ENVIRONMENTAL PHYSIOLOGY
Printed in U.S.A.

Heat exchange and energetic balance during exercise in highlanders and lowlanders at sea level and high altitude

Reprinted from Proceedings of
International Symposium on Environmental
Physiology (Bioenergetics)
FASEB, 1972

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THIS STUDY WAS DESIGNED to determine the effects of changes in both cutaneous circulation (15) and kinetics of oxygen uptake (20) at high altitude on mechanisms of heat exchange during exercise. From a theoretical point of view, determination of heat balance by partitional calorimetry is an interesting complement to metabolic balance that has been studied comparatively many times at low (SL)[1] and high (HA) altitudes (5, 10, 18) on lowlanders during acclimatization and in highlanders (14, 21).

METHODS

The experiments were performed on three lowlanders (LL) in Paris (46 m) and after 3 weeks in La Paz (3,800 m), and on five native residents of La Paz (HL) at high altitude. Globe temperature (T_g), dry bulb temperature (T_{db}), and wet bulb temperature (T_{wb}) were measured every 10 min. P_{H_2O} was calculated from T_{db} and T_{wb} according to Bergier (3).

The esophageal and rectal thermocouples (measuring T_e and T_{re}, respectively) were inserted 60 cm and 25 cm, respectively; 10 skin thermocouples were placed so that the junctions were in contact with the skin. The subjects were dressed in shorts and shoes. After 1 hour of rest, control measurements were made. The subject was weighed on a scale accurate to ±20 g. Submaximal exercise began abruptly and continued for 25 min on a bicycle ergometer (type Minjhart) at constant speed of 60 rpm; the mechanical power ($\dot{W}_{mec}$) was about 53 W/m^2.

Electrically calibrated copper-constantan thermocouples were connected to a potentiometric recorder. The different body temperatures were measured every 2 min. Mean skin temperature ($\bar{T}_s$) was computed from the average of 10 skin temperatures weighted according to the site explored (11).

[1] Abbreviations: SL, low altitude; HA, high altitude; LL, lowlanders; HL, highlanders.

The subjects breathed through a mouthpiece. The expiratory gases were collected in Douglas bags every minute during exercise and the first 5 min of recovery, and at longer intervals afterward. Oxygen consumption ($\dot{V}_{O_2}$) was measured using an open-circuit method. The subject was weighed again after 5 min of recovery. The variables used in the total energetic balance equation were calculated as follows:

$$\dot{W}_{O_{2sse}} = \dot{W}_{rc} + \dot{W}_e + \dot{W}_{mec} + \dot{W}_s \qquad (1)$$

where $\dot{W}_{O_2}$ = metabolic rate computed from $\dot{V}_{O_2}$ (20 kJ/lO_2); $\dot{W}_{rc}$ (R + C) = sum of rates of radiant and convective heat loss; $\dot{W}_e$ (E) = rate of evaporative heat loss; $\dot{W}_s$ (S) = rate of heat storage; $\dot{W}_{O_{2sse}}$ = metabolic rate during the steady state of exercise.

Symbol $\dot{W}$ expresses power in watts per square meter (w/m^2). A dot over any symbol denotes the time rate of change, and obviously the symbols of *equation 1* are substituted to those used for special quantities of body heat balance (13).

$\dot{W}_{rc}$ was calculated with the following linear coefficients (h) (25).

$$h_r = 3.8 \text{ kcal/h per m}^2 \text{ per C}$$

$$h_c = [1.9 + 6.4\, \nu^{0.67}] \frac{P_B{}^{0.67}}{760} \qquad (2)$$

$$h_{rc} \text{ at SL} = 6.6 \text{ w/m}^2 \text{ per C}$$

$$h_{rc} \text{ at HA} = 6.1 \text{ w/m}^2 \text{ per C}$$

$$\dot{W}_{rc} = h_{rc}/(T_g - \bar{T}_{s\,t1,t2\ldots})$$

$\dot{W}_e$ was calculated from the total weight loss corrected for expired carbon. Enthalpy of evaporation was 2.4 kJ/g. The rate of heat storage ($\dot{W}_s$) during 2 min was calculated as follows:

$$\dot{W}_s = \frac{0.84 \text{ kcal} \times \text{body weight} \times (0.8\ \Delta T_{core} + 0.2\ \Delta \bar{T}_s) \times 4.180}{\text{BSA m}^2 \times 120 \text{ sec}} \cdot (\text{w/m}^2 \text{ per C}) \quad (3)$$

Physiological conductance ($h\phi$) was directly and indirectly computed at the steady state of exercise according to the following equations:

$$h\phi \text{ direct} = \frac{\dot{W}_e + \dot{W}_{rc}}{T_{es} - \bar{T}_s} \quad (4)$$

$$h\phi \text{ indirect} = \frac{\dot{W}_{O_2} - (\dot{W}_{mec} + \dot{W}_s)}{T_{es} - \bar{T}_s} \quad (5)$$

$h\phi$ has been calculated also using T_{es}.

