$ . It might appear that the decreasing  $O_2$  supply leads consequently and directly to the decreasing  $m\dot{V}O_2$ . Yet in normoxic muscle the decreasing intracellular  $O_2$  leads to an increasing  $m\dot{V}O_2$ , which implies a critical role for the  $O_2$  gradient instead of the  $O_2$  supply



**Figure 6.** Relationship between delta change in muscle oxygen consumption ( $\Delta m\dot{V}O_2$ ) and estimated  $O_2$  gradient between microvascular oxygen tension ( $P_{cap}O_2$ ) and intracellular oxygen tension ( $P_{mb}O_2$ ) under exercising condition. Delta change in  $m\dot{V}O_2$  due to muscle contraction increased linearly as a function of estimated  $O_2$  gradient ( $P_{cap}O_2 - P_{mb}O_2$ ). Regression line is based on mean values ( $m\dot{V}O_2 = 0.020 \times (P_{cap}O_2 - P_{mb}O_2)$ ,  $R^2 = 0.99$ ,  $n = 5$  in each point). Each data point represents a mean  $\pm$  SD.

alone. An analysis of the  $O_2$  gradient as reflected in ( $P_{cap}O_2 - P_{mb}O_2$ ) shows that despite the decreasing intracellular  $O_2$ , the  $O_2$  gradient appears to have increased during hypoxia. The low  $m\dot{V}O_2$  in resting muscle most likely creates a shallow gradient, which obscures measurement accuracy. Nevertheless, the constant L/P ratio would argue that the  $O_2$  supply and  $m\dot{V}O_2$  have not compromised oxidative metabolism, which would require glycolysis to compensate for any energy deficit. Consistent with a previous findings, the decreasing  $O_2$  supply did not affect the low  $m\dot{V}O_2$  at rest (Shiota and Sugano 1986).

However, when muscle begins to contract,  $m\dot{V}O_2$  rose and the  $P_{mb}O_2$  decreased further from the resting levels. At 47.5%  $O_2$ , the  $P_{mb}O_2$  drops below the critical  $PO_2$  level that limits oxidative phosphorylation in mitochondria (1.5 mmHg) (Kreutzer et al. 1992). L/P rises more at 47.5%  $O_2$  than at 95.0%  $O_2$ . However, the drop in  $P_{mb}O_2$  also expands the  $O_2$  gradient under all  $O_2$  saturation conditions during muscle contraction. But the widening  $O_2$  gradient does not sufficiently enhance the  $O_2$  flux to meet the cell's oxidative needs. Anaerobic glycolysis commences to supplement the energy demand, especially as the buffer  $PO_2$  drops to 47%.

These findings indicate that even under hypoxia  $m\dot{V}O_2$  rises during contraction. Given the same  $O_2$  saturation conditions, the rise in  $m\dot{V}O_2$  required an increase in  $DO_2$  or ( $P_{cap}O_2 - P_{mb}O_2$ ) as shown in equation (Richardson et al. 1995; Takakura et al. 2010). Even though the  $P_{mb}O_2$  decreases, the  $O_2$  gradient has widened to increase the  $O_2$  flux to balance out the  $O_2$  supply and demand. A decreasing  $P_{mb}O_2$  with a rising  $m\dot{V}O_2$  agree with the



previously reported observations (Molé et al. 1999; Takakura et al. 2010). In contrast, Richardson et al. (1995) reported that under normoxic or hypoxic condition, the  $P_{mb}O_2$  did not decrease proportionally to muscle contraction, once the contraction has exceeded about 40% of maximum work exercise workload. Even under hypoxic condition, the Mb desaturation level does increase as the leg  $\dot{V}O_2$  rose to its maximum level (Richardson et al. 1995). In addition, the  $P_{mb}O_2$  reaches a low level (<5 mmHg) in the skeletal muscle, even when moderate levels of work were performed (Molé et al. 1999; Chung et al. 2005; Takakura et al. 2010). These findings have led researchers to ignore the  $P_{mb}O_2$  variable from the formula for the calculation of the amount of  $O_2$  consumption in the muscle tissue in hypoxic environments (Gonzalez et al. 2006).

