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Heart rate and rectal temperature relationships during work in hot humid environments

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KAMON, ELIEZER, AND HARWOOD S. BELDING. *Heart rate and rectal temperature relationships during work in hot humid environments.* J. Appl. Physiol. 31(3): 472–477. 1971.—Nine young male subjects, acclimatized to heat, were exposed for 2 hr daily to work at about 25–35% of their maximal aerobic capacity in ambient temperatures of 36–37° C and under the following treatment combinations: seminude or clothed, ambient water vapor pressure (P_a) at levels up to 40 mm Hg, wind velocities of 1.0, 2.5, or 3.3 m/s, and level walking at either 3.2, 4.5, and 5.6 km/hr. P_a either *a*) was kept constant throughout the 2 hr but changed from day to day, or *b*) was kept constant during the 1st hr then was raised by 1 mm Hg each 10 min of the 2nd hr. Continuous recording of rectal temperature (T_{re}) and heart rate (HR) showed that up to a certain critical P_a, depending on the other exposure conditions, the equilibrium level of each parameter is independent of P_a: T_{re} at about 37.9° C with small interindividual variation, HR at about 115 beats/min with large interindividual variation. Beyond the critical P_a both T_{re} and HR either equilibrate at higher levels or continue to rise to the end of the exposure time. Consecutive 10-min values of the experiments at and above the critical P_a were tested for linear correlation between T_{re} and HR. Individual regressions of T_{re} on HR averaged 0.029° C/beat, with an average standard error of estimate of ±0.27° C, and agreed well with regression coefficients computed for some of the data in the literature on similar work levels but over a wider range of ambient air temperatures.

body temperature during work in heat; heart rate during work in heat; regression of rectal temperature on heart rate

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EXERCISE INVOLVES ADJUSTMENT of heart rate and body core temperature to levels above resting; the rise to the "steady state" of both parameters is proportional to the work load performed by the individual (1–3, 9, 13, 18). In some studies it was shown that for a wide range of climatic conditions both rectal temperature and heart rates equilibrate at a level independent of ambient temperature (11, 17). However, it has also been reported that in warmer environments heart rates may equilibrate at higher levels, whereas rectal temperatures are unaffected (12).

At even higher temperatures or humidities rectal temperature and heart rate both rise, either toward a higher equilibrium value or to the limit of tolerance (7, 14, 16).

For practical purposes observations on prolonged work in the heat must be restricted to light or moderate work which requires about 0.8–1.2 L oxygen/min and represents about 25–35% of the maximal aerobic capacity (1, 2). These levels of work have been used in several studies of physiological responses to work in hot environments (7, 11, 17, 18).

The principal purpose of this paper is to describe the time course of rectal temperature and heart rate and demonstrate the relationship between these two parameters for moderate work. The observations were restricted to ambient air temperature of 36–37° C but variable heat stress was provided by using a wide range of ambient water vapor pressure.

PROCEDURE

The nine male student participants were preacclimatized to work in hot environments by ten 2-hr exposures to dry heat (T_a = 40° C; P_a = 13 mm Hg). Every Monday was devoted to reacclimatization under the above conditions. The experiments were carried out daily, Tuesday through Friday, each individual always at the same time of day. Each testing session lasted 2 hr.

Table 1 summarizes the treatments. Air temperature (T_a) was kept at either 36 or 37° C. Water vapor pressure in the air (P_a) either *a*) was kept constant throughout the 2-hr exposure but changed from day to day in an attempt to find the effect of rise of P_a on rectal temperature (T_{re}) and heart rate (HR), or *b*) was kept constant during the 1st hr of exposure then raised by about 1 mm Hg each 10 min of the 2nd hr. Under the second protocol the P_a for the 1st hr was set at a level where T_{re} was humidity independent, i.e., where free evaporative cooling was sufficient to allow T_{re} equilibrium at its characteristic work-specific level. During the 2nd hr the step-wise elevation of P_a was intended at some point to bring about environmentally induced rise in T_{re}. For each exposure the air speed was set at one of three levels and the subject was either seminude or clothed (Table 1). Seminude included shorts and gym shoes. When "clothed" the subjects wore khaki, long-sleeved shirt, and trousers. Table 1 includes a listing of some extra experiments on one subject (*DW*) in hot, dry ambient conditions (T_a = 40–50° C; P_a = 12 mm Hg).

