Tissue temperatures and whole-animal oxygen consumption after exercise

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forced treadmill running caused rat muscle and rectal temperatures to increase 8.1 and 5.1 °C, respectively. After exercise, muscle temperature fell exponentially but did not reach control values in an hour. Rectal temperature fell rapidly for the first 20 min after exercise, after which only a slow rate of return to resting levels was apparent. An exercise-induced adjustment in the hypothalamic set point was suggested. O₂ consumption was high immediately after exercise, declined rapidly for the first 20 min of recovery, and then plateaued at a level significantly above resting. The hypothesis that a sizable portion of postexercise O₂ consumption is due to increased tissue temperatures is substantiated. The fact that severe exercise results in a large, prolonged elevation in tissue temperature necessitates, as a consequence of the Q₁₀ effect, that O₂ consumption be significantly elevated. Since a part of the postexercise O₂ consumption is not associated with recovery from anaerobic metabolism, the classical definition of O₂ debt requires revision.

Oxygen debt; temperature regulation; metabolism; exertion

Methods

Nineteen female rats were trained daily to be able to run for an hour on a motor-driven treadmill at 18 m/min up a 10% grade. The 11 best runners were then randomly divided into two groups, an exhaustive-exercise and a moderate-exercise group. Moderate exercise consisted of a 45-min run at 18 m/min on 10% grade. Animals in the exhaustive-exercise group were run for an hour at 18 m/min at 10% grade, following which the work load was increased to 27 m/min at 10% grade; most rats continued for at least another 30 min at this work load. Exhaustion was determined to be that point at which animals were no longer able to keep pace with the treadmill even in response to unpleasant stimuli. To insure maximum performance of experimental animals during exhaustive runs, a small, nylon-bristled brush was suspended immediately before the rear electrified wall of the treadmill compartment. Until the onset of fatigue, contact with the brush was usually sufficient to keep animals running at the front of the exercise compartment. However, as animals tired and tended to remain at the rear of the treadmill, an air jet was brought in to play as an additional stimulus. All experimental runs were conducted in a large room, with the temperature held constant at 73 ± 2 °F. Animals were placed on the treadmill at 7 min to 14 min before the run began. After the run, animals were placed in a recovery room and allowed to continue to run on the treadmill if they wished. The treadmill was then turned off and the animals were allowed to walk about the room for a period of 20 min. During this period, the temperature of the room was increased to 85 ± 2 °F.

The measured quantity of oxygen consumed above resting levels after severe exercise (the O₂ debt) is invariably at least 3 times larger than the theoretical debt estimated from the sum of all potential O₂-requiring sources (5, 11, 22, 23). Previous considerations of the biochemical basis underlying O₂ debt (12, 14, 15) have assumed that the coupling between the mitochondrial electron transfer chain and its associated ATP-synthesizing system was complete (i.e., that for each atom of oxygen consumed, about 3 molecules of ATP are synthesized), and that cellular respiration did not proceed at an appreciable rate in the absence of ADP. However, adequate attention has not been paid to effects of elevated tissue temperatures on respiration. Recent studies (1, 2) have indicated that O₂ debts were inexplicably high when tissue temperatures were increased as the result of exercise. This observation prompted us to determine operating temperatures on respiration.

The effects of high physiological temperatures on respiratory functions of rat skeletal muscle (4, 5) and liver mitochondria (4) in vitro were determined.

At high physiological temperatures, rat skeletal muscle (4, 5) and liver mitochondria (4) in vitro were characterized by a lower phosphorylative efficiency (ADP:O ratio) and a greatly increased respiratory rate in the absence of exogenous ADP (state 4). The decreased ADP:O ratio and increased state 4 respiratory rate at higher temperatures were ascribable to an increased mitochondrial ATPase activity, and a molecular mechanism consistent with the observed effects was presented (5). A temperature-dependent exaggeration of the respiratory rate in the absence of exogenous ADP and decreased phosphorylative efficiency (i.e., nonconservative respiration) could theoretically explain much of the large discrepancy between measured O₂ debts and estimates of debts based on resting concentrations of known potential O₂-requiring sources. In the present study we attempt to elucidate the relationship between tissue temperatures (muscle and rectal) and whole-animal O₂ consumption after exercise.

