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Relationship of Physiological Strain to Change in Heart Rate during Work in the Heat

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Data collected from experiments involving (1) intermittent cycling and load carrying in dry, neutral to hot, ambient temperatures and (2) prolonged walking (3 to 3.5 mph) in hot, humid environments were used for correlation analysis between some measured physiological variables. Increasing the air temperature (T_a) resulted in (1) a shift of regression line of heart rate (*HR*) on oxygen uptake (Vo_2) such that, for a given Vo_2, *HR* was 10 beats/min higher for a rise of 10°C in T_a, and (2) apparent slope for the linear regression of the *HR* during the last minute of work on the *HR* during the first minute of recovery becoming less steep with rise in T_a. For prolonged work loads requiring Vo_2 of about 1 liter/min (representing about 30% of maximal Vo_2) and Vo_2 of about 1.5 to 2.8 liters/min (representing 40 to 60% of maximal Vo_2) the regression of rectal temperature on *HR* was 0.03°C and 0.01°C per beat per minute respectively. It was concluded that the rate of change rather than absolute values of these parameters might provide a better guide for evaluation of strain, particularly when intermittent type of work is involved.

Introduction

ENDURANCE TIME for physical work is inversely related to its physiological cost. The time limit for a given work load depends on the functional capabilities of the systems involved in transporting and using oxygen in the metabolic processes. The circulatory capacity is most important in this case. If some heat stress is added to the working condition, the circulatory system is strained by the need to transfer excessive heat from the core to the periphery of the body. Naturally when the systems involved in work and/or heat dissipation are utilized to their full capacity, pauses for rest are needed to restore their functional capabilities. Predictability of the physiological responses to a particular work under given conditions will enable suitable work schedules that will prevent the development of strain.

The criteria most used to estimate the physiological cost for physical work are oxygen utilization (metabolic cost), heart rate (*HR*), and core body temperature such as rectal (T_{re}). These responses equilibrate at levels above their resting values, depending on the work load. There is a linear relationship of each of these responses to work load.[1,2] While the metabolic cost provides a general knowledge of the physiological demand of the work, it is an insufficient yardstick to indicate strain, particularly for work under unfavorable thermal conditions. Here T_{re} and *HR* seem to be better criteria for strain. Although at a given oxygen uptake (Vo_2) T_{re} equilibrates at the same level for a wide range of ambient air temperatures,[3] strain is indicated by a forced rise in the core temperature under ambient conditions that prevent dissipation of the metabolic heat.[4] The *HR* is more sensitive than T_{re} to change in ambient air temperature (T_a). The relative steady-state *HR* for a given Vo_2 (at temperate room temperature), with the apparent linear regression of *HR* on Vo_2, was used to estimate the maximal aerobic capacity by extrapolation from submaximal work levels.[5,6] However, even though these methods call for short-term exercise, the possible elevation in *HR* due to an increase in T_a might lead to the underestimation of the maximal aerobic capacity.[7,8]

Since the sensitivity of *HR* to higher ambient air temperatures also affects deceleration during recovery, Brouha[9] advised that cardiac strain be estimated from recovery *HR*. This is most useful for intermittent work when apparent upward creeping due to heat stress indicates strain despite the rest allowed. This is also a more practical approach, since most of the jobs involve intermittent work, not necessarily restricted to one or two work levels, where, compared to working *HR*, recovery *HR* is easier to measure.

Thus, to find some quantitative relationship between the stress of work under unfavorable ambient conditions and the abovementioned physiological responses, three methods were tried: (1) progressively rising short-term work loads which provide regression of *HR* on V_{O_2}; (2) intermittent work involving walking, carrying loads, and resting, 5 minutes each for 1 hour; and (3) continuous, prolonged work under progressively rising air vapor pressure, and under dry, hot temperatures and very hot, ambient temperatures.

Methods

Subjects

A summary of the physical characteristics, age, and type of test used on each group is given in Table I. Each subject took part in one of the tests only, except for three subjects who participated in the two first tests on cycling and carrying loads.