The physical characteristics of the subjects, oxygen uptake ($\dot{V}O_2$), and the percentage from the $\dot{V}O_{2\,max}$ for the administered walking speed are presented in Table 2. The % $\dot{V}O_{2\,max}$ was about 20 for walking at 4.5 km/hr and 33 for walking at 5.6 km/hr for *group A* and *group C*. The two subjects in *group D* showed a somewhat lower % $\dot{V}O_{2\,max}$

(24) for walking at 5.6 km/hr and 15% for walking at 3.2 km/hr.

The subjects reported to the laboratory 1 hr prior to the testing time. The preparations for the test included the following: attachment of chest electrodes for the recording of heart rates, insertion of a thermister probe into the rectum (about 10 cm), and careful adjustment of an ear thermocouple. For the latter a custom-molded earplug (Bioplastic; Ward's Natural Science Establishment, Inc.) was used. Thermocouple wires (copper constantan; 40 AWG) were inserted through a hole drilled in the plug.

The subject determined the placement within the meatus by sliding the thermocouple inward to the point where he felt pain. Then the assistant withdrew the wires by about 1 mm and taped them to the outside of the plug. No further insulation was applied over the plug because the expected gradient between T_a and T_{ea} was never more than 2.0° C. After that the subjects sat quietly outside the temperature-controlled room (T_a = 22–24° C). Upon entering the exposure chamber they sat for 10 min before walking.

Every 0.5 hr the walking was stopped for 3 min during which the subject was weighed and given tepid water to replace the weight loss.

METHODS

Oxygen consumption was measured twice, at the 40th and the 70th min of the experiment. The open-circuit method was used. Expired air was collected in a wet spirometer; oxygen partial pressure of inspired and expired air was measured using a Beckman C paramagnetic oxygen analyzer.

A cardiotachometer which integrates the R-to-R wave intervals was used directly to monitor heart rates.

Rectal, ear, and air temperatures were monitored continuously on a multichannel recorder. Dry bulb and wet bulb air temperatures were also recorded as a basis for precise control over the vapor pressure (±1 mm Hg). Skin temperature was measured every 10 min with thermocouples at the following six sites: the right-side forearm, chest, back, forehead, and right and left thighs. When tested in seminude condition the subject was asked to use a 30 AWG copper-constantan thermocouple which was stretched on a bow. He lightly pressed the junction point to each site until the recorded temperature stabilized. When a subject was tested in "clothed" condition, prior to putting the cloth on, a thermocouple was held over each site with the aid of a ring glued to the skin with collodion; the junction was not covered. The averaged value was used as skin temperature ($\bar{T}_s$).

Thermal conductance (k) was calculated from the following equation:

$$k = M/(T_{re} - \bar{T}_s)$$

where

k = W/(m²·°C)
M = W/m² calculated from the measured oxygen consumption
T_{re} = rectal temperature, °C
$\bar{T}_s$ = skin temperature, °C

TABLE 1. *Number of 2-hr exposures at controlled air vapor pressure (P_a) conditions*

Subj	Air Temp, °C	Wind Speed, m/sec	Seminude		Clothed	
			P_a range, mm Hg	No. of exposures	P_a range, mm Hg	No. of exposures
I. P_a kept constant throughout 2 hr						
JS	37	1.0	19–40	13	19–32	9
		3.3	29–40	4	25–33	4
LH	37	1.0	21–40	10	19–32	7
		3.3	19–40	12	21–35	7
DW	37	1.0	19–37	9	18–33	9
		3.3	20–38	8	22–33	6
DB	36	1.0	20–37	7	18–32	6
		2.5	22–37	8	22–34	7
WJ	36	1.0	18–37	7	16–27	8
RP	36	1.0	20–36	7	21–30	5
		2.5	22–37	7		
DW	40–50	1.0		3		3
		3.3	12	3	12	1
II. P_a kept constant during 1st hr and raised every 10 min during 2nd hr						
MK	36	1.0	18–30	9		
		2.5	28–32	3		
		1.0	28–37	7	16–26	2
KC	36	2.5	30–40	4	28–38	2
		3.3	32–40	3	29–37	2
		1.0	27–35	6	16–22	2
MS	36	2.5	22–40	3	27–34	2
		3.3	33–40	2	29–36	2

TABLE 2. *Subjects grouped according to ambient air vapor pressure and walking speed, showing their ages, physical characteristics, oxygen requirements, and percent of max O_2 uptake*

Group	Walking Speed, km/hr	Subj	Age, yr	Ht, cm	Wt, kg	O_2 Uptake, L/min	% Max O_2 Uptake
*I. Constant vapor pressure**							
A	4.5	*JS*	24	179	68	0.83	20†
		LH	22	175	63	0.71	18†
		DW	22	183	86	0.95	26
B	5.6	*DB*	22	177	75	1.12	30
		WJ	21	180	83	1.30	31
		RP	20	172	74	1.13	40
*II. Increasing vapor pressure**							
C	4.5	*MK*	21	163	65	0.82	23
	5.6					1.14	33
D	3.2	*KC*	22	168	68	0.60	14
	5.6					1.05	23
	3.2	*MS*	22	178	67	0.72	16
	5.6					1.22	25

* *I:* air vapor pressure was kept constant throughout 2-hr of each experiment. *II:* air vapor pressure was kept constant during the 1st hr and raised every 10 min during 2nd hr of exposure. † $\dot{V}O_{2\,max}$ was estimated by extrapolation from several submaximal tests on a bicycle ergometer.

In effect this represented dermal conductance except that no correction was made for heat loss by respiratory evaporation. Under our circumstances of moderate work, requiring minute O_2 uptake of 0.7–1 L the respiratory evaporative heat loss value was only 2–6% of the metabolic rate.

Possible changes in body heat content were not taken into account because on the few occasions under the highest P_a when T_{re} was not at equilibrium the rate of change was not more than 0.1° C for the 15 min; this could lower the conductance value by only 7%.

RESULTS

Typical time courses of heart rate (HR) and rectal temperature (T_{re}) are given in Fig. 1*A* for work under constant vapor pressure (P_a) throughout and in Fig. 2*A* for work under constant P_a during the 1st hr and increasing P_a during the 2nd hr of exposure. It should be noted that after the beginning of work at constant P_a both HR and T_{re} rise rapidly and then tend to level off (Figs. 1*A*, 2*A*) but when P_a is being raised during the 2nd hr both HR and T_{re} again begin to rise (Fig. 2*A*). These typical examples are also chosen to demonstrate individual differences in the absolute values of HR and T_{re}. Figure 1*A* shows that *subject WJ* has a much lower HR, as compared to *DW* for similarly high T_{re} and in Fig. 2*A* the subject showing somewhat lower HR levels has a somewhat higher T_{re}. For an individual, the parallel changes in HR and T_{re} suggest a linear relationship between the two as demonstrated in Figs. 1*B* and 2*B*.

The time-course of T_{re} and HR for low P_a shown in Fig. 1*A* is a typical example of the responses observed for all subjects. At the lower levels of P_a the rise in T_{re} and HR lasts 40–60 min before equilibrium is reached.

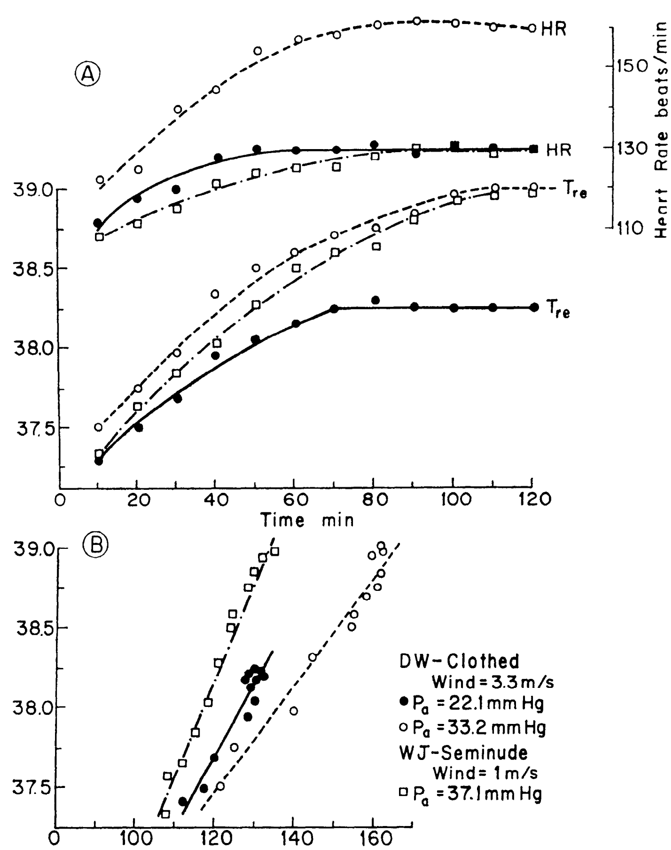

FIG. 1. Time course of rectal temperature and heart rate (*A*) and relationship between them (*B*) for 2 subjects exposed for 2 hr to environmental conditions denoted above and at T_a = 37° C. Data points are 10-min consecutive values.