However, probably due to a signal-to-noise ratio limitation, Richardson et al. (2006) could not detect the  $P_{mb}O_2$  at rest in hypoxic muscle. As a result, the study could not determine the true magnitude of the change in the intracellular oxygen environment during exercise. Our study's unique experimental model, with the subjects placed under Hb-free perfusion, suggests that changes in the intracellular oxygen environment and the  $O_2$  gradient can contribute to the  $\Delta m\dot{V}O_2$  during hypoxia. In addition, the  $P_{mb}O_2$  at the resting muscle did not reach a nadir as a result of the hypoxia. Instead, the  $P_{mb}O_2$  can decrease further during the muscle contraction even in the hypoxic conditions.

### Change in $P_{mb}O_2$ from muscle contraction modulating change in $m\dot{V}O_2$ under Hb-Free perfusion

The study investigated whether the  $m\dot{V}O_2$  during muscle contraction in various oxygen concentration conditions depend on the changes in the  $P_{mb}O_2$  or the  $O_2$  gradient. Because the oxygen delivery remained constant at any muscle contraction condition in the perfusion model at a constant flow, the decrease in  $P_{mb}O_2$  due to muscle contraction widen the  $O_2$  gradient between the microvasculature and myocyte as reported in the our previous study (Takakura et al. 2010). This change contributes the increase in  $m\dot{V}O_2$  due to muscle contraction. This interpretation is proven by the following equation;

$$m\dot{V}O_2 = kDO_2 \times (P_{cap}O_2 - P_{mb}O_2)$$

Because  $kDO_2$  does not significantly contribute to the increase in  $m\dot{V}O_2$  due to muscle contraction in the constant-flow hindlimb perfusion model, the  $m\dot{V}O_2$  cannot increase unless the  $O_2$  gradient expands by decrease in  $P_{mb}O_2$  in our previous studies (Takakura et al. 2010,

2015). In the present study, the results have confirmed the hypothesis that the delta change in  $P_{mb}O_2$  and in the  $O_2$  gradient contributes to delta increase in  $m\dot{V}O_2$  during muscle contraction. Our results show that under all oxygenation conditions,  $m\dot{V}O_2$  rises but  $P_{mb}O_2$  continues to decline by muscle contraction between 77% and 88% of maximal voluntary contraction (MVC). However, rise in the  $m\dot{V}O_2$  and  $O_2$  gradient expansion under hypoxia conditions are much less than the corresponding changes under normoxic conditions. The observation then agree with the studies by Molé et al. (1999) and Takakura et al. (2010), which indicate the progressive expansion of the  $O_2$  gradient between the  $P_{cap}O_2$  and the  $P_{mb}O_2$  during muscle contraction contribute to the  $O_2$  flux supporting the rising  $m\dot{V}O_2$ . No  $P_{mb}O_2$  plateau even under hypoxia condition seems apparent at MVC well above 40%.

Moreover, a changing  $m\dot{V}O_2$  in constant flow model also supports a  $P_{mb}O_2$  contribution. In constant flow perfusion, a constant flow-induced vasodilatation occurs at a given flow rate. As a consequence, the model maintains a constant diffusion conductance throughout the perfusion (Hepple et al. 2003). Consequently, any change in  $\Delta m\dot{V}O_2$  must have a contribution from  $P_{mb}O_2$ . Therefore, the mechanism behind the  $m\dot{V}O_2$  in hypoxic environments, includes then a contribution  $P_{mb}O_2$  (Molé et al. 1999; Takakura et al. 2010).