Procedure

The subjects reported to the laboratory about an hour prior to the testing time. Preparation for the experiments—changing into shorts or test clothing, and application of chest electrodes and rectal thermocouple—took about half an hour. Thereafter the subjects rested sitting in room temperature (22° ± 1°C) until the beginning of the experiment. Prior to each experiment at other than room temperature they were seated in the climatic room for 10 minutes.

Intermittent Work

Cycling

Intermittent test methods were used. Pedaling against a given resistance lasted 5 minutes. After a rest period pedaling was continued against a higher resistance (△30 watts). At the lower loads 5 minutes of rest was allowed between cycling periods. At the higher loads, when heart rate was above 140 beats/min (above about 600 kpm), 10 minutes of rest was allowed between cycling.

Work under three dry, ambient temperatures was tested; 20°C, 35°C, and 45°C (wet-bulb temperatures were 15°C, 20°C,

TABLE I
Characteristics of the Groups of Participants and the Specification of the Tasks Involved

Number of Subjects	Range of Body Weight (kg)	Range of Height (cm)	Task Tested
5	68–89	166–192	Intermittent cycling[a]
3	70–89	166–192	Carrying[a] loads
6	63–86	172–183	Walking at different P_a[b]
3	65–68	163–178	Walking at increasing P_a[b]
10	60–88	170–182	Cycling for 30 minutes

[a]Five to ten minutes of rest were allowed between each 5 to 10 minutes of working period (for details see methods).
[b]For details see Table II.

and 25°C, respectively).

Carrying Loads

This series was carried out under the same ambient conditions as the cycling tests.

The load was a cardboard carton (30 × 40 × 30) weighing 10, 15, or 20 kg. Walking speeds and grades were 67 or 83 m/min (4 or 5 km/hr) at 0 or 4% grade. A single experiment included one of the thirty-six combinations shown in Figure 1. It lasted 65

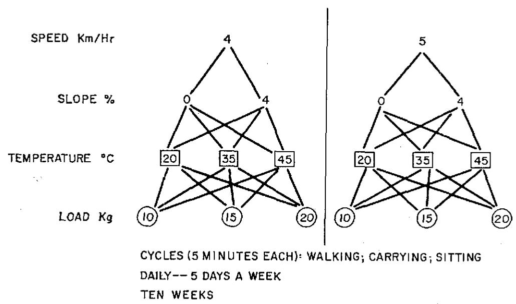

Figure 1. The combinations of the treadmill speed, its inclination, the load carried, and the ambient temperature used in the load-carrying experiments.

minutes and was programmed as follows: "warm-up," walk 10 minutes; rest while sitting, 5 minutes; and three cycles of carrying loads. Each cycle consisted in three 5-minute periods: Cycle 1—walking, carrying the load, sitting; cycle 2—carrying the load, walking, sitting; cycle 3—same as cycle 1.

The load was placed on a waist-high shelf at the front of a motor-driven treadmill. The subject was asked to lift the load away from the shelf while walking. After carrying the load for 5 minutes on both hands, he placed it back on the shelf while walking. The weight of the loads, the combinations of treadmill speed and grade, and the thermal conditions for each experiment were randomized.

Continuous Work

Walking in Hot, Humid Environments

A summary of the treatments employed is given in Table II. Notice the treatments of increasing vapor pressure (P_a). In treatment I, P_a was kept constant throughout the 2-hour exposure but changed from day to day. In treatment II, P_a was kept constant during the first hour, then raised about 1 mm Hg each 10 minutes for the second hour. For each exposure the air speeds was set at one of three levels and the subject was either seminude or clothed. Seminude included shorts and gym shoes; clothed included, in addition, a khaki long-sleeved shirt and trousers.

Every half-hour the walking was stopped

TABLE II
Ambient Air Temperature, vapor Pressure, Wind Speed, and Working level employed in the Tests on Prolonged Walking

Number of Subjects	Air Temperature (°C)	Vapor Pressure Range (mm Hg)	Wind (m/sec)	Walking (km/hr)	Oxygen Uptake (liters/min)
I. P_a kept constant throughout 2 hours					
			1.0		
3	37	19–40	3.3	4.5	0.8–1.0
			1.0		
3	36	18–37	2.5	5.6	1.1–1.3
			1.0		
1[a]	45	12	3.3	4.5	1.0
II. P_a kept constