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Skeletal muscle phosphocreatine recovery in exercise-trained humans is dependent on O₂ availability

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Haseler, Luke J., Michael C. Hogan, and Russell S. Richardson. Skeletal muscle phosphocreatine recovery in exercise-trained humans is dependent on O₂ availability. *J. Appl. Physiol.* 86(6): 2013–2018, 1999.—In skeletal muscle, phosphocreatine (PCr) recovery from submaximal exercise has become a reliable and accepted measure of muscle oxidative capacity. During exercise, O₂ availability plays a role in determining maximal oxidative metabolism, but the relationship between O₂ availability and oxidative metabolism measured by ³¹P-magnetic resonance spectroscopy (MRS) during recovery from exercise has never been studied. We used ³¹P-MRS to study exercising human gastrocnemius muscle under conditions of varied fractions of inspired O₂ (F_IO₂) to test the hypothesis that varied O₂ availability modulates PCr recovery from submaximal exercise. Six male subjects performed three bouts of 5-min steady-state submaximal plantar flexion exercise followed by 5 min of recovery in a 1.5-T magnet while breathing three different F_IO₂ concentrations (0.10, 0.21, and 1.00). Under each F_IO₂ treatment, the PCr recovery time constants were significantly different, being longer in hypoxia [33.5 ± 4.1 s (SE)] and shorter in hyperoxia (20.0 ± 1.8 s) than in normoxia (25.0 ± 2.7 s) ($P \leq 0.05$). End-exercise pH was not significantly different among the three treatments (7.08 ± 0.01 for 0.10, 7.04 ± 0.01 for 0.21, and 7.04 ± 0.02 for 1.00). These results demonstrate that PCr recovery is significantly altered by F_IO₂ and suggest that, after submaximal exercise, PCr recovery, under normoxic conditions, is limited by O₂ availability.

oxidative capacity; mitochondria; intracellular oxygenation; 31-phosphorus-magnetic resonance spectroscopy; fraction of inspired oxygen

AFTER SUBMAXIMAL EXERCISE CONDITIONS in which the intracellular pH fall is not severe, resynthesis of phosphocreatine (PCr) occurs primarily by oxidative processes (3, 5, 17, 19). Under such conditions, the recovery of PCr is described by a monoexponential time course (23, 28, 40), and the time constant for PCr recovery (τ) has been shown to be independent of stimulation frequency, exercise intensity, and end-exercise levels of PCr (26, 40). Thus PCr recovery data are generally considered to be an important and robust measure of mitochondrial respiration that provide an index of skeletal muscle oxidative capacity (3, 17, 19).

Consequently, the measurement of PCr recovery has proven useful in identifying a range of skeletal muscle oxidative capacities. PCr recovery was slowed in clinically proven cases of mitochondrial myopathy (2, 8, 30)

and in chronic disease conditions such as cardiac failure that are known to result in reduced mitochondrial content and oxidative capacity (38–40). In contrast, PCr recovery was enhanced with endurance training in athletes (22, 26, 42), consistent with the increased mitochondrial content and activities of the enzymes associated with oxidative metabolism allowing a greater capacity for oxidative generation of ATP (6, 14, 24). Additionally, McCully et al. (27) have demonstrated a linear relationship between PCr recovery and citrate synthase activity in human skeletal muscle. More recently, Paganini et al. (29) demonstrated in rats that the rate constant for PCr recovery in skeletal muscle is linearly dependent on oxidative capacity as indicated by the mitochondrial marker enzyme citrate synthase. These authors concluded that PCr recovery measurements can be used as an index of relative oxidative capacity or mitochondrial content in muscle.

During exercise, O₂ availability has been well documented as both a modulator of muscle bioenergetics (10, 11) and a determinant of maximal oxidative capacity (32, 35). However, the role of O₂ availability, manipulated by the fraction of inspired O₂ (F_IO₂), in the determination of skeletal muscle oxidative metabolism assessed in recovery by ³¹P-magnetic resonance spectroscopy (MRS) has never been examined. Consequently, we studied the effect of F_IO₂ on PCr recovery in humans after submaximal plantar flexion exercise to test the hypothesis that increased O₂ availability would enhance PCr recovery, whereas decreased O₂ availability would slow PCr recovery, which would illustrate that, under normoxic conditions, trained skeletal muscle mitochondrial respiration during recovery from submaximal exercise is limited by O₂ availability.

METHODS

Subjects. Six healthy men aged 21–42 yr volunteered to participate in this study and gave written informed consent. The study was approved by the Human Subjects Committee of the University of California, San Diego. Subjects were all healthy and active, ranging from moderately to well-trained athletes. The subjects refrained from strenuous exercise for 24 h before data collection.

Exercise protocol. Subjects were familiarized with plantar flexion exercise in the confines of a whole body magnetic resonance imaging system. At this time, ~60% of maximum work rate was determined for each subject. Subjects performed constant-load submaximal plantar flexion at this intensity (range 7–8 W) at a frequency of 1 contraction/s (keeping time with an electronic metronome) while lying supine in a superconducting 1.5-T magnet. Throughout each exercise bout, subjects breathed through a low-resistance two-way breathing valve (model 2700, Hans-Rudolph, Kansas City, MO), and end-tidal O₂ and CO₂ were sampled

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continuously, allowing the calculation of arterial O_2 saturation (assuming no alveolar to arterial PO_2 gradient and no significant metabolic acidosis). Heart rate was monitored continuously throughout the experiment with a finger probe (Omni-Trak, In Vivo Research). In each $F_{I_{O_2}}$ (0.1, 0.21, and 1.00), subjects performed a 5-min warm-up period followed by 5 min of rest, and then they performed 5 min of exercise followed by 5 min of recovery. Subjects were allowed 40 min of rest between each complete exercise bout. The order of the three treatments was varied to allow all six possible orders to be performed once and to minimize any ordering effects. Throughout the study subjects were unaware of the treatment order.

³¹P-MRS. MRS was performed by using a clinical 1.5-T General Electric Signa system (version 4.8) operating at 25.86 MHz for ³¹P. ³¹P-MRS data were acquired with a transmit/receive surface coil (diameters 20 and 10 cm, respectively) placed under the calf at its maximum diameter. The centering of the leg over the coil was confirmed by T_1 -weighted ¹H localizing images obtained in the axial plane. Magnetic field homogeneity was optimized by shimming on the proton signal from tissue water. For ³¹P-MRS the pulse power was adjusted so that ~72% of the signal acquired was from tissue within 5 cm of the surface coil. The spectral width was 2,500 Hz, and a single free induction decay (FID) was acquired every 4 s for the 5 min of exercise and 5 min of recovery. As a result, the data are expressed with a time resolution of 4 s.

Data analysis. Data were processed by using SAGE/IDL software on a Silicon Graphics Indigo workstation. Each FID consisted of 1,024 complex points and was processed with 5-Hz exponential line broadening before zero filling and

Fourier transformation. All spectra were manually phased by using zero- and first-order phase corrections. There were no phase variations among rest, exercise, and recovery during the experiment. The levels of PCr determined from the intensity of that peak were normalized to 100% by using the average value obtained from the last 40 s of rest acquired for each subject as a reference. Muscle intracellular pH was calculated from the chemical shift difference (δ) of the P_i peak relative to the PCr peak by using the following equation: $pH = 6.75 + \log[(\delta - 3.27)/(5.69 - \delta)]$ (37). Signal-to-noise ratios (~20:1) were sufficient to allow PCr levels to be determined with a temporal resolution of 4 s during exercise and recovery. Changes in PCr during recovery were fit to a monoexponential function

$$PCr(t) = PCr_0 + PCr_1 [1 - e^{-(t-TD/\tau)}]$$

where PCr_0 is the baseline value, PCr_1 is the difference between the baseline and the recovery value, t is time, TD is the time delay, and τ is the time constant.

Statistical analysis. Data were tested with repeated-measures ANOVA (Tukey post hoc) by using a commercially available software package (Instat, San Diego, CA). Data were considered significantly different when $P \leq 0.05$. The results are presented as means \pm SE.

RESULTS

A stack plot showing typical signal-to-noise ratios (~20:1 for the PCr resonance) during exercise and the recovery transition is shown in Fig. 1. Each spectrum represents a single acquisition with a temporal resolu-