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ducted in a thermostatically controlled, heated and air-conditioned room in which the ambient temperatures ranged from 24 to 26 °C. No special care was taken to control movement of air across exercising animals because of the air-jet stimulator.

For temperature measurements after exercise, animals were rapidly placed in a Plexiglas restraining apparatus and two copper-constantan thermocouples were inserted, one by needle into the thigh muscles of the right hindleg and the other 5 cm into the rectum. Several hundred holes had been drilled in the walls of the restraining cage and several large cutouts were made where possible for the dissipation of heat. Temperatures were measured on a Minneapolis-Honeywell recorder. Due to difficulties in restraining non-exhausted rats, a temperature reading at the end of the 1st min of recovery was not possible in these animals. Resting temperatures of all animals were recorded using restraint, but only after a 48-hr respite from forced exercise. All temperature measurements were conducted in the same thermostatically controlled environment as during exercise runs.

For the measurement of rates of O₂ consumption in intact animals, a water-jacketed glass chamber (Quality Glass Blowing Co., Ann Arbor, Mich.) was used. Water temperature was maintained at 25.0 ± 0.1 °C by means of a heated and refrigerated bath (Forma Scientific, model 2095). In order to remove metabolic CO₂, the chamber was preloaded with CO₂ absorbent (Mallinckrodt Chemicals, St. Louis, Mo.), from which the animals were separated by a wire-mesh grid. Prior to the insertion of an animal, the walls of the chamber were swabbed with warm H₂O, and 30 ml of warm H₂O in a plastic cup were placed in the chamber beneath the grid to insure saturation of the environment with H₂O vapor. The system was then flushed with pure O₂, which had been bubbled through a diffuser to saturate it with H₂O₂ and sealed to await receipt of the animal. During insertion of the animal, the system was again flushed with H₂O-saturated O₂. A volumeter (model 160, Mcdc-Electronics, St. Louis, Mo.), connected to the metabolic chamber to form a closed system, was used to measure O₂ consumption by the animal. After a short period for pressure equilibration within the system following insertion of the animal, O₂ consumption in ATPS was read directly from the volumeter. Gas volumes were subsequently corrected to STPD by means of the appropriate factors (9).

O₂ consumption was observed in rats immediately after exhaustive exercise and during rest. To help minimize physical activity during measurements, a white cardboard shroud was placed around the cylindrical wall of the metabolic chamber, but the ends were left open so that animals could be observed. Initially, attempts were made to perform oxygen consumption measurements while animals were restrained, as during the determinations of tissue temperatures. Although the average resting values obtained using restraint were similar to some published values (16), the minute-to-minute values were very erratic. As expected, it was observed that attempts by the animals to free themselves from restraint resulted in increased O₂ consumption during that period. If the animals were left in the chamber unrestrained, however, significantly lower, and less variable, readings were obtained. Therefore, it was decided not to use restraint during O₂ uptake determinations and to perform measurements only during the ebb of the animal’s diurnal activity cycle.

Postexercise O₂ consumption was measured on 10 animals randomly selected from among those used in the temperature experiments. Animals were not postabsorptive since they were used immediately after removal from communal cages. The rats were again run to exhaustion and immediately sealed in the metabolic chamber. After a 2-min lag period, O₂ consumption was recorded continuously at 1-min intervals over a 1-hr recovery period. During all metabolic measurements, rats were observed and activity was noted. In nonexercised animals, the lowest O₂ consumption rate recorded for a consecutive 10-min period was taken to represent the resting rate.

