Effect of increased muscle temperature on oxygen uptake kinetics during exercise

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Koga, Shunsaku, Tomoyuki Shiojiri, Narihiko Kondo, and Thomas J. Barstow. Effect of increased muscle temperature on oxygen uptake kinetics during exercise. J. Appl. Physiol. 83(4): 1333–1338, 1997.—To test whether increased muscle temperature (Tm) would improve O2 uptake (VO2) kinetics, seven men performed transitions from rest to a moderate work rate [below the estimated lactate threshold (LTrest)] and a heavy work rate (VO2 = 50% of the difference between LTest and peak VO2) under conditions of normal Tm (N) and increased Tm (H), produced by wearing hot water-perfused pants before exercise. Quadriceps Tm was significantly higher in H, but rectal temperature was similar for the two conditions. There were no significant differences in the amplitudes of the fast component of VO2 or in the time constants of the on and off transients for moderate and heavy exercise between the two conditions. The increment in VO2 between the 3rd and 6th min of heavy exercise was slightly but significantly smaller for H than for N. These data suggest that elevated Tm before exercise onset, which would have been expected to increase O2 delivery and off-loading to the muscle, had no appreciable effect on the fast exponential component of VO2 kinetics (invariant time constant). These data further suggest that elevated Tm does not contribute to the slow component of VO2 during heavy exercise.

Several studies have examined the effects of increased temperature on muscle metabolism and exercise tolerance. Increased temperature elevates O2 consumption (O2) of isolated mitochondria by a Q10 effect and by decreasing the phosphorylation potential (ADP/O ratio) (7, 36). An increase in blood temperature may facilitate unloading of O2 from hemoglobin in the muscle capillaries by a rightward shift of the oxyhemoglobin dissociation curve. However, the net effect of elevated temperature on muscle and whole body metabolism in intact humans during exercise is controversial. Pulmonary O2 uptake (VO2) has been reported to be higher (24, 27), lower (14, 37), or unchanged (15, 32) in the heat compared with control ambient conditions. In addition to equivocal effects on steady-state VO2, it is unknown whether the kinetics of adjustment of muscle and pulmonary VO2 during the first few minutes of moderate- or heavy-intensity exercise would be altered by increased temperature. The kinetics of muscle and pulmonary VO2 are thought to be primarily determined by intramuscular processes (19, 25, 26) and modifiable by the kinetics of O2 delivery to the working muscles (21). The kinetics of VO2 can be slowed by decreasing arterial O2 content and/or delivery (13). However, there is no compelling evidence that increased muscle O2 delivery can increase VO2 kinetics in healthy humans.

Elevated muscle temperature (Tm) may speed VO2 kinetics in at least two ways: 1) It may speed the limiting reaction(s) associated with oxidative phosphorylation, and/or 2) a rightward shift of the oxyhemoglobin dissociation curve and any muscle vasodilation associated with increased temperature may facilitate O2 delivery during the transition to exercise. This expected improvement in O2 delivery could result in faster VO2 kinetics if the muscle VO2 kinetics were O2 delivery dependent in the control condition. Current thinking suggests that this is more likely to be true for exercise above than for exercise below the lactate threshold (LT). We thus hypothesized that elevated Tm would lead to faster VO2 kinetics for exercise above the LT, but not for exercise below the LT.

It has also been speculated that the additional, slowly developing VO2 (slow component) seen during heavy exercise may be the result of the effect of rising Tm on mitochondrial respiration and the phosphorylation potential mentioned above (36). A second hypothesis we tested was that the slow component of VO2 during heavy exercise would be greater when Tm was elevated before exercise onset.