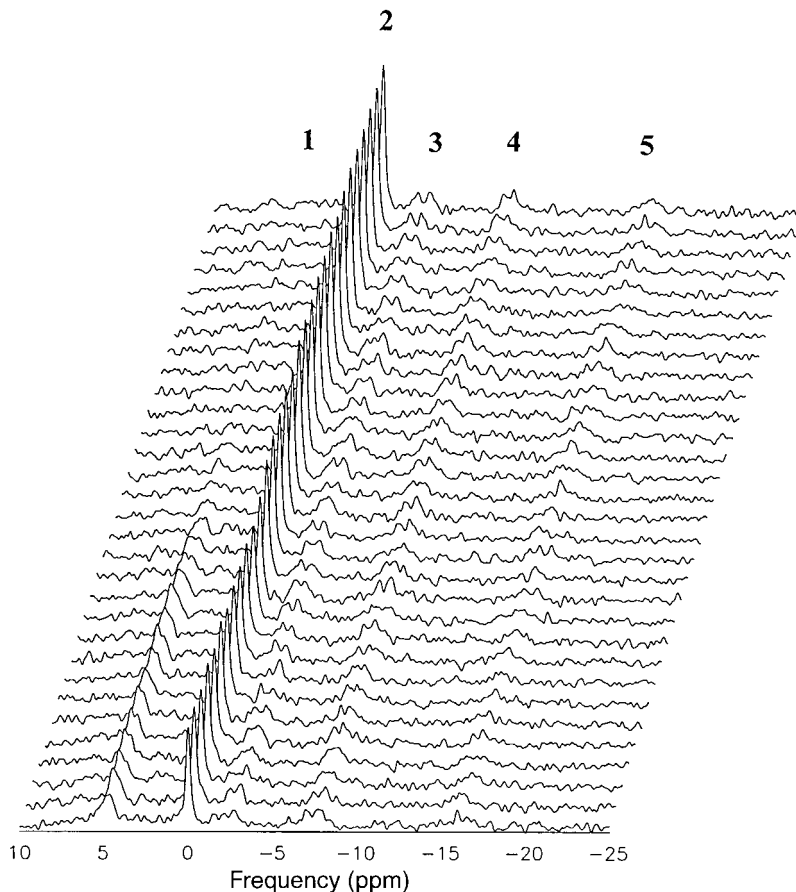


Fig. 1. Stack plot showing spectra during last 40 s of exercise and during first 80 s of recovery transition. Each spectrum is a single acquisition, and temporal resolution is 4 s. Peak assignments are as follows: 1, inorganic phosphate; 2, phosphocreatine; 3, 4, and 5, γ -, α -, and β -phosphates of ATP, respectively. ppm, Parts/million.

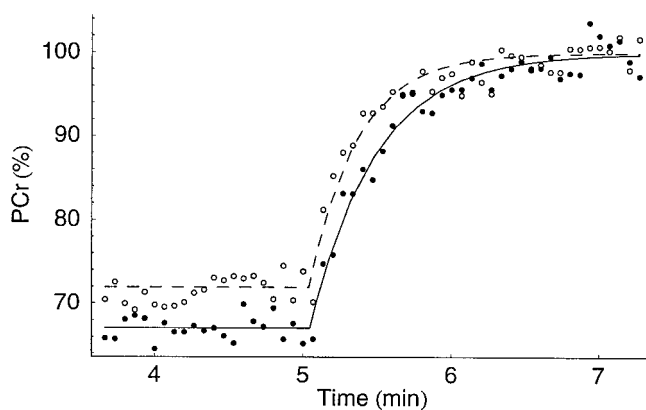


Fig. 2. Recovery curves for an individual subject showing raw data and monoexponential fit. \circ , Hyperoxia; \bullet , hypoxia. For clarity, normoxic data are not shown. Time constants calculated from monoexponential fit for this subject were 19.5 and 26.6 s for hyperoxia and hypoxia, respectively (normoxia = 21.8 s, not shown). PCr, phosphocreatine.

tion of 4 s. Figure 2 illustrates recovery curves for an individual subject. For clarity, only the hypoxic and hyperoxic treatments are shown with the τ values calculated from the monoexponential fit being 26.6 and 19.5 s, respectively (normoxia = 21.8 s, not shown) for this individual. For the complete subject pool, τ values were significantly different in each of the three $F_{I_{O_2}}$ treatments and are shown in Table 1.

The mean work done by the subjects in each exercise bout was 7.2 ± 0.6 W. At rest, $F_{I_{O_2}}$ had no effect on PCr levels. The end-exercise levels of PCr, expressed as a percentage of resting levels, were not significantly different among $F_{I_{O_2}}$ treatments: $64.0 \pm 3.5\%$ for 0.10, $68.6 \pm 3.6\%$ for 0.21, and $70.2 \pm 5.5\%$ for 1.00 (averaged over last 40 s of exercise). End-exercise pH values showed no significant differences in each of the gases: 7.08 ± 0.01 for 0.10, 7.04 ± 0.01 for 0.21, and 7.04 ± 0.02 for 1.00 and were not significantly different from the initial resting pH values (7.04 ± 0.01 for 0.10, 7.04 ± 0.01 for 0.21, and 7.03 ± 0.01 for 1.00).

The calculated arterial O_2 saturations for the three $F_{I_{O_2}}$ treatments were 77.0 ± 0.5 , 97.4 ± 0.5 , and 100% for 0.10, 0.21, and 1.00, respectively. These arterial O_2 saturations for the different $F_{I_{O_2}}$ correspond to arterial PO_2 values of ~ 45 , 100, and 600 Torr, respectively.

DISCUSSION

Previously, Idstrom et al. (16) have demonstrated that PCr recovery is slowed in perfused rat hindlimb

Table 1. PCr recovery time constants under conditions of different $F_{I_{O_2}}$

	$F_{I_{O_2}}$		
	0.10	0.21	1.00
τ , s	$33.5 \pm 4.1^*$	25.0 ± 2.7	$20.0 \pm 1.8^*$

Values are means \pm SE in hypoxia [0.10 fraction of inspired O_2 ($F_{I_{O_2}}$)], normoxia (0.21 $F_{I_{O_2}}$), and hyperoxia (1.00 $F_{I_{O_2}}$). PCr, phosphocreatine; τ , time constant. *Significantly different from normoxia, $P < 0.05$.

muscles when O_2 delivery is reduced. The results of the present study build on these observations and, in fact, demonstrate that PCr recovery from submaximal exercise in exercise-trained humans is altered by increases and decreases in $F_{I_{O_2}}$. The increase in τ with hypoxia and decrease in τ with hyperoxia suggest that O_2 availability plays a role in mitochondrial function. These results suggest limited metabolic capacity due to O_2 availability during recovery from exercise, similar to that previously documented during maximal exercise (31, 35).