Problems in measurements of O₂ consumption due to movement were also encountered during recovery from exhaustive exercise. Immediately after exhaustion and insertion into the chamber, rats made no attempt to move about in the chamber. Generally, they remained quiescent for the first 15–20 min of recovery. After that time, however, they were usually sufficiently recovered to investigate their environment. To correct the metabolic measurements for this uncontrolled activity of animals, it was decided to report the data in 5-min intervals. Any sudden, unexpected, large 1-min readings associated with movement during recovery were rejected, and the previous minute’s value substituted. The seven experiments reported are ones in which the animals were relatively inactive during recovery runs.

According to the well-known Q₁₀ effect, one would expect to observe a direct correlation between tissue temperature and O₂ consumption rate. As a reflection of this, a close temporal correspondence should exist between the decay curves for tissue temperature and O₂ consumption rate. This is indeed the case.

Temperature changes after exhaustive exercise. Figure 1 shows the decline of muscle and rectal temperatures (mean ± se) after both exhaustive and moderate bouts of exercise. Resting temperatures (mean ± se) are indicated by cross-hatched areas. Severe physical exercise resulted in an 8.1 °C increase in muscle temperature and 5.1 °C increase in rectal temperature. Thus, the normal temperature gradient that existed between core and periphery at rest was reversed in the immediate postexercise period. On the cessation of extreme exertions (i.e., at exhaustion), muscle temperatures initially fell exponentially, but did not reach control values even after an hour (P < 0.02). Rectal temperature did not fall as rapidly as did muscle temperature and, in fact, in several instances did not reach a peak until the first minutes after exercise ceased. The rectal temperature curve was sigmoidal, with the most rapid phase of decrease occurring between the 4th and the 20th min of recovery. After about 20 min of recovery, a plateau was reached at about 40 °C. Rectal temperature thereafter declined very slowly during recovery (slope = -0.025 °C/min) and was still about 1.6 °C above resting at the end of an hour (P < 0.01). Resting rectal temperatures (38.3 ± 0.1 °C) corresponded to published values for rats of similar sex and age (7).
TEMPERATURE AND \( O_2 \) CONSUMPTION POSTEXERCISE

**Fig. 1.** Thigh muscle and rectal temperatures of rats as a function of time after exhaustive and moderate bouts of physical exercise. Each point represents mean \( \pm \) se of seven experiments. Resting rectal and muscle temperatures (mean \( \pm \) se) are indicated by cross-hatched areas. Points at 0 time after moderate exercise are extrapolations and confidence limits are not given.

Temperature changes after moderate exercise. At the end of moderate exercise (Fig. 1), muscle and rectal temperatures were significantly elevated compared to their resting levels. Both muscle and rectal temperatures at \( t = 0 \) were estimated by extrapolation from the adjacent empirically derived points, and hence confidence limits are not given. In the rectal temperature curve, this point coincided with the linear extrapolation of the plateau attained during recovery. Muscle temperature after moderate exercise fell exponentially, but unlike the exhaustive situation, resting levels were reached within an hour (\( P = 0.4 \)). It is interesting that rectal temperature invariably reached a maximum several minutes after cessation of moderate exercise. This peak was transient, and within 0–10 min a gradual, steady rate of return to the resting temperature was established. As after severe exercise, the plateau in rectal temperature reached after moderate exercise was around 40 C. After an hour of recovery from moderate exercise, rectal temperature was still approximately 1 C above the resting level.

\( O_2 \) consumption in vivo. The decline in \( O_2 \) consumption rate after exercise in rats (Fig. 2) is similar to that reported previously (16). \( O_2 \) consumption was high immediately after exercise, and declined exponentially for approximately the first 20 min of recovery. Thereafter, \( O_2 \) uptake leveled off, and only a gradual rate of decline was apparent. During this plateau phase, the slope of the decline in the \( O_2 \) consumption rate with respect to time was only \(-0.05 \) ml \( O_2 \) kg\(^{-1}\) min\(^{-1}\). After an hour of recovery, the rate was still significantly elevated above resting (\( P < 0.01 \)). Our measured values for resting \( O_2 \) consumption rates (17.8 \( \pm \) 0.5 ml \( O_2 \) kg\(^{-1}\) min\(^{-1}\)) better reflected the true resting metabolic rate than those of McArdle (16) (23.4 ml \( O_2 \) kg\(^{-1}\) min\(^{-1}\)), who did not correct for physical activity, and approach published values of 11.9–1.26 ml \( O_2 \) kg\(^{-1}\) min\(^{-1}\) established as the absolute minimum \( O_2 \) consumption in rats of similar age and sex while anesthetized or sleeping (7).