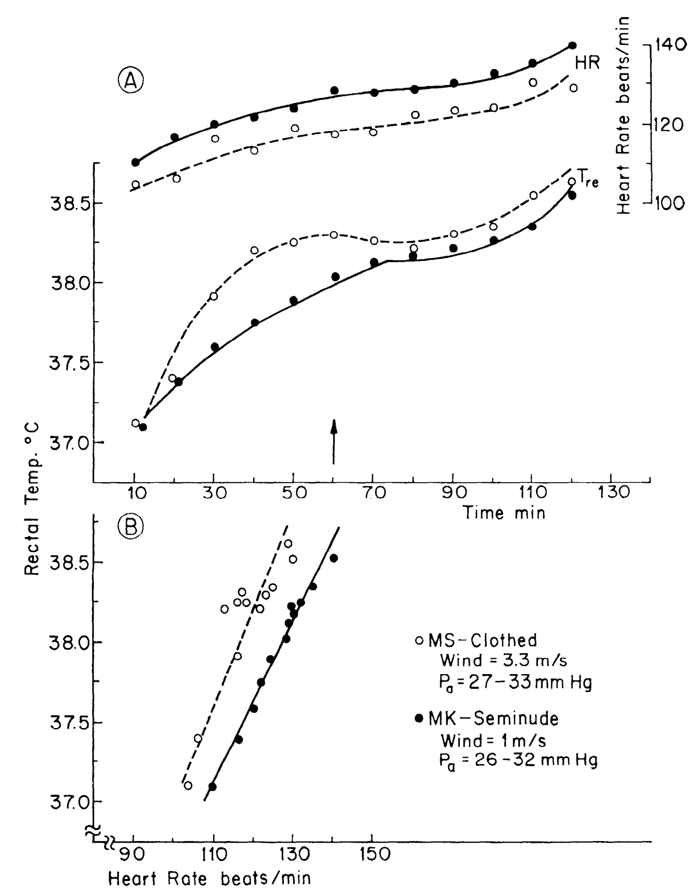

FIG. 2. Time course of rectal temperature and heart rate (*A*) and relationship between them (*B*) for 2 subjects exposed to environmental conditions denoted above and at T_a = 36° C. Data points are 10-min consecutive values. Arrow marks the time when P_a was raised, at 10-min intervals, from lowest to highest level as denoted at the bottom for each subject.

At the higher levels of P_a, the T_{re} and HR respond to work in the heat by a steeper rise and by delayed equilibration; the final equilibrium is at levels above those observed for the lower vapor pressures. When P_a is increased to still higher levels, T_{re} and HR continue their rise, further delaying the equilibration, until at the highest levels of P_a equilibrium is not achieved within the 2 hr of exposure (Fig. 1*A*).

The final equilibrium values, observed during the last 10 min of exposure, were used to plot the relationship of T_{re} and HR to P_a. A typical example for the tests in category I, where P_a was kept constant throughout the 2 hr of exposure, is shown in Fig. 3. This example is for seminude subjects exposed to the low wind speed for a walking speed of 4.5 km/hr. It is seen that up to P_a of 32 mm Hg, HR and T_{re} are largely independent of P_a. This is in the range of P_a at which equilibrium is reached toward the end of the 1st hr.

The horizontal line describing the mean T_{re} and HR at the P_a of 18–32 mm Hg changes to a slope for P_a levels above 32 mm Hg. Under the same conditions but with the subject clothed the point of inflection of the line is at P_a of 24 mm Hg. The point of inflection depends on the conditions as follows. It is at lower P_a for clothed than for seminude, for low wind speed than for higher, and for higher metabolic rate ($\dot{V}O_2$) than for lower. The average equilib-

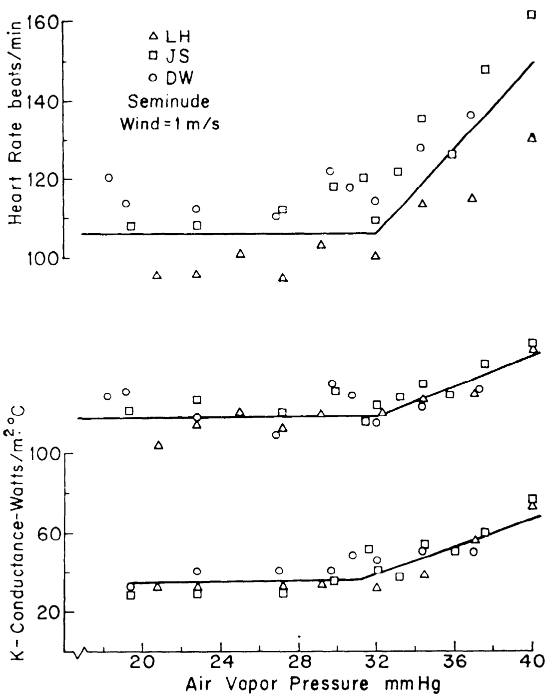

FIG. 3. Relationship of heat conductance, rectal temperature, and heart rate to air vapor pressure for 3 subjects. $T_a = 37°$ C.

rium level of T_{re} before the inflection point was 37.9° C for all subjects.

To verify the apparent linear relationship between HR and T_{re} the data from all the exposures to the higher levels of P_a were used for each subject separately. Most of the data from the exposures to the lower levels of P_a (the range before the inflection point of Fig. 3) were not used since for these exposures HR and T_{re} repeatedly leveled off at the same values. Except for the 30th, 60th, and 90th min at which weighing was carried out the consecutive 10-min values of all the selected experiments were subjected to analysis of regression using the least-squares method.

Typical results obtained from two subjects are shown in Fig. 4. Figure 4*A* shows tests at one walking speed on *subject DW*. Figure 4*B* shows results at two walking speeds for *subject MK*. Table 2 summarizes the regression equations for T_{re} on HR for all the subjects.

The slower walking speed results in lower HR; thus the regression line of T_{re} on HR is shifted to the left (Fig. 4*B*) and it seems that for all three subjects who were tested at different walking speeds the regression coefficient is somewhat higher for slower as compared to the higher walking speed (*group II*, Table 3). The average standard error of estimate about the regression is ±0.27° C (range 0.2–0.4° C).

One subject (*DW*) was also tested for walking under dry, very hot conditions. As shown in Table 3, the yield of the regression of T_{re} on HR for dry heat exposure does not differ in a practical sense from that apparent for exposure at lower air temperature but with higher vapor pressures.

The ear canal temperature (T_{ea}) was monitored during all the experiments. Except under the very high vapor pressure conditions T_{ea} rose more rapidly than T_{re} and leveled off somewhat earlier but was about 0.5° C lower than T_{re}. At the higher P_a levels T_{ea} and T_{re} changes were parallel

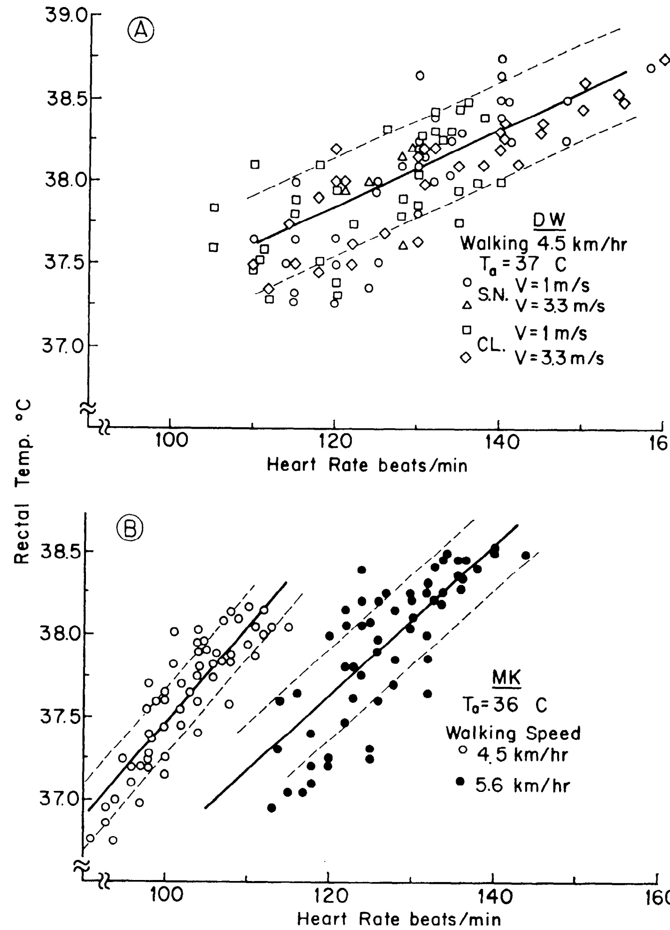

FIG. 4. Regression of rectal temperature on heart rate (——) and SE of estimate (- - -). *A:* different ambient conditions separately denoted for *subject DW*. *B:* separate ambient conditions are not denoted for *subject MK*.