$F_{I_{O_2}}$ and cellular oxygenation. During exercise, the O_2 required for oxidative phosphorylation in skeletal muscle moves from the blood to mitochondria down a PO_2 pressure gradient between the capillary and the cell (32). The flux of O_2 is dependent on this diffusion-induced pressure difference between the capillary and the cytoplasm and is determined by the rate of mitochondrial respiration. Previously, it has been demonstrated that breathing hyperoxic and hypoxic gases during exercise results in a rise and fall in the calculated mean capillary PO_2 (32, 33). In the cell this results in increased or decreased intracellular PO_2 (32, 33). These studies also revealed that intracellular PO_2 remained constant, in a given $F_{I_{O_2}}$, over a range of submaximal to maximal exercise intensities. Because the present work intensity was similar (50–60% of maximum), it seems reasonable to assume a similar level of intramuscular oxygenation. Additionally, on the basis of this prior work, it can be assumed that changes in $F_{I_{O_2}}$ and the subsequent changes in arterial and capillary PO_2 altered the intracellular PO_2 of the exercising muscle. Therefore, it is likely that the results of the present study were due to changes in intracellular PO_2 caused by breathing the different $F_{I_{O_2}}$.

Altered PCr recovery: oxidative capacity vs. mitochondrial function. The measurement of PCr recovery data has proven useful in determining the oxidative capacity of skeletal muscle to synthesize ATP in a variety of conditions (22, 26, 29, 30, 39, 42). En masse, these studies illustrate the sensitivity of PCr recovery to changes in oxidative capacity. Thus the present results could be interpreted as a change in the oxidative capacity of the muscle, similar to the increase seen in response to training (22, 26, 42) or the decrease as a result of disuse or myopathy (29, 40), although smaller in magnitude. Because this was an acute repeated-measures design, it is clear that such structural changes (e.g., altered mitochondrial content) cannot explain the altered PCr τ and apparent change in oxidative capacity with varied $F_{I_{O_2}}$.

As discussed above, it is unlikely that the present data represent a change in mitochondrial capacity but rather a change in mitochondrial function. Maximal mitochondrial respiratory rate is dependent on substrate availability, including not only O_2 but also ADP, P_i , and $NAD^+/NADH$. It is speculated that this altered mitochondrial function may be specifically due to changes in O_2 availability, the result of varied $F_{I_{O_2}}$, and take the form of either altered mitochondrial recruitment as previously hypothesized (11) or another ex-

ample of limited mitochondrial function due to O_2 supply (32, 35). It is noteworthy that both of these theories are complementary and may be somewhat interrelated. The latter theory is supported by previous studies that have observed slowed PCr recovery due to a reduction in the arterial PO_2 (1) and in cases of reduced muscle blood flow (9) (discussed in detail in *Evidence of mitochondrial O_2 supply-dependent ATP synthesis*). However, the former theory is supported by the observation that altered tissue oxygenation during steady-state submaximal exercise results in altered PCr levels, suggesting that tissue or intracellular oxygenation plays a role in modulating regulators of cellular respiration (10, 11). Thus cellular levels of O_2 may influence metabolic control even during submaximal exercise. It is also known that exercise training increases the mitochondrial content of the cell (12, 13), and this alters the mitochondrial sensitivity to the regulators of respiration (7). Thus mitochondrial content itself has been shown to play a role in controlling oxidative phosphorylation (6, 7). Under conditions of identical submaximal stimulation, PCr decreased less and ADP and P_i increased less in muscle from trained rats compared with untrained rats (6, 7). Greater mitochondrial density results in less energy production per mitochondria; thus less stimulus for respiration is required. Additionally, the effect of exercise training in humans has been demonstrated by ^{31}P -MRS to show that trained muscle has an increased potential for oxidative metabolism (20). Because intracellular PO_2 during submaximal exercise varies with different $F_{I_{O_2}}$ (32, 33), it has previously been postulated that O_2 availability affects mitochondrial sensitivity through mitochondrial recruitment (11). Under hyperoxic conditions and a higher mean intracellular PO_2 , there would be a greater number of mitochondria with adequate oxygenation resulting in enhanced PCr recovery from exercise, analogous to a trained state. Conversely, under hypoxic conditions, there may be fewer mitochondria that have adequate O_2 . Subsequently, PCr recovery would be slowed, eliciting a similar response to that of reduced mitochondrial content. This suggests that greater intracellular oxygenation results in a more tightly controlled system, allowing faster rates of recovery. The converse is true in hypoxia, resulting in slower rates of recovery.