The previous studies cited above focused on the effects of elevated ambient temperature on exercise energetics and exercise tolerance during prolonged protocols at heavy-intensity exercise. From these studies it is unclear whether elevated Tm per se, without concomitant increases in core temperature and the resulting systemic responses, would alter the initial energetic responses to moderate- or heavy-intensity exercise. Therefore, the overall aim of the present study was to evaluate the effects of increased Tm on the energetics of short-term (6 min) moderate-intensity (below LT) and heavy-intensity (above LT) exercise under conditions where elevation in core temperature and the resulting systemic responses were minimized.

METHODS

Subjects. Seven healthy men (age 25.7 ± 9.2 yr, height 171.8 ± 7.2 cm, weight 73.1 ± 12.4 kg) volunteered for the study. After a detailed explanation of the study, informed consent was obtained. The study was approved by the Human Subjects Committee of our university.

Protocols. A ramp exercise protocol (30 W/min) on an upright cycle ergometer was utilized to estimate each individual’s peak VO2 (the highest VO2 achieved during exercise) in a
thermonuclear environment (25°C, 50% relative humidity). LT was estimated \( (LT_{ext}) \) from gas-exchange criteria by finding the \( \dot{V}O_2 \) above which the ventilatory equivalent for \( O_2 \) and the end-tidal \( P_O_2 \) increased without an increase in the ventilatory equivalent for \( CO_2 \) or a decrease in end-tidal \( P_{CO_2} \) \( (35) \).

Rest-to-exercise transition tests were conducted under two \( T_m \) conditions on separate days: normal \( T_m \) (N) and increased \( T_m \) (H), where the subjects wore hot water-perfused pants to raise \( T_m \) of the legs. In the N condition, no water was circulated through the pants. The temperature of the laboratory was maintained at 25°C for both conditions. For each of the tests, the subject rested sitting on the ergometer for 40 min before performing exercise. All rest-to-exercise transitions were initiated with the flywheel of the ergometer turning at 60 rpm before the onset of exercise. At least 2 min of baseline resting data were collected before the beginning of each test.

For the moderate-exercise tests, we selected a work rate of 50 W, which was below each subject’s \( LT_{ext} \) \( (-60-70\% \) of the work rate at \( LT_{ext} \)). Each subject was allowed 10 min of rest before starting the next exercise transition. A recovery period of 10 min was found to be adequate for gas-exchange variables to return to resting levels. To minimize random noise and enhance the underlying response patterns, subjects performed a total of four repetitions of the rest-to-exercise transition, three of 3-min duration and one of 6-min duration under each \( T_m \) condition. The short duration of the 3-min exercise was adopted to minimize changes in the baseline resting condition before the next exercise transition. Furthermore, use of a 3-min fitting window allowed a single-exponential fit of the \( \dot{V}O_2 \) response \( (28) \). The final exercise period was 6 min to determine the steady-state response. No more than four transitions were completed by each subject on a single day.

For the heavy-exercise tests, we chose a work rate that was estimated to require a \( \dot{V}O_2 \) equal to 50% of the difference \( (\Delta) \) between the subject’s \( LT_{ext} \) and peak \( \dot{V}O_2 \), i.e., \( LT_{ext} + 0.5\Delta \), based on the initial \( \dot{V}O_2 \) work rate observed during the ramp exercise. Subjects performed one rest-to-exercise transition of 6-min duration followed by a 5-min recovery period under each \( T_m \) condition.

Measurements. Rectal temperature was continuously monitored by a thermistor probe \( (model \ 401, \ Yellow \ Springs \ Instruments) \) inserted 10 cm beyond the anal sphincter. Skin temperatures were measured by four thermistors placed on the upper arm, chest, front of the thigh, and calf. Thermistors were inserted into the vastus lateralis in each subject.

Analysis. Individual responses during the rest-to-exercise transitions were time interpolated to 1-s intervals. Responses to moderate exercise were further averaged across all transitions for each subject and condition. For the on and off transients, the response curves of \( \dot{V}O_2 \) and \( CO_2 \) output \( (\dot{V}CO_2) \) during phase 2 \( (i.e., \) after the first 15-25 s up to 3 min of exercise) were fit by a single-exponential function that included an amplitude, a time constant, and a time delay, using nonlinear least-squares regression techniques \( (8, \ 21, \ 22, \ 35) \).

The duration of phase 1 was determined as the time from the onset of exercise to the inflection points in the respiratory exchange ratio, end-tidal \( P_O_2 \) and end-tidal \( P_{CO_2} \) \( (35) \).

The initial 3 min of the response curves of \( \dot{V}O_2 \) and \( \dot{V}CO_2 \) during phase 2 of the on and off transients to heavy exercise were similarly fit by a single-exponential function that included an amplitude of the fast component, a time constant, and a time delay \( (2, \ 4, \ 28) \). Furthermore, the increment in \( \dot{V}O_2 \) between the 3rd and 6th min of the transition was calculated as an index of the slow component of the \( \dot{V}O_2 \) kinetics \( (6, \ 18, \ 28) \).

Mean skin temperature of the thigh and calf immediately before exercise was significantly higher in condition H than in condition N: 39.4 ± 0.9 and 32.9 ± 0.7°C, respectively \( (P < 0.01) \). Mean skin temperature of the upper arm and chest was similar for the two conditions: 32.8 ± 0.7 and 32.4 ± 1.0°C for N and H, respectively. Rectal temperature immediately before exercise was similar for the two conditions: 37.3 ± 0.2 and 37.4 ± 0.2°C for N and H, respectively. \( T_m \) before exercise was significantly higher in condition H: 36.0 ± 1.0 and 38.0 ± 0.5°C in N and H, respectively \( (P < 0.05) \). In separate experiments \( (n = 4) \), \( T_m \) immediately before and after the 6-min exercise bout was significantly higher in condition H than in condition N \( (Fig. \ 1) \): for moderate exercise, 35.3 ± 0.4 and 38.6 ± 0.3°C in N and H, respectively \( (P < 0.01) \); for heavy exercise, 35.4 ± 0.4 and 38.9 ± 0.1°C in N and H, respectively \( (P < 0.01) \); for heavy exercise, 38.8 ± 0.4 and 40.3 ± 0.5°C in N and H, respectively \( (P < 0.05) \). Thus we were successful in selectively warming the leg muscles before exercise and maintaining this elevated \( T_m \) over the course of exercise without causing significant elevations in core temperature.

The response for \( \dot{V}O_2 \) from rest to exercise in a representative subject is shown for the two conditions in \( Fig. \ 2 \). Selective warming of the legs did not result in an increase in resting metabolic rate before exercise \( (Table \ 1) \). There was no significant difference in amplitude of the fast component of \( \dot{V}O_2 \) between the two \( T_m \) conditions for moderate or heavy exercise. Also, the gain for the difference in the fast component between work rates was not significantly altered by elevated \( T_m \): 10.3 ± 1.7 and 10.1 ± 1.2 ml·min⁻¹·W⁻¹ in N and H,
respectively (Table 1). Furthermore, as shown in Table 1, there was no significant effect of $T_m$ or exercise intensity on the time constants for the on and off transients of $V\dot{O}_2$. The increment in $V\dot{O}_2$ between the 3rd and 6th min of heavy exercise was significantly smaller for H than for N: 138 ± 66 and 205 ± 70 ml/min, respectively ($P$, 0.05; Fig. 3).

There was no significant difference in amplitudes of $V\dot{CO}_2$ between the two conditions for moderate or heavy exercise (Table 2). Furthermore, there was no significant difference between the two conditions in the time constants for the on and off transients of $V\dot{CO}_2$ for moderate or heavy exercise.

The respiratory exchange ratio at the end of 6 min of exercise was similar for the two conditions: for moderate exercise, 0.89 ± 0.03 and 0.89 ± 0.05 in N and H, respectively; for heavy exercise, 1.09 ± 0.06 and 1.08 ± 0.04 in N and H, respectively.

HR was significantly higher in H than in N at rest (68 ± 6 and 79 ± 5 beats/min in N and H, respectively, $P < 0.01$) and at the end of 6 min of moderate exercise (95 ± 11 and 106 ± 8 beats/min in N and H, respectively, $P < 0.05$). HR at the end of 6 min of heavy exercise tended to be higher in H than in N: 163 ± 16 and 152 ± 15 beats/min, respectively ($P = 0.07$).

**DISCUSSION**

We had hypothesized that the kinetics of $V\dot{O}_2$ after the onset of heavy exercise would be faster when $T_m$ was increased before exercise onset. However, we found no significant reduction in the on and off time constants of $V\dot{O}_2$ for moderate or heavy exercise as a consequence of elevated $T_m$, contrary to our first hypothesis. Furthermore, there was no significant difference between the

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<tr>
<th>Table 1. Kinetics of $V\dot{O}_2$ during exercise with normal and increased muscle temperature</th>
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<td>N</td>
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<tr>
<td><strong>Resting $V\dot{O}_2$, ml/min</strong></td>
</tr>
<tr>
<td>$\tau_{on}$, s</td>
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<td>$\tau_{off}$, s</td>
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<td>$A$, ml/min</td>
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<td><strong>Heavy work ($&gt;LT_{on}$)</strong></td>
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<tr>
<td><strong>Resting $V\dot{O}_2$, ml/min</strong></td>
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<td>$\tau_{on}$, s</td>
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<td>$\tau_{off}$, s</td>
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<tr>
<td>$A$, ml/min</td>
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<tr>
<td>$\Delta V\dot{O}_2$, ml/min</td>
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<td>$G$, ml·min⁻¹·W⁻¹</td>
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Values are means ± SD; $n = 7$ subjects. N, normal muscle temperature; H, increased muscle temperature; $LT_{on}$, estimated lactate threshold; $\tau_{on}$, time constant of on-transient response; $\tau_{off}$, time constant of off-transient response; A, amplitude $O_2$ uptake ($V\dot{O}_2$) fast component during exercise; $\Delta V\dot{O}_2$, increment in $V\dot{O}_2$ between 3rd and 6th min of exercise; G, increase in A of $V\dot{O}_2$ for heavy exercise bout above A for moderate exercise divided by corresponding increase in work rate (i.e., $\Delta V\dot{O}_2/\Delta W$). *Significantly different from N, $P < 0.05$. 

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**Fig. 1.** Muscle temperature immediately before and after 6-min bout of moderate (A) and heavy exercise (B). Muscle temperature was significantly higher in condition of increased muscle temperature (○, dashed line) than in condition of normal muscle temperature (●, solid line). Values are means ± SD; $n = 4$ subjects.

**Fig. 2.** $O_2$ uptake ($V\dot{O}_2$) for transition from rest to moderate (A) and heavy exercise (B) in a representative subject under conditions of normal muscle temperature (solid line) and increased muscle temperature (dashed line). There were no significant differences for amplitudes of fast component of $V\dot{O}_2$ or for time constants of on and off transients for moderate and heavy exercise between normal and increased muscle temperature.
temperature in the muscle tissues. Consequently, O₂ occurred as a result of a possible increase in blood rates above the LT compared with moderate exercise rate (2, 4, 13, 28), the time constant has been found to consistently been found to increase linearly with work (speeded) the kinetics of the V˙O₂ response to exercise by facilitate (i.e., speed) muscle Q˙O₂ kinetics only if Q˙O₂ amplitude of the primary exponential rise in V ˙O₂ has ever, if it is assumed that the fast component of V˙O₂ were O 2-delivery or -diffusion limited. We did not measure muscle blood flow in the present study. How-

Table 2. Kinetics of VCO₂ during exercise with normal and increased muscle temperature

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<thead>
<tr>
<th></th>
<th>N</th>
<th>H</th>
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<tbody>
<tr>
<td><strong>Resting VCO₂</strong></td>
<td>297 ± 56</td>
<td>321 ± 92</td>
</tr>
<tr>
<td>T₁₀, s</td>
<td>44.9 ± 23.3</td>
<td>48.4 ± 22.5</td>
</tr>
<tr>
<td>T₉₀, s</td>
<td>44.4 ± 16.4</td>
<td>42.5 ± 14.7</td>
</tr>
<tr>
<td>A, ml/min</td>
<td>614 ± 194</td>
<td>616 ± 92</td>
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<tr>
<td><strong>Heavy work</strong></td>
<td></td>
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<tr>
<td>Resting VCO₂, ml/min</td>
<td>337 ± 105</td>
<td>327 ± 98</td>
</tr>
<tr>
<td>T₁₀, s</td>
<td>59.3 ± 20.7</td>
<td>53.9 ± 16.0</td>
</tr>
<tr>
<td>T₉₀, s</td>
<td>61.0 ± 12.0</td>
<td>68.4 ± 26.0</td>
</tr>
<tr>
<td>A, ml/min</td>
<td>2,626 ± 472</td>
<td>2,583 ± 347</td>
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Values are means ± SD; n = 7 subjects. VCO₂, CO₂ output; A, amplitude of fast component; see Table 1 for definition of other abbreviations.

The increment in VCO₂ between the 3rd and 6th min of heavy exercise was slightly but significantly smaller for increased than for normal muscle temperature. Two conditions in the amplitudes of the fast component of VCO₂ during moderate or heavy exercise. Whereas the amplitude of the primary exponential rise in VCO₂ has consistently been found to increase linearly with work rate (2, 4, 13, 28), the time constant has been found to remain unchanged (2, 4) or lengthen (13, 28) for work rates above the LT compared with moderate exercise intensities.

Increased Tm during exercise could have affected (speeded) the kinetics of the VCO₂ response to exercise by 1) speeding the rate-limiting metabolic reaction(s) associated with oxidative phosphorylation, and/or 2) speeding the increase of O₂ delivery to the capillaries and mitochondria, if indeed the kinetics were O₂-delivery dependent under the test conditions. A rightward shift in the O₂-hemoglobin dissociation curve may have occurred as a result of a possible increase in blood temperature in the muscle tissues. Consequently, O₂ unloading from hemoglobin would be enhanced during exercise in an increased Tm condition. This would facilitate (i.e., speed) muscle QO₂ kinetics only if QO₂ were O₂-delivery or -diffusion limited. We did not measure muscle blood flow in the present study. However, if it is assumed that the fast component of VCO₂ kinetics reflects muscle oxidative phosphorylation kinetics (1, 10, 19, 34), the finding of unaltered time constants during phase 2 for below- and above-LT exercise suggests that the factor(s) that determine muscle QO₂ kinetics was not affected by increased Tm.

One expectation was that increased Tm would lead to an increase in transient and steady-state muscle and pulmonary VCO₂ due to a Q₁₀ effect on muscle metabolism and a decrease in the phosphorylation efficiency (ADP/O) in the muscle (7, 36). However, this did not appear to occur, inasmuch as VCO₂ in H was not appreciably different from VCO₂ in N. One putative explanation for this finding is that oxidative phosphorylation becomes uncoupled only above 40°C (7). Because Tm in the present study was ≤40°C on average, even for the elevated temperature condition, the phosphorylation efficiency presumably would not have been affected.

Conversely, an increased Tm may have increased mechanical efficiency of working muscles and thus reduced VO₂ because of the lowered viscous resistance in the muscle (11). Any temperature-related increase in VO₂ may thus have been offset by increased mechanical efficiency (32), with the net result being no measurable change in VCO₂.