The mechanism of the oxygen transport to the mitochondria in the myocytes is dependent on the Mb-mediated oxygen transport or the dissolved  $O_2$  flux. The contribution from the Mb-mediated oxygen transport increases with decreasing  $P_{mb}O_2$ . Below the equipoise diffusion  $PO_2$  value (1.77 mmHg), 50% of the total oxygen transport to the mitochondria stems from the Mb-mediated oxygen transport (Lin et al. 2007). The  $P_{mb}O_2$  during muscle contraction in the 47.5%  $O_2$  fraction condition was  $0.4 \pm 0.3$  mmHg. As this was below the equipoise diffusion  $PO_2$  value, the Mb-mediated oxygen transport mechanism will dominate. In addition, any increase in Mb concentration will raise the equipoise  $PO_2$  (Lin et al. 2007; Takakura et al. 2015). Because people acclimated to high altitudes often have a high concentration in Mb, muscle contraction under hypoxic conditions in these people may also benefit from Mb-mediated transport (Reynafarje 1962; Reynafarje and Morrison 1962).

Van der Laarse et al. (2005) have examined about the value of the diffusion coefficient for oxygen from extracellular region in muscle. The diffusion coefficient is important because it is a determinant of the extracellular oxygen tension at which the core of muscle fibers becomes anoxic ( $PO_{2crit}$ ). According to Hill (1965),  $PO_{2crit}$  at the maximum rate of oxygen consumption ( $\dot{V}O_{2max}$ ; in  $nmol\ mm^{-3}\ sec^{-1}$ ) is given by

$$PO_{2crit} = \dot{V}O_{2max} \times CSA / 4\pi D\alpha$$

where CSA is the cross-sectional area of the cell ( $mm^2$ ),  $D$  is the diffusion coefficient for oxygen in the muscle cell ( $mm^2/sec$ ), and  $\alpha$  is the solubility of oxygen in muscle cell ( $mmol/L$  per  $mmHg$ ).  $D\alpha$  is known as Krogh's diffusion coefficient.  $D\alpha$  seems to depend on fat content, extracellular space, and unknown factors (Jones and Kennedy 1986; Dutta and Popel 1995; Baranov et al. 2000). Indeed,  $D\alpha$  increased with enlargement of extracellular space in the preparation (van der Laarse et al. 2005). However, the results of the previous study indicated that Hill's model for oxygen diffusion is valid for single muscle fibers without myoglobin and a fairly homogeneous mitochondrial distribution consuming oxygen at the maximum rate. Because above Hill's equation is based on the following assumption: (1) the cross section of the fiber is a circle, and oxygen diffuses in the radial direction only; (2)  $\dot{V}O_2$  is distributed homogeneously in the cells; (3)  $\dot{V}O_2$  by mitochondria is independent of local intracellular  $PO_2$ ; and (4) myoglobin-facilitated oxygen diffusion is negligible, the role of Mb was not taken account of above  $D\alpha$ . We have conducted the maximal twitch contraction under three  $O_2$  fraction conditions to the same individual in the present perfusion model. Moreover, as the order of the three  $O_2$  condition was randomized and no sign of edema in the hindlimb was seen at the given flow rate, change in extracellular space would be almost none. Thus,  $D\alpha$  in the above equation would not be affected throughout the perfusion experiment in this study. On the other hand, others and we reported the effect of Mb on the intracellular  $O_2$  diffusion to the mitochondria (Lin et al. 2007; Takakura et al. 2010, 2015). As mentioned above, Lin et al. (2007) reported that 50% of the total oxygen transport to the mitochondria stems from the Mb-mediated oxygen transport below the equipoise diffusion  $PO_2$  value (1.77  $mmHg$ ). Also, we reported that decrease in  $P_{mb}O_2$  directly contribute the expansion of the  $O_2$  gradient to lead the increased  $m\dot{V}O_2$  (Takakura et al. 2010, 2015). As for a key factor regulating  $O_2$  diffusion to intracellular mitochondria, the change in  $P_{mb}O_2$  might be one of candidates, because the change in  $P_{mb}O_2$  affects  $O_2$  gradient, Mb-mediated  $O_2$  transport and mitochondria respiratory.

## Conclusion

This study investigated the effects of reduced oxygen supply on the  $P_{mb}O_2$  at rest and during muscle contraction, as well as the effect of the  $\Delta P_{mb}O_2$  on the  $\Delta m\dot{V}O_2$  during muscle contraction. Our findings showed that the resting  $P_{mb}O_2$  decreases with the decrease in oxygen supply. However, the decrease in  $P_{mb}O_2$  expands the  $O_2$  gradient,

which then supports the rising  $\Delta m\dot{V}O_2$  during muscle contraction even under hypoxic conditions. The results suggest that the  $\Delta P_{mb}O_2$  is a key determinant factor of the  $\Delta m\dot{V}O_2$ .

