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 (VO2peak) 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 (QO2) 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 (LTest) from gas-exchange criteria by finding the VO₂ above which the ventilatory equivalent for O₂ and the end-tidal P O₂ increased without an increase in the ventilatory equivalent for CO₂ or a decrease in end-tidal P CO₂ (35).

Rest-to-exercise transition tests were conducted under two Tm conditions on separate days: normal Tm (N) and increased Tm (H), where the subjects wore hot water-perfused pants to raise Tm 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 LTest (~60–70% of the work rate at LTest). 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 and heart rate (HR) 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 Tm 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 VO₂ 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 VO₂ equal to 50% of the difference (Δ) between the subject’s LTest and peak VO₂, i.e., LTest + 0.5Δ, based on the initial VO₂/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 Tm 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. The thigh and calf values were averaged together, as were the upper arm and chest values, for comparison between conditions. Tm was measured 4 min before exercise onset for at least one transition to each work rate by a sterile 24-gauge needle thermistor (model 524, Yellow Springs Instruments) that was inserted 3 cm into the vastus lateralis. In addition, in separate experiments in four of the original subjects, Tm was measured before the 6-min exercise transition to each work rate and within 30 s of the cessation of the exercise.

Subjects breathed through a low-resistance valve (Hans Rudolph) connected to two pneumotachographs for measurement of inspiratory and expiratory flows. This system was calibrated repeatedly by inputting known volumes of room air at various mean flows and flow profiles. Respired gases were analyzed by mass spectrometry (model MGA-1100, Perkin-Elmer) from a sample drawn continuously from the mouthpiece. Precision-analyzed gas mixtures were used for calibration. Gas-exchange variables at the mouth were calculated breath by breath (5). HR was continuously monitored via a three-lead electrocardiogram.

Results. 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 VO₂ and CO₂ output (VCO₂) 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 O₂, and end-tidal P CO₂ (35).

The initial 3 min of the response curves of VO₂ and VCO₂ 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 VO₂ between the 3rd and 6th min of the transition was calculated as an index of the slow component of the VO₂ kinetics (6, 18, 28).

Values are means ± SD. The data were analyzed by using a repeated-measures analysis of variance design. Significant results were further analyzed by Scheffe’s post hoc test. Significance was declared at P < 0.05.

RESULTS

Peak VO₂ averaged 44.5 ± 9.8 ml·kg⁻¹·min⁻¹ and LTest averaged 23.2 ± 8.7 ml·kg⁻¹·min⁻¹.

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. Tm 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), Tm 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, before exercise (P < 0.01) and 36.3 ± 0.9 and 39.2 ± 0.5°C in N and H, respectively, after exercise (P < 0.01); for heavy exercise, 35.4 ± 0.4 and 38.9 ± 0.1°C in N and H, respectively, before exercise (P < 0.01) and 38.8 ± 0.4 and 40.3 ± 0.5°C in N and H, respectively, after exercise (P < 0.05). Thus we were successful in selectively warming the leg muscles before exercise and maintaining this elevated Tm over the course of exercise without causing significant elevations in core temperature.

The response for VO₂ 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 VO₂ between the two Tm 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 Tm:
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 $\dot{V}O_2$. The increment in $\dot{V}O_2$ 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 $\dot{V}CO_2$ 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 $\dot{V}CO_2$ 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 ($P = 0.07$).

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**DISCUSSION**

We had hypothesized that the kinetics of $\dot{V}O_2$ 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 $\dot{V}O_2$ 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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**Table 1. Kinetics of $\dot{V}O_2$ during exercise with normal and increased muscle temperature**