RESULTS

Thermal Data (Table 1, Fig. 1)

Environmental data. T_g is the same at SL and HA (20.5 C, 20.9 C). Even though T_{wb} is lower at HA, P_{H_2O} is not very different from P_{H_2O} at SL because P_B is introduced in its calculation (3), (SL = 9.3 and HA = 8.1 torr).

Core and skin temperatures. The increase of T_{re} falls behind that of T_{es}, and at the 25th min of exercise, there is no identity between the two core temperatures. The absolute difference of T_{es} between rest and the end of exercise is similar for the three types of experiments (LL at SL = +0.55 C; at HA = +0.57; and HL = +0.65). The values of T_{re} are more scattered so calculations including T_{core} are calculated with T_{re} and T_{es}. In previous experiments (12), T_{es} was studied as a function of anatomic references. The thermocouples located near the left atrium and the stomach area gave the same temperature independent of expiratory mean flow.

There is not a plateau in T_{es} or T_{re}. There is a steady temperature increase at the end of exercise. The most interesting results are: *a*) the increase of $\bar{T}_s$ at the end of exercise in LL and HL in their own environment (LL = +0.85 C; HL = +0.47); *b*) the decrease of $\bar{T}_s$ in LL translocated to HA (LL = −0.47). The forehead and hand temperatures are given as examples of local temperatures.

TABLE 1. *Body temperature changes at the 25th min of exercise and environmental characteristics*

	Sea Level, 50m	High Altitude, 3,800m	
	LL	LL	HL
ΔT_e C	+0.55	+0.57	+0.65
ΔT_{re} C	+0.32	+0.45	+0.60
$\Delta \bar{T}_s$ C	+0.85	−0.47	+0.47
T_g C	20.9	20.5	20.9
P_B torr	761	493	494
P_{H_2O} torr	9.3	8.1	8.8

Energetic Data

Metabolic rate. At rest, $\dot{W}_{O_2}$ is higher for LL translocated to HA. This fact has already been described for the same subjects at HA (19) and confirms the identical observation made by other investigators (7, 9). However, gross $\dot{W}_{O_2}$ at steady-state exercise is identical for LL at SL and HA (265 w/m²; 276 w/m²). The $\dot{W}_{O_2}$ at steady-state exercise of HL is larger (322 w/m²) than $\dot{W}_{O_2}$ of LL because the mechanical power per square meter is higher. This discrepancy does not affect the general conclusions.

Heat loss and heat storage. At rest, the sum of the radiant and convective heat loss ($\dot{W}_{rc}$) is larger than $\dot{W}_{O_2}$ in the three groups. This probably means that the body is

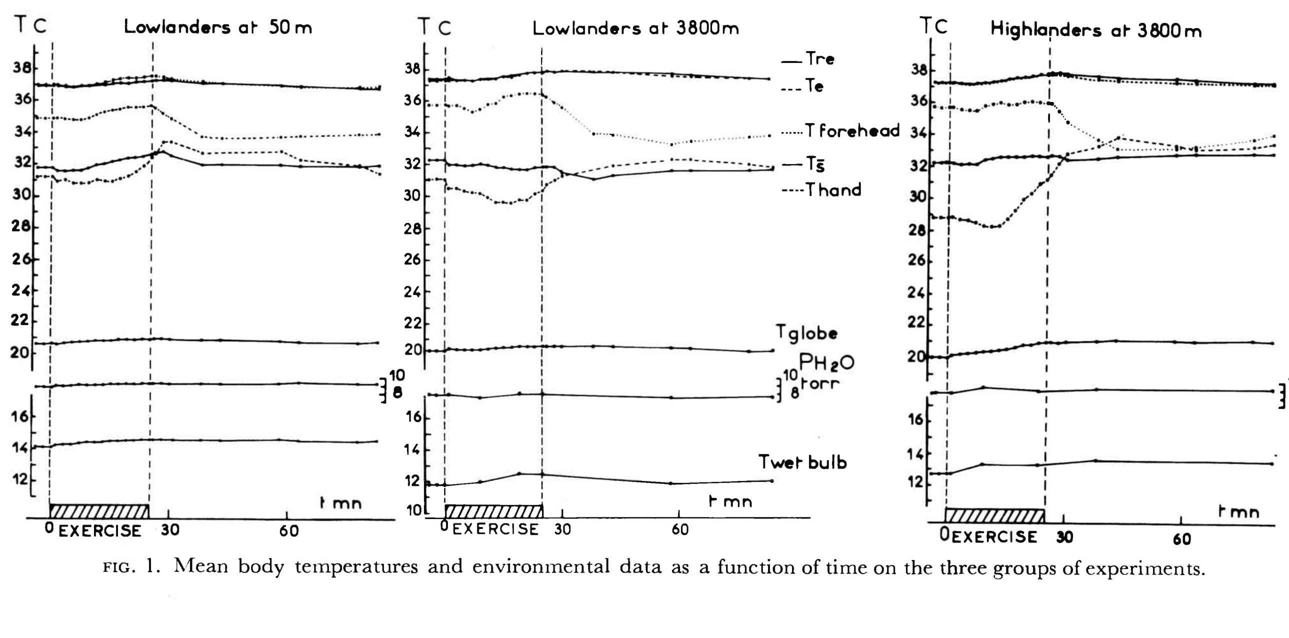

FIG. 1. Mean body temperatures and environmental data as a function of time on the three groups of experiments.

cooling off because the nude surface of the body exposed to air is too large.

During exercise, $\dot{W}_{rc}$ increases slightly for subjects in their original environment because $\bar{T}_s$ increases during exercise. $\dot{W}_{rc}$ decreases in LL at HA on account of the decrease in $\bar{T}_s$.

The evaporative rate ($\dot{W}_e$) is calculated from the weight loss measured at the 5th min of recovery. $\dot{W}_e$ is not corrected for ventilatory $\dot{W}_e$. The calculation of ventilatory $\dot{W}_e$ involves too many hypotheses, because P_{H_2O} and temperature of the expired air were not measured. $\dot{W}_e$ by the skin is obviously overestimated at HA but the error is the same for the two groups of subjects at HA. Since the rate of weight loss was impossible to follow, it is assumed that $\dot{W}_e$ is constant throughout the exercise. It is interesting to note that $\dot{W}_e$ is larger for LL at HA (129 w/m²) than at SL (96 w/m²). The increase is due to a greater rate of sweating because P_{H_2O} and T_g are similar at SL and at HA.

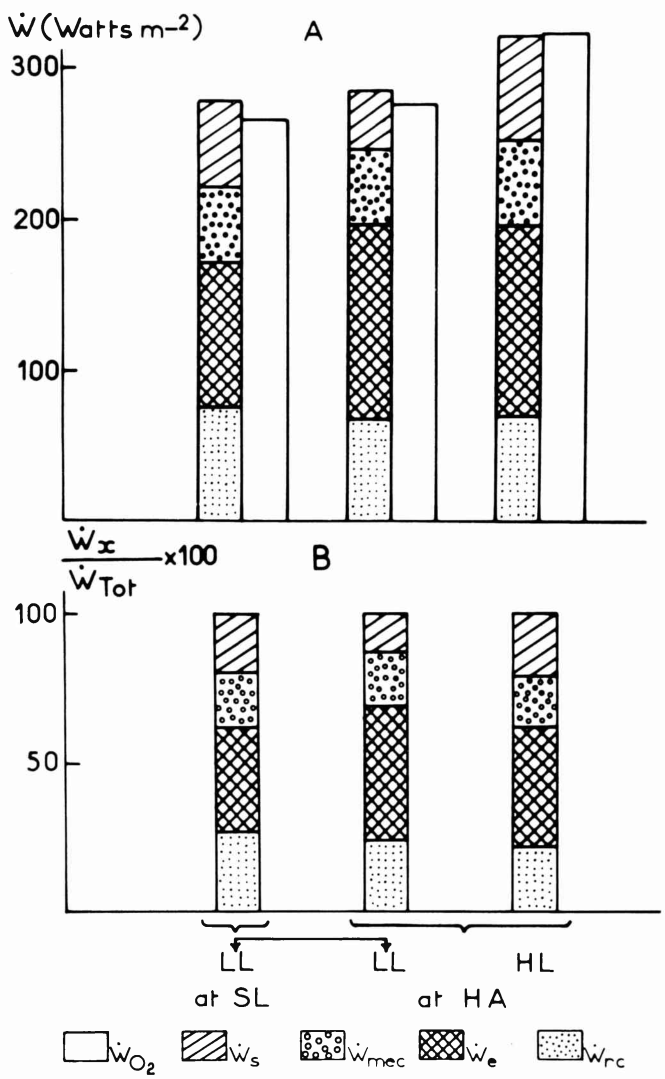

FIG. 2. Comparison of the energetic balance in *A:* absolute and *B:* relative value. This balance has been computed from the experimental data obtained between the 15th and 25th min of muscular exercise.

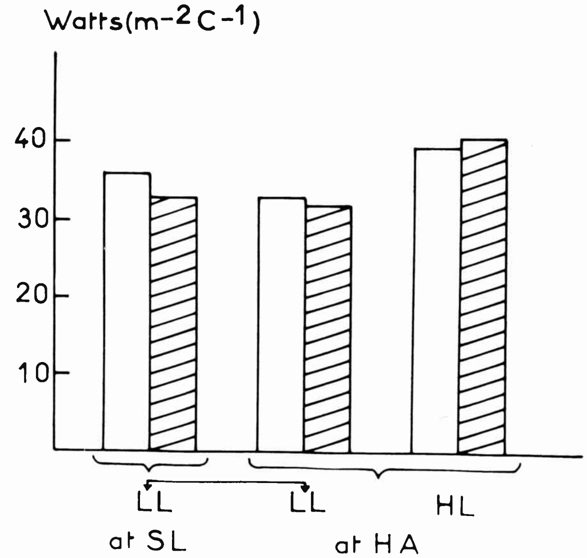

FIG. 3. Physiological conductance (hϕ) computed at the 25th min of exercise from T_{re} and $\bar{T}_s$ through the direct method (*eq 4*, white column) and indirect method (*eq 5*, hatched column).

The rate of heat storage ($\dot{W}_s$) has been calculated with the same ratio of core–shell to body mass at SL and HA. The decrease of $\bar{T}_s$ is responsible for the smaller $\dot{W}_s$ in LL at HA.

The different elements of the balance that have been calculated above are represented in Fig. 2*A*. This figure compares aerobic energetic input flow to the sum of the energetic output flows. This balance has been calculated during the last 10 min of exercise. All the values are measured independently. There is a good agreement between the two members of *equation 1*. Since $\dot{W}_{O_2}$ is not exactly identical on LL and HL, the elements of the balances are in percentage of total values in Fig. 2*B*. Therefore, it is easier to compare the different energy losses (thermal and mechanical). Physiological conductance (hϕ) had been calculated by two independent methods: the direct method using *equation 4*, and the indirect method using *equation 5*.

Figure 2 depicts the equality of the two terms of the balance, so it is not surprising to find a very small difference between the values of hϕ computed through the two methods (Fig. 3). It is seen that hϕ in LL at HA (37 w/m² per C) is slightly lower than at SL (33 w/m² per C).

DISCUSSION

Four results must be emphasized: *a*) As shown in Fig. 1, the body continuously stores heat. The thermal steady state is not reached at the 25th min of exercise nor later as it has been reported (23). *b*) The total energy production ($\dot{W}_{O_2}$) is identical for the three groups of subjects. Hence, if the efficiency is equal, the absolute heat load is comparable at SL and HA. *c*) The rise in core temperature is the same for subjects at HA and SL; so the results of thermoregulatory mechanisms are affected neither by the decrease of P_B nor by the relative workload. The relative workload increases at HA because of the decrease of $\dot{V}O_{2max}$ (2, 6). These results agree with Asmussen (1) and Greenleaf et al. (8) and support Nielsen's hypothesis that the level of core temperature is not affected by environmental conditions and depends only on thermoregulatory adjustments (16, 17). *d*) Figure 2*A* shows that the experimental data closely fit that calculated from *equation 1.* Hence, it seems well founded to calculate energy balance at exercise and to use the same core–shell ratio in the calculation of heat storage. When LL are exercising at SL or HA, the heat production ($\dot{W}O_2$–$\dot{W}_{mec}$) is equal in the two cases, so is, obviously, the sum of heat loss by the different mechanisms and heat storage. However, the relative importance is different: at HA, convective heat loss ($\dot{W}_c$) is lower because of a lower PB (*eq 2*). Radiant heat loss is also diminished because of a cooler skin temperature. For this latter reason, a decrease in heat storage in the shell occurs at HA. The core temperature following the same time course in the two environments does not induce by itself a change in $\dot{W}_s$. Consequently, from a theoretical point of view, one has to expect that evaporative heat loss is larger on LL translocated to HA if the balance is equilibrated. This logical necessity is experimentally verified.

In conclusion, during exercise the circulatory system has to satisfy two simultaneous needs: *a*) an increase in blood flow to working muscles for oxygen and fuel supply; and *b*) an increase in blood flow to the skin for heat dissipation (4, 22, 24).

In this conflicting situation, the partition of blood flow is different at SL and HA. At HA there is a reduction in cutaneous blood supply at rest and exercise (15) probably for the benefit of the working muscles.

Even though skin blood flow decreases, the mechanisms of thermoregulation, at least for moderate exercise, are efficient since the same absolute heat load induces the same increase of core temperature at SL and HA. High altitude modifies the relative part of heat dissipating mechanisms; $\dot{W}_e$ becomes larger and $\bar{T}_s$ becomes cooler. The same heat flow from the core to the shell is possible in spite of a decrease in cutaneous blood flow because the difference of temperature between core and shell is larger. However, the mechanisms of these new adjustments remain unclear.

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