DISCUSSION

Large excursions in both internal and muscle temperatures in rats as a result of extreme exertion corroborate reports of similar findings in humans (18–20). Additionally, Dr. Lamb (personal communication) has observed that the gut temperatures of guinea pigs forced to exercise exceed those reached in rats by several degrees centigrade. As originally described by Nielsen (17) and discussed by Snellen (21) in a recent review, internal temperatures in humans during exercise are proportional to the overall metabolic rate. Our results obtained on rats confirm this.

Muscle and rectal temperatures at exhaustion of 44.1 \( \pm \) 0.1 C and 43.4 \( \pm \) 0.1 C, respectively (Fig. 1), indicate that the heat load generated by the musculature resulted in a large increase in both muscle and internal temperatures. Presumably, this heat load was sufficient to drive the internal temperature up despite the activity of heat loss mechanisms. Whereas at rest, core temperature always exceeds that of skeletal muscle (19, 20), this gradient is reversed following extreme exertion. Thus, the core may function to absorb the peripheral heat load helping to maintain muscle temperature below the points where a reduction in phosphorylative efficiency (4, 5) and massive irreversible thermal damage may occur.

Temperature changes in core and muscle after moderate bouts of exercise can be interpreted as supportive of the hypothesis that the core functions somewhat as a heat sink for the musculature. Such a mechanism may operate not only during exercise, but immediately afterward also. The peak in rectal temperature coinciding with the rapid decline
in muscle temperature after moderate exercise (Fig. 1) is interpreted as the result of heat being carried from the musculature to the core by vascular conduction. Similarly, the rapid decline in muscle temperature parallel with a slower decline in rectal temperature during the first 4 or 5 min of recovery from exhaustion (Fig. 1) can be explained as a "heat-dumping" phenomenon.

Following both exhaustive and moderate exercise, rectal temperature fell and then reached a plateau. In view of the great rate at which animals were able to dissipate heat in the early minutes of recovery, it is interesting that rectal temperature did not return to normal sooner. Nielsen (17) has hypothesized that during physical exertion there is an elevation in the set point of the hypothalamic temperature control center. Irrespective of ambient temperature or the efficacy of the environment for heat conduction, even moderate exercise has been observed to result in an elevation of internal temperature (21) and also, supposedly, the hypothalamic set point.

The great rates at which muscle and rectal temperatures fell immediately after the cessation of exercise also indicate that the restraining apparatus did not limit the dissipation of heat. Moreover, this conclusion is supported by the observation (data not reported) that restraint for periods as long as the postexercise recovery period (1 hr) did not result in increased temperatures.

Our experiments showed (Fig. 1) that even after an hour of recovery from only moderate exercise, rectal temperature was still significantly elevated above normal, and only a gradual rate of return toward the resting value was apparent. We interpreted this prolonged elevation in O2 consumption after exercise to be due, in part, to the hypothalamic readjustment hypothesized by others (17, 21). The determinations by Benedict and Cathcart (3) of elevated BMR in humans 24 hr or more after the cessation of physical exercise may also be explained, in part, in this way.

Additionally, it is possible that the elevated postexercise internal temperature is, in part, a reflection of increased nonconservative respiration by a population of mitochondria which sustained a degree of thermal damage during exercise. Such a mechanism, suggested by our studies on isolated skeletal muscle and liver mitochondria (4, 5), cannot yet be excluded as contributory to elevated postexercise O2 consumption.