Evidence of mitochondrial O_2 supply-dependent ATP synthesis. At the end of exercise, PCr τ represents mitochondrial ATP synthesis (i.e., function) (3, 4). Provided that end exercise pH has not reached a low value, recovery can be thought of as an aerobic challenge in which the rate constant for PCr recovery ($1/\tau$) is a function of the maximum rate of oxidative ATP synthesis (\dot{Q}_{max}), which can be estimated as $\dot{Q}_{max} = (1/\tau)[PCr_{rest}]$, with the apparent \dot{Q}_{max} a function of the density and capacity of working mitochondria and the supply of substrate and O_2 , independent of muscle mass, and where $[PCr_{rest}]$ is PCr concentration in resting muscle (18). Recently, it has been shown that the rate constant for PCr recovery can be directly interpreted as a measure of oxidative capacity with a

linear dependence of $1/\tau$ on oxidative capacity (27, 29). Because $[PCr_{rest}]$ is constant for a given subject, the rate constant for PCr recovery, \dot{Q}_{max} , and maximal O_2 consumption ($\dot{V}O_{2max}$) are all indicative of the maximal rate of oxidative ATP synthesis. Thus it is not surprising that there is a strong similarity between O_2 consumption and PCr on- and off-exercise kinetics (25) or that both \dot{Q}_{max} and $\dot{V}O_{2max}$ are linearly dependent on muscle oxidative capacity (15, 29). Consequently, PCr exercise-recovery data are clearly indicative of both muscle $\dot{V}O_{2max}$ and muscle oxidative capacity: a greater oxidative capacity leads to a greater capacity to consume O_2 and a shorter PCr τ and vice versa. The present data provide the first MRS evidence of a dissociation between the first two variables (muscle $\dot{V}O_{2max}$ and oxidative capacity) due to altered $F_{I_{O_2}}$. This is evident by the fact that the rate constant for PCr recovery (similar in many respects to $\dot{V}O_{2max}$) is altered by varying O_2 availability while oxidative capacity remained unchanged due to the acute nature of the study. This dependence of PCr recovery on $F_{I_{O_2}}$ may be due to the altered intracellular oxygenation. Because of hardware constraints of the present magnetic resonance system, intracellular PO_2 measurements were not obtained. However, with the assumption that the intracellular PO_2 of exercising human gastrocnemius muscle has a similar intracellular PO_2 response to changes in $F_{I_{O_2}}$ as observed in the human quadriceps (32, 33), it can be illustrated that the rate constant for PCr recovery measured here has a dependence on intracellular oxygenation (Fig. 3). The dependence of

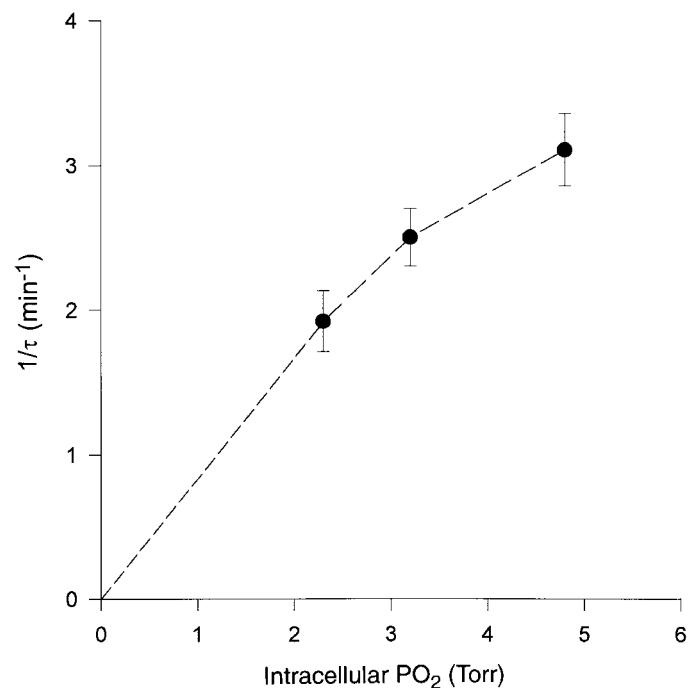


Fig. 3. Present data (y -axis) combined with intracellular PO_2 reported by Richardson et al. (32, 33) (x -axis) illustrate dependence of maximal rate of ATP synthesis on O_2 availability. These data suggest that dependence of rate constant for PCr recovery ($1/\tau$) may be approaching a plateau whereby further increments in intracellular PO_2 will have a diminishing effect on $1/\tau$.

the PCr rate constant on oxygenation seen in Fig. 3 suggests that PCr recovery from submaximal exercise is limited by O_2 availability. The observation here that PCr recovery is enhanced with increased intracellular oxygenation provides evidence that under normoxic conditions \dot{Q}_{max} is determined by O_2 availability and not mitochondrial metabolic limits. Figure 3 provides further evidence of an in vivo correlate of the effect of O_2 tension on cellular respiration rate (32), as originally demonstrated in vitro by Wilson et al. (41). These data suggest that the dependence of the rate constant for PCr recovery on O_2 availability may be approaching a plateau whereby further increments in intracellular PO_2 will have a diminishing effect. These findings are consistent with the concept that $\dot{V}_{O_{2max}}$ is dependent on the availability of O_2 (31, 35).

There is prior evidence in untrained subjects performing small-muscle-mass exercise that suggests the effect of varying $F_{I_{O_2}}$ on O_2 delivery is dampened by an alteration in muscle blood flow (36). In that case, convective O_2 delivery would remain constant, whereas the diffusive component of O_2 transport would be altered (35). Such a scenario has been reported previously, where the convective delivery of O_2 and the O_2 diffusing capacity (DO_2) were unchanged between hypoxia and normoxia, but the significantly reduced PO_2 gradient from capillary ($P_{C_{O_2}}$) to tissue ($P_{m_{O_2}}$) decreased both $\dot{V}_{O_{2max}}$ and $P_{m_{O_2}}$ [$\dot{V}_{O_{2max}} = DO_2(P_{C_{O_2}} - P_{m_{O_2}})$] (34). In a study of cyanotic patients with congenital heart disease, slowed PCr recovery times have been reported, again consistent with the reduced PO_2 gradient available to drive O_2 into the myocyte (1). In the present study, the similar increase in the PCr recovery rate constant in hyperoxia (20%) and decrease in hypoxia (23%) are also suggestive of this scenario because the most significant effect of hyperoxia is to raise blood PO_2 because Hb saturation is already close to its ceiling in normoxia. Hence, it is suggested that in hyperoxia the gradient from blood to muscle was enhanced, resulting in an elevated intracellular PO_2 , facilitating increased oxidative metabolism, and ultimately a shorter PCr τ (Fig. 2). The converse occurs in hypoxia. These data indicate that under normoxic conditions the rate constant for PCr recovery, \dot{Q}_{max} , and therefore $\dot{V}_{O_{2max}}$ are limited by O_2 availability. It should be recognized that mitochondrial capacity is unaltered in these conditions. Therefore, the conclusions are identical, but the scientific approach is very different from many studies that have previously illustrated a strong dependency between O_2 supply and skeletal muscle oxidative capacity during maximal exercise (21, 31).

Summary. This study demonstrated that PCr recovery after submaximal exercise is slowed with breathing of a hypoxic gas mixture and enhanced with breathing of a hyperoxic gas compared with normoxia. This suggests that tissue oxygenation plays a role in mitochondrial function, resulting in changes similar to those observed in situations of altered oxidative capacity. The increase in PCr recovery rate constant observed by increasing the PO_2 driving gradient for O_2

into the cell suggests that under normal conditions the recovery of PCr is limited by O_2 supply. This can be interpreted as further evidence that diffusion of O_2 from erythrocyte to mitochondria, and ultimately intracellular PO_2 , plays an important role in determining skeletal muscle $\dot{V}_{O_{2max}}$. Finally, the practical implication of these data is that PCr recovery measurements should be interpreted with caution because differences in τ between subjects may not be due to metabolic limitations but rather to variations in O_2 availability. Hence a lengthened τ exhibited in a diseased state may be due to O_2 supply limitations and not to a metabolic abnormality.