In addition to possibly affecting aerobic metabolism, increased Tm has been shown to cause a shift to greater anaerobic metabolism, as evidenced by increased intramuscular ATP utilization and creatine phosphate degradation, and anaerobic glycolysis (12, 14, 15, 23, 37). In the present study, blood lactate levels were not measured. However, we speculate that transient lactate increase during short-term exercise (reflecting anaerobic metabolism) was likely to have been similar in the two conditions, since the respiratory exchange ratio and the kinetics of VCO₂ were not significantly different.

The fast component of the VCO₂ off-transient response is a reflection of the rate of readjustment of oxidative phosphorylation during recovery and is not affected by anaerobic metabolism (10). Therefore, the similarity of on- and off-transient time constants of VCO₂ (symmetrical fast component (3, 13, 33)) under the two Tm conditions in the present study suggests that muscle O₂ utilization during recovery in the increased Tm condition was not different from that in the normal condition.

The increment in VCO₂ between the 3rd and 6th min of heavy exercise was slightly but significantly smaller when Tm was elevated. A number of factors have been postulated to contribute to the slow component of VCO₂ observed during heavy exercise (1, 9, 16, 17, 33). These include the effects of lactate, epinephrine, cardiac and ventilatory work, temperature, less-efficient mitochondrial P-O coupling, reduced chemical-mechanical coupling efficiency, and recruitment of lower-efficiency fast-twitch motor units. Although the mechanism(s) underlying the phenomenon remains speculative, the primary origin of the VCO₂ slow component appears to be the working limbs (3, 6, 29, 33).

It has been postulated that the increase in Tm during exercise may, via the Q₁₀ effect, contribute to the slow component of VO₂ during heavy exercise (20). Recently, Willis and Jackman (36) suggested that a 3°C rise in Tm could result in an ~10% reduction in the efficiency of...
coupling of \( \text{O}_2 \) to ATP production (ADP/O ratio) and thus contribute to the increase in the slow component from the active limb during heavy exercise. However, in vivo, neither increased \( T_m \) [estimated from venous blood temperature (29)] nor elevated core temperature (9, 30, 31) is associated with an increase in leg or pulmonary \( \text{O}_2 \), respectively, in exercising humans. In the present study, increased \( T_m \) was associated with a significant reduction in the slow component of \( \dot{\text{V}}_2 \) during heavy exercise. These results are inconsistent with the hypothesis that an exercise-induced increase in \( T_m \) is the predominant mechanism of the slow component of \( \dot{\text{V}}_2 \) during heavy exercise.

An alternative mechanism suggested for the \( \dot{\text{V}}_2 \) slow component is the recruitment of lower-efficiency, fast-twitch fibers that have a higher \( \text{O}_2 \) cost and a longer time constant (1, 3, 17, 33). The small reduction in the \( \dot{\text{V}}_2 \) slow component observed with elevated \( T_m \) conditions. These data suggest that \( \dot{\text{V}}_2 \) uptake kinetics depend on the extent of \( T_m \) and/or metabolic activity. Conclusions regarding the mechanisms of the reduced slow component of \( \dot{\text{V}}_2 \) during heavy exercise under the condition of increased \( T_m \) require further analysis.

In conclusion, there were no significant differences for the amplitude or the time constants of the fast component of the on and off transients of \( \dot{\text{V}}_2 \) during moderate and heavy exercise between control and elevated \( T_m \) conditions. These data suggest that as work intensity or \( T_m \) increased, \( \dot{\text{V}}_2 \) uptake was not limiting the initial, predominant muscle \( \dot{\text{Q}}_2 \) (and thus \( \dot{\text{V}}_2 \)) kinetics. Furthermore, the increment in \( \dot{\text{V}}_2 \) between the 3rd and 6th min of heavy exercise was slightly but significantly smaller for elevated \( T_m \) than for control. These data contradict the hypothesis that an increase in \( T_m \) contributes significantly to the slow component of \( \dot{\text{V}}_2 \) during heavy exercise.

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Received 20 February 1997; accepted in final form 11 J une 1997.

REFERENCES