The postexercise pattern of return to a normal rate of O2 consumption in rats is similar, in general, to that of humans (23). However, because a rat's high resting metabolic rate prevents it from increasing its O2 consumption more than 4 or 5 times during exercise (6), whereas in humans the exercise O2 consumption rate may exceed 20 times the resting rate, there are some differences between the postexercise recovery curves of the two species. As opposed to the fairly rapid return toward normal of the O2 consumption rate of humans after exercise (23), the O2 consumption rate of rats recovering from exercise returned to normal only slowly (Fig. 2), with a relatively prolonged elevation in the plateau phase. Nevertheless, because of the similarity of the postexercise O2 consumption curves among different species, the results of this investigation make possible a new and more meaningful description of the general phenomenon of elevated postexercise O2 consumption referred to as the O2 debt.

Figure 3 shows a composite of Figs. 1 and 2; the top set of coordinates depicts the rate of O2 consumption after exhaustive exercise, and below this are shown the decay curves of muscle and internal temperatures. The decline in the rate of O2 consumption after exercise is comprised of two phases. Phase 1 is typified by a rapid decrease in the rate of O2 consumption. In the rat, this phase lasts 15 to 20 min (Fig. 2), and O2 consumed during this period probably represents that used to reesterify creatine and ADP, perhaps...
at a reduced phosphorylative efficiency (4, 5), as well as that which is consumed due to the direct acceleration of respiration by increased muscle and core temperatures. Since the resynthesis of ATP and CP requires only a few minutes (8) and can account for only a small fraction of the total O₂ uptake (5, 11, 22, 23), a substantial part of the O₂ consumed during this initial phase must be nonconservative O₂ consumption due to the direct stimulation of cellular respiration by the elevated temperature. Cardiorespiratory work is also undoubtedly responsible for some of the O₂ consumption during this phase (14, 23).

Phase 2 is typified by a slow decline in the rate of O₂ uptake toward the resting level (cross-hatched area). During this phase, the O₂ consumption rate may remain elevated above the resting level because of an adjustment in the hypothalamic set point of core temperature. The demand for O₂ to provide energy for endergonic processes, such as mitochondrial repair, gluconeogenesis, and other anabolic activities, would also contribute. The influence of increased circulating levels of hormones, especially epinephrine and thyroxine, may also play a role in determining the increased O₂ consumption rate observed during both phases of recovery after exercise (13).

Our observations of prolonged increases in both internal and muscle temperatures following severe exercise, their correlation with O₂ uptake rates, and the effects of such elevated temperatures on muscle and liver mitochondrial respiration in vitro require that current concepts of post-exercise O₂ consumption be modified. The mere fact that strenuous exercise results in a large, prolonged elevation in tissue temperatures necessitates, as a consequence of the Q₁₀ effect, that O₂ consumption be significantly elevated when temperature is. DuBois (10) has shown that the basal metabolic rate in humans during fever is increased about 13% for each degree centigrade elevation in body temperature. Exercise-induced hyperthermia has a similar effect. Moreover, mitochondrial studies (4, 5) clearly show that at high physiological temperatures this increase in O₂ consumption occurs at the expense of energy-trapping efficiency.

The data presented here strongly support our contention (4, 5) that there exists a previously undescribed major component contributing to the total O₂ consumption observed after exercise which is independent of the so-called “lactacid” and “alactacid” debts. This component is not directly related to the repayment of an energy debt. It is, in fact, largely nonconservative in nature, and is a consequence of the well-known effect of temperature on the rates at which biochemical reactions proceed. On this basis it would appear that it is not valid to equate the extra O₂ consumed after exercise with the anaerobic metabolism which occurs during exertion. Since much of the O₂ consumed after exercise may be unrelated to recovery from anaerobic metabolism, it is suggested that the applicability of the term “O₂ debt” be carefully reexamined. Other investigators (11, 22) concur with us in this conclusion. We recommend the adoption of a descriptive term such as “postexercise O₂ consumption” be considered.

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