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REFERENCES

1. **Adatia, I., G. J. Kemp, D. J. Taylor, G. K. Radda, B. Rajagopalan, and S. G. Haworth.** Abnormalities in skeletal muscle metabolism in cyanotic patients with congenital heart disease: a ^{31}P nuclear magnetic resonance spectroscopy study. *Clin. Sci. (Colch.)* 85: 105–109, 1993.
2. **Argov, Z., W. J. Bank, J. Maris, S. Eleff, N. G. Kennaway, R. E. Olson, and B. Chance.** Treatment of mitochondrial myopathy due to complex III deficiency with vitamins K_3 and C: a ^{31}P -NMR follow-up study. *Ann. Neurol.* 19: 598–602, 1986.
3. **Arnold, D. L., P. M. Matthews, and G. K. Radda.** Metabolic recovery after exercise and the assessment of mitochondrial function in vivo in human skeletal muscle by means of ^{31}P NMR. *Magn. Reson. Med.* 1: 307–315, 1984.
4. **Arnold, D. L., D. J. Taylor, and G. K. Radda.** Investigation of human mitochondrial myopathies by phosphorus magnetic resonance spectroscopy. *Ann. Neurol.* 18: 189–196, 1985.
5. **Bendahan, D., S. Confort-Gouny, G. Kozak-Reiss, and P. Cozzone.** Heterogeneity of metabolic response to muscular exercise in humans. New criteria of invariance defined by in-vivo phosphorus-31 NMR. *FEBS Lett.* 272: 155–158, 1990.
6. **Constable, S. H., R. J. Favier, J. A. McLane, R. D. Fell, M. Chen, and J. O. Holloszy.** Energy metabolism in contracting rat skeletal muscle: adaptation to exercise training. *Am. J. Physiol.* 253 (*Cell Physiol.* 22): C316–C322, 1987.
7. **Dudley, G. A., P. C. Tullson, and R. L. Terjung.** Influence of mitochondrial content on the sensitivity of respiratory control. *J. Biol. Chem.* 262: 9104–9114, 1987.
8. **Eleff, S., N. G. Kennaway, N. R. M. Buist, and B. Chance.** ^{31}P -NMR study of improvement in oxidative phosphorylation by vitamins K_3 and C in a patient with a defect in electron transport at complex III in skeletal muscle. *Proc. Natl. Acad. Sci. USA* 81: 3529–3533, 1984.
9. **Hands, L. J., P. J. Bore, G. Galloway, P. J. Morris, and G. K. Radda.** Muscle metabolism in patients with peripheral vascular disease investigated by ^{31}P nuclear magnetic resonance spectroscopy. *Clin. Sci. (Colch.)* 71: 283–290, 1986.
10. **Haseler, L. J., R. S. Richardson, J. S. Videen, and M. C. Hogan.** Phosphocreatine hydrolysis during submaximal exercise: the effect of $F_{I_{O_2}}$. *J. Appl. Physiol.* 85: 1457–1463, 1998.
11. **Hogan, M. C., P. G. Arthur, D. E. Bebout, P. W. Hochachka, and P. D. Wagner.** Role of O_2 in regulating tissue respiration in dog muscle working in situ. *J. Appl. Physiol.* 73: 728–736, 1992.
12. **Holloszy, J. O.** Biochemical adaptations in muscle: effect of exercise on mitochondrial oxygen uptake and respiratory enzyme activity in skeletal muscle. *J. Biol. Chem.* 242: 2278–2282, 1967.