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<tr>
<td><strong>Moderate work (&lt;LT_{est})</strong></td>
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<tr>
<td>Resting $\dot{V}O_2$, ml/min</td>
<td>355 ± 71</td>
<td>381 ± 102</td>
</tr>
<tr>
<td>$t_{on}$, S</td>
<td>28.1 ± 10.4</td>
<td>28.8 ± 5.3</td>
</tr>
<tr>
<td>$t_{off}$, S</td>
<td>34.9 ± 9.6</td>
<td>35.4 ± 7.3</td>
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<tr>
<td>$A$, ml/min</td>
<td>703 ± 170</td>
<td>728 ± 102</td>
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<tr>
<td><strong>Heavy work (&gt;LT_{est})</strong></td>
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<tr>
<td>Resting $\dot{V}O_2$, ml/min</td>
<td>343 ± 134</td>
<td>285 ± 38</td>
</tr>
<tr>
<td>$t_{on}$, S</td>
<td>31.2 ± 5.1</td>
<td>29.3 ± 3.2</td>
</tr>
<tr>
<td>$t_{off}$, S</td>
<td>30.8 ± 3.4</td>
<td>31.7 ± 5.7</td>
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<tr>
<td>$A$, ml/min</td>
<td>1,960 ± 343</td>
<td>2,025 ± 335</td>
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<tr>
<td>$\Delta\dot{V}O_2$, 6-3, ml/min</td>
<td>205 ± 70</td>
<td>138 ± 66*</td>
</tr>
<tr>
<td>$G$, ml·min⁻¹·W⁻¹</td>
<td>10.3 ± 1.7</td>
<td>10.1 ± 1.2</td>
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Values are means ± SD; $n = 7$ subjects. N, normal muscle temperature; H, increased muscle temperature; LT_{est}, estimated lactate threshold; $t_{on}$, time constant of on-transient response; $t_{off}$, time constant of off-transient response; $A$, amplitude $O_2$ uptake ($\dot{V}O_2$) fast component during exercise; $\Delta\dot{V}O_2$, increment in $\dot{V}O_2$ between 3rd and 6th min of exercise; $G$, increase in $A$ of $\dot{V}O_2$ for heavy exercise bout above $A$ for moderate exercise divided by corresponding increase in work rate (i.e., $\Delta\dot{V}O_2/\Delta W$). *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 ($\dot{V}O_2$) 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 $\dot{V}O_2$ or for time constants of on and off transients for moderate and heavy exercise between normal and increased muscle temperature.**

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**Fig. 3.**
two conditions in the amplitudes of the fast component of VO₂ during moderate or heavy exercise. Whereas the amplitude of the primary exponential rise in VO₂ 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 VO₂ 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 VO₂ 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 VO₂ 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, as O₂ in H was not appreciably different from VO₂ 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 VO₂.

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 VO₂ were not significantly different.

The fast component of the VO₂ 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 VO₂ (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 VO₂ 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 VO₂ 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 VO₂ 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 Ackman (36) suggested that a 3°C rise in Tₘ could result in an ~10% reduction in the efficiency of

Table 2. Kinetics of VO₂ during exercise with normal and increased muscle temperature

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<tr>
<td><strong>Moderate work (&lt;LTₘ)</strong></td>
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<tr>
<td>Resting VO₂, ml/min</td>
<td>297 ± 56</td>
<td>321 ± 92</td>
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<tr>
<td>τ₁, s</td>
<td>44.9 ± 23.3</td>
<td>48.4 ± 22.5</td>
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<tr>
<td>τ₂, 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 (&gt;LTₘ)</strong></td>
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<tr>
<td>Resting VO₂, ml/min</td>
<td>337 ± 105</td>
<td>327 ± 98</td>
</tr>
<tr>
<td>τ₁, s</td>
<td>59.3 ± 20.7</td>
<td>53.9 ± 16.0</td>
</tr>
<tr>
<td>τ₂, s</td>
<td>61.0 ± 12.0</td>
<td>68.4 ± 26.0</td>
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<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. VO₂, CO₂ output; A, amplitude of fast component; see Table 1 for definition of other abbreviations.
coupling of $\dot{Q}_O_2$ 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 $\dot{V}_O_2$, respectively, in exercising humans. In the present study, increased $T_m$ was associated with a significant reduction in the slow component of $\dot{V}_O_2$ during heavy exercise. These results are consistent with the hypothesis that an exercise-induced increase in $T_m$ is the predominant mechanism of the slow component of $\dot{V}_O_2$ during heavy exercise.

An alternative mechanism suggested for the $\dot{V}_O_2$ slow component is the recruitment of lower-efficiency, fast-twitch fibers that have a higher $O_2$ cost and a longer time constant (1, 3, 17, 33). The small reduction in the $\dot{V}_O_2$ slow component observed with increased $T_m$ may indicate a slight alteration in motor unit recruitment pattern, perhaps reflecting activation of fewer fast-twitch fibers and/or more slow-twitch motor units with a higher oxidative capacity. Conclusions regarding the mechanisms of the reduced slow component of $\dot{V}_O_2$ 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 $\dot{V}_O_2$ during moderate and heavy exercise between control and elevated $T_m$ conditions. These data suggest that as work intensity or $T_m$ increased, $O_2$ supply was not limiting the initial, predominant muscle $Q_O_2$ (and thus $\dot{V}_O_2$) kinetics. Furthermore, the increment in $\dot{V}_O_2$ 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 $\dot{V}_O_2$ during heavy exercise.

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