TABLE 3. *Regression coefficient (b) of rectal temperature (T_{re}) on heart rate, T_{re} intercept (a), standard error of estimate (SE), and correlation of fit (r) for subjects exposed to increasing P_a*

Subj	n	*b*	*a*	SE	*r*
		*I. Constant vapor pressure**			
JS	152	0.0163	35.94	0.28	0.54
LH	148	0.0335	34.54	0.27	0.68
DW	130	0.0237	35.00	0.29	0.72
DB	148	0.0373	33.57	0.40	0.67
WJ	189	0.0399	33.56	0.24	0.87
RP	143	0.0284	34.36	0.26	0.78
DW†	45	0.0223	35.24	0.38	0.63
		*II. Increasing vapor pressure**			
MK	56‡	0.0576	31.71	0.20	0.86
	65§	0.0453	32.18	0.28	0.80
KC	70‡	0.0288	34.77	0.25	0.60
	112§	0.0211	35.52	0.22	0.75
MS	74‡	0.0268	35.46	0.28	0.64
	55§	0.0223	35.49	0.22	0.62

* See footnote for Table 2. † Experiments at dry hot environments; 40–50° C; P_a = 12 mm Hg. ‡ Walking speed 4.5 km/hr for *MK* and 3.2 km/hr for *KC* and *MS*. § Walking speed of 5.6 km/hr.

although T_{ea} was lower than T_{re}. T_{re} was chosen as the index of core body temperature because some of the T_{ea} values were invalidated by mechanical or electrical difficulties.

Figure 3 also shows the relationship of the conductance (k) to the vapor pressure. It can be seen that the conductance follows the same course as the HR and T_{re}, it is independent of P_a at lower levels of P_a and inflects to a positive slope with increased P_a at higher levels.

DISCUSSION

The two primary demands on the circulatory system during work in the heat are the transportation of oxygen to the working muscles and the transfer of heat to the periphery. The latter might account for the observed linear correlation between the HR and the T_{re}. Further evidence of the role that the circulatory system plays in heat dissipation is provided by the fact that the conductance (k, Fig. 3) showed a relationship with P_a similar to the HR and T_{re}. The implication that increased blood flow to the periphery is responsible for the increased conductance is found in Lind's measurements (7) showing that forearm blood flow rises sharply (as do HR and T_{re}) beyond the "prescriptive zone" of corrected effective temperature.

Since conductance is inversely related to the temperature gradient between core and skin ($\bar{T}_s$), its increase means that with the increase in P_a beyond the inflection point $\bar{T}_s$ is rising at a steeper rate than T_{re}. In other words increased P_a impairs evaporative cooling of the skin, thus increasing the burden on the circulatory system. Indeed at the higher P_a levels large amounts of sweat drip onto the treadmill.

Our experiments were restricted to air temperature of 36–37° C at which $\bar{T}_s$ was at about 35° C for P_a rise up to the inflection point. In this same P_a range, T_{re} and HR equilibrated at levels independent of P_a. Saltin et al. (12) found that, for moderate work at T_a of 10, 20, and 30° C, $\bar{T}_s$ was 28, 31, and 34° C, respectively. While T_{re} was unaffected by the three thermal conditions HR, like $\bar{T}_s$, was higher with higher T_a. Similar tests on only two of the participants in this study were consistent with this finding of Saltin et al. but the small sample did not allow definite conclusion. When T_a was held constant but P_a changed, $\bar{T}_s$ was forced to rise due to the impairment in the dissipation of the metabolic heat. Under a wide range of T_a but with low P_a, $\bar{T}_s$ is more affected by external than by metabolic heat load. An association between $\bar{T}_s$ and HR cannot be ruled out although to further confirm it more data on a wider range of T_a is needed.

TABLE 4. *Rectal temperature under different ambient conditions reported by some investigators for work loads requiring 1 L/min of O_2*

Ambient Temp, Dry Bulb/Wet Bulb, °C	Work Duration, hr	Rectal Temp, °C	Ref
35/33.5, 50/29	4–6	38.2	Robinson et al. (11)
29/29–33/33	4	37.9	Wyndham et al. (16)
18/10–33/25	1	37.8	Lind (7)
20/12	0.5–1	37.5	Saltin et al. (12)
10/5, 20/12, 30/19	1	37.4	Saltin and Hermansen (13)
36–37/24–35	2	37.9	This study

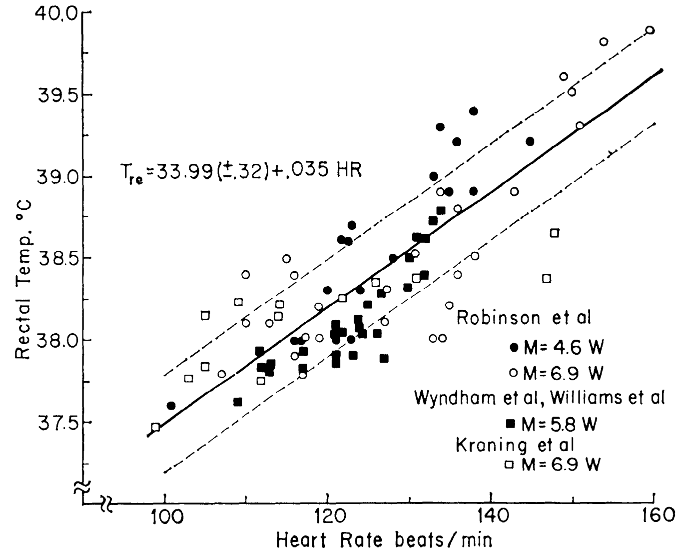

FIG. 5. Regression of rectal temperature on heart rate for data reported from different laboratories.

The observation that with the moderate work loads used in this study the average equilibrium level of T_{re} was 37.9° C for a wide range of vapor pressures is in good agreement with the data of others for a wide range of climatic conditions (7, 11, 12, 13, 16). The comparison is summarized in Table 4 and it should be noted that in two cases (11, 16) the experiments involved 4–6 hr of work.

Finally, if the equilibrium level of T_{re} in the present study was about the same as that reported by others for similar work loads but in a variety of climatic conditions, how consistent are the present relationships between HR and T_{re} with those observed by others? To answer this question, Fig. 5 gives values of others to describe the relationship between HR and T_{re}. As can be seen the regression of T_{re} on HR for these data lies well within the range of the individual regressions presented in Table 3.

Pirnay et al. (10) conducted a series of experiments on 23 subjects, exposing them to work loads requiring 1 L O_2/min at 46° C dry bulb and 35° C wet bulb for 0.5 hr. When they used 5-min consecutive measures of T_{re} and HR they found a regression coefficient of 0.030. This is similar to the coefficient of 0.035 for the values of others as shown in Fig. 5 and to the average coefficient of this study (0.029).

In use of consecutive 10-min values to derive linear regression of HR on T_{re} the early period after the onset of work in which a marked difference exists between the HR and T_{re} responses was excluded. Within the first 2 min after the onset of work HR rose rapidly to a relative plateau value which was maintained for about 5 min. During this period rectal temperature either dropped slightly or did not change. It was after this, that both HR and T_{re} rose gradually toward the final equilibrium level. The rapid rise in HR soon after the onset of work reflects circulatory adjustments to the immediate need of oxygen transportation to the working muscles (3). The lag in response of T_{re} is a result of the blood redistribution that accompanies onset of work (4, 5). Our findings of earlier rise and lower equilibrium levels of T_{ea}, as compared to T_{re}, are similar to those reported by Minard and Copman (8). When samples of undistorted T_{ea} recordings were tested for linear regression, as expected from these differences the position of the line changed but the regression coefficient was the same as for T_{re} on HR.

The intersubject variability of body temperature, only 0.3° C for similar relative work loads, is not given much physiologic significance. Also, it is well known that absolute values of HR are subject to individual variation which is meaningfully related to such factors as fitness and age. However, our results show that for moderate work loads, if an individual's cardiovascular fitness is known it is possible to predict rectal temperature response to work and heat on the basis of heart rate. Even if fitness is not known change in T_{re} can be predicted from change in HR.

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