13. **Holloszy, J. O., and F. W. Booth.** Biochemical adaptations to endurance exercise in skeletal muscle. *Annu. Rev. Physiol.* 38: 273–291, 1976.
14. **Holloszy, J. O., and E. F. Coyle.** Adaptations of skeletal muscle to endurance exercise and their metabolic consequences. *J. Appl. Physiol.* 56: 831–838, 1984.
15. **Hoppeler, H., H. Howald, K. Conley, S. L. Lindstedt, H. Claassen, P. Vock, and E. R. Weibel.** Endurance training in humans: aerobic capacity and structure of skeletal muscle. *J. Appl. Physiol.* 59: 320–327, 1985.
16. **Idstrom, J. P., V. H. Subramanian, B. Chance, T. Schersten, and A. Bylund-Fellenius.** Oxygen dependence of energy metabolism in contracting and recovering rat skeletal muscle. *Am. J. Physiol.* 248 (*Heart Circ. Physiol.* 17): H40–H48, 1985.
17. **Iotti, S., R. Lodi, C. Frassinetti, P. Zanioli, and B. Barbiroli.** In-vivo assessment of mitochondrial functionality in human gastrocnemius muscle by ^{31}P NMR. *NMR Biomed.* 6: 248–253, 1993.
18. **Kemp, G. J., and G. K. Radda.** Quantitative interpretation of bioenergetic data from ^{31}P and ^1H magnetic resonance spectroscopic studies of skeletal muscle: an analytical review. *Magn. Reson. Q.* 10: 43–63, 1994.
19. **Kemp, G. J., D. J. Taylor, and G. K. Radda.** Control of phosphocreatine resynthesis during recovery from exercise in human skeletal muscle. *NMR Biomed.* 6: 66–72, 1993.
20. **Kent-Braun, J. A., K. K. McCully, and B. Chance.** Metabolic effects of training in humans: a ^{31}P -MRS study. *J. Appl. Physiol.* 69: 1165–1170, 1990.
21. **Knight, D. R., W. Schaffartzik, D. C. Poole, M. C. Hogan, D. E. Bebout, and P. D. Wagner.** Hyperoxia increases leg maximal oxygen uptake. *J. Appl. Physiol.* 75: 2586–2594, 1993.
22. **Laurent, D., H. Reutenauer, J.-F. Payen, A. Favre-Juvin, J. Eteradossi, J. Lebas, and A. Rossi.** Muscle bioenergetics in skiers: studies using NMR spectroscopy. *Int. J. Sports Med.* 13: S150–S152, 1992.
23. **Mahler, M.** First-order kinetics of muscle oxygen consumption, and an equivalent proportionality between $\dot{V}O_2$ and phosphoryl-creatine level. *J. Gen. Physiol.* 86: 135–165, 1985.
24. **McAllister, R. M., and R. L. Terjung.** Training-induced muscle adaptations: increased performance and oxygen consumption. *J. Appl. Physiol.* 70: 1569–1574, 1991.
25. **McCreary, C. R., P. D. Chilibeck, G. D. Marsh, D. H. Paterson, D. A. Cunningham, and R. T. Thompson.** Kinetics of pulmonary oxygen uptake and muscle phosphates during moderate-intensity calf exercise. *J. Appl. Physiol.* 81: 1331–1338, 1996.
26. **McCully, K. K., B. P. Boden, M. Tuchler, M. R. Fountain, and B. Chance.** Wrist flexor muscles of elite rowers measured with magnetic resonance spectroscopy. *J. Appl. Physiol.* 67: 926–932, 1989.
27. **McCully, K. K., R. A. Fielding, W. J. Evans, J. S. Leigh, and J. D. Posner.** Relationships between in vivo and in vitro measurements of metabolism in young and old human calf muscles. *J. Appl. Physiol.* 75: 813–819, 1993.
28. **Meyer, R. A.** A linear model of muscle respiration explains monoexponential phosphocreatine changes. *Am. J. Physiol.* 254 (*Cell Physiol.* 23): C548–C553, 1988.
29. **Paganini, A. T., J. M. Foley, and R. A. Meyer.** Linear dependence of muscle phosphocreatine kinetics on oxidative capacity. *Am. J. Physiol.* 272 (*Cell Physiol.* 41): C501–C510, 1997.
30. **Radda, G. K., P. J. Bore, D. G. Gadian, B. D. Ross, P. Styles, D. J. Taylor, and J. Morgan-Hughes.** ^{31}P NMR examination of two patients with NADH-CoQ reductase deficiency. *Nature* 295: 608–609, 1982.
31. **Richardson, R. S., D. R. Knight, D. C. Poole, S. Sadi Kurdak, M. C. Hogan, B. Grassi, and P. D. Wagner.** Determinants of maximal exercise $\dot{V}O_2$ during single leg knee-extensor exercise in humans. *Am. J. Physiol.* 268 (*Heart Circ. Physiol.* 37): H1453–H1461, 1995.
32. **Richardson, R. S., E. A. Noyszewski, K. F. Kendrick, J. S. Leigh, and P. D. Wagner.** Myoglobin O_2 destaturation during exercise. *J. Clin. Invest.* 96: 1916–1926, 1995.
33. **Richardson, R. S., E. A. Noyszewski, J. S. Leigh, and P. D. Wagner.** Myoglobin PO_2 a determinant of maximal mitochondrial O_2 consumption (Abstract). *Med. Sci. Sports Exerc.* 29: S272, 1997.
34. **Richardson, R. S., E. A. Noyszewski, J. S. Leigh, and P. D. Wagner.** Lactate efflux from exercising human skeletal muscle: role of intracellular PO_2 . *J. Appl. Physiol.* 85: 627–634, 1998.
35. **Richardson, R. S., K. Tagore, L. J. Haseler, M. Jordan, and P. D. Wagner.** Increased $\dot{V}O_{2\max}$ with a right-shifted Hb- O_2 dissociation curve at a constant O_2 delivery in dog muscle in situ. *J. Appl. Physiol.* 84: 995–1002, 1998.
36. **Rowell, L. B., B. Saltin, B. Kiens, and N. J. Christensen.** Is peak quadriceps blood flow in humans even higher during exercise with hypoxemia? *Am. J. Physiol.* 251 (*Heart Circ. Physiol.* 20): H1038–H1044, 1986.
37. **Taylor, D. J., P. J. Bore, P. Styles, D. G. Gadian, and G. K. Radda.** Bioenergetics of intact human muscle. A ^{31}P nuclear magnetic resonance study. *Mol. Biol. Med.* 1: 77–94, 1983.
38. **Thompson, C. H., G. J. Kemp, B. Rajagopalan, and G. K. Radda.** Metabolic abnormalities in skeletal muscle after myocardial infarction. *Clin. Sci. (Colch.)* 87: 403–406, 1994.
39. **Thompson, C. H., G. J. Kemp, B. Rajagopalan, and G. K. Radda.** Abnormal ATP turnover in rat leg muscle during exercise and recovery following myocardial infarction. *Cardiovasc. Res.* 29: 344–349, 1995.
40. **Thompson, C. H., G. J. Kemp, A. L. Sanderson, and G. K. Radda.** Skeletal muscle mitochondrial function studied by kinetic analysis of postexercise phosphocreatine resynthesis. *J. Appl. Physiol.* 78: 2131–2139, 1995.
41. **Wilson, D. F., M. Erecinska, C. Drown, and I. A. Silver.** Effect of oxygen tension on cellular energetics. *Am. J. Physiol.* 233 (*Cell Physiol.* 2): C135–C140, 1977.
42. **Yoshida, T., and H. Watari.** Metabolic consequences of repeated exercise in long distance runners. *Eur. J. Appl. Physiol.* 67: 261–265, 1993.