## Conflict of interest

There is no conflict of interest for this study.

## References

- Baranov, V. I., V. M. Belichenko, and C. A. Shoshenko. 2000. Oxygen diffusion coefficient in isolated chicken red and white skeletal muscle fibers in ontogenesis. *Microvasc. Res.* 60:168–176.
- Bassett, D. R., and E. T. Howley. 2000. Limiting factors for maximum oxygen uptake and determinants of endurance performance. *Med. Sci. Sports Exerc.* 32:70–84.
- Behnke, B. J., C. A. Kindig, T. I. Musch, S. Koga, and D. C. Poole. 2001. Dynamics of microvascular oxygen pressure across the rest-exercise transition in rat skeletal muscle. *Respir. Physiol.* 126:53–63.
- Box, G. E. P., W. G. Hunter, and J. S. Hunter. 1978. *Statistics for Experimenters: An Introduction to Design, Data Analysis, and Model Building.* John Wiley & Sons, New York.
- Calbet, J. A., R. Boushel, G. Radegran, H. Sondergaard, P. D. Wagner, and B. Saltin. 2003. Why is  $VO_2$  max after altitude acclimatization still reduced despite normalization of arterial  $O_2$  content? *Am. J. Physiol. Regul. Integr. Comp. Physiol.* 284:R304–R316.
- Calbet, J. A., G. Radegran, R. Boushel, and B. Saltin. 2009. On the mechanisms that limit oxygen uptake during exercise in acute and chronic hypoxia: role of muscle mass. *J. Physiol.* 587:477–490.
- Chung, Y., P. A. Molé, N. Sailasuta, T. K. Tran, R. Hurd, and T. Jue. 2005. Control of respiration and bioenergetics during muscle contraction. *Am. J. Physiol. Cell Physiol.* 288:C730–C738.
- Dutta, A., and A. S. Popel. 1995. A theoretical analysis of intracellular oxygen diffusion. *J. Theor. Biol.* 176:433–445.
- Ferguson, S. K., C. T. Holdsworth, J. L. Wright, A. J. Fees, J. D. Allen, A. M. Jones, et al. 2015. Microvascular oxygen pressures in muscles comprised of different fiber types: Impact of dietary nitrate supplementation. *Nitric Oxide* 48:38–43.
- Gonzalez, N. C., S. D. Kirkton, R. A. Howlett, S. L. Britton, L. G. Koch, H. E. Wagner, et al. 2006. Continued divergence in  $VO_{2max}$  of rats artificially selected for running endurance is mediated by greater convective blood  $O_2$  delivery. *J. Appl. Physiol.* (1985) 101:1288–1296.
- Hepple, R. T., D. J. Krause, J. L. Hagen, and C. C. Jackson. 2003.  $VO_{2max}$  is unaffected by altering the temporal pattern of stimulation frequency in rat hindlimb *in situ*. *J. Appl. Physiol.* 95:705–711.

- Hill, A. V. 1965. *Trails and Trailas in Physiology*. Edward Arnold, London.
- Howlett, R. A., S. D. Kirkton, N. C. Gonzalez, H. E. Wagner, S. L. Britton, L. G. Koch, et al. 2009. Peripheral oxygen transport and utilization in rats following continued selective breeding for endurance running capacity. *J. Appl. Physiol.* (1985) 106:1819–1825.
- Jones, D. P., and F. G. Kennedy. 1986. Analysis of intracellular oxygenation of isolated adult cardiac myocytes. *Am. J. Physiol.* 250:C384–C390.
- Kano, Y., S. Miura, H. Eshima, O. Ezaki, and D. C. Poole. 2014. The effects of PGC-1 $\alpha$  on control of microvascular  $PO_2$  kinetics following onset of muscle contractions. *J. Appl. Physiol.* (1985) 117:163–170.
- Kreutzer, U., D. S. Wang, and T. Jue. 1992. Observing the  $^1H$  NMR signal of the myoglobin Val-E11 in myocardium: an index of cellular oxygenation. *Proc. Natl Acad. Sci. USA* 89:4731–4733.
- van der Laarse, W. J., A. L. des Tombe, A. L. van Beek-Harmsen, M. B. Lee-de Groot, and R. T. Jaspers. 2005. Krogh's diffusion coefficient for oxygen in isolated *Xenopus* skeletal muscle fibers and rat myocardial trabeculae at maximum rates of oxygen consumption. *J. Appl. Physiol.* (1985) 99:2173–2180.
- Lin, P. C., U. Kreutzer, and T. Jue. 2007. Myoglobin translational diffusion in rat myocardium and its implication on intracellular oxygen transport. *J. Physiol.* 578:595–603.
- Lundby, C., J. A. Calbet, G. van Hall, B. Saltin, and M. Sander. 2004. Pulmonary gas exchange at maximal exercise in Danish lowlanders during 8 wk of acclimatization to 4,100 m and in high-altitude Aymara natives. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* 287:R1202–R1208.
- Masuda, K., H. Takakura, Y. Furuichi, S. Iwase, and T. Jue. 2010. NIRS measurement of  $O_2$  dynamics in contracting blood and buffer perfused hindlimb muscle. *Adv. Exp. Med. Biol.* 662:323–328.
- McCullough, D. J., R. T. III Davis, J. M. II Dominguez, J. N. Stabley, C. S. Bruells, and B. J. Behnke. 2011. Effects of aging and exercise training on spinotrapezius muscle microvascular  $PO_2$  dynamics and vasomotor control. *J. Appl. Physiol.* (1985) 110:695–704.
- Molé, P. A., Y. Chung, T. K. Tran, N. Sailasuta, R. Hurd, and T. Jue. 1999. Myoglobin desaturation with exercise intensity in human gastrocnemius muscle. *Am. J. Physiol.* 277:R173–R180.
- Philip, L. A., and S. D. Dorothy. 1971. *Respiration and Circulation*. Federation of American Societies for Experimental Biology, Bethesda.
- Reynafarje, B. 1962. Myoglobin content and enzymatic activity of muscle and altitude adaptation. *J. Appl. Physiol.* 17:301–305.
- Reynafarje, B., and P. Morrison. 1962. Myoglobin levels in some tissues from wild Peruvian rodents native to high altitude. *J. Biol. Chem.* 237:2861–2864.
- Richardson, R. S., E. A. Noyszewski, K. F. Kendrick, J. S. Leigh, and P. D. Wagner. 1995. Myoglobin  $O_2$  desaturation during exercise. Evidence of limited  $O_2$  transport. *J. Clin. Invest.* 96:1916–1926.
- Richardson, R. S., S. Duteil, C. Wary, D. W. Wray, J. Hoff, and P. G. Carlier. 2006. Human skeletal muscle intracellular oxygenation: the impact of ambient oxygen availability. *J. Physiol.* 571:415–424.
- Schenkman, K. A., D. R. Marble, D. H. Burns, and E. O. Feigl. 1997. Myoglobin oxygen dissociation by multiwavelength spectroscopy. *J. Appl. Physiol.* 82:86–92.
- Shiota, M., and T. Sugano. 1986. Characteristics of rat hindlimbs perfused with erythrocyte- and albumin-free medium. *Am. J. Physiol.* 251:C78–C84.
- Takakura, H., K. Masuda, T. Hashimoto, S. Iwase, and T. Jue. 2010. Quantification of myoglobin deoxygenation and intracellular partial pressure of  $O_2$  during muscle contraction during haemoglobin-free medium perfusion. *Exp. Physiol.* 95:630–640.
- Takakura, H., Y. Furuichi, T. Yamada, T. Jue, M. Ojino, T. Hashimoto, et al. 2015. Endurance training facilitates myoglobin desaturation during muscle contraction in rat skeletal muscle. *Sci. Rep.* 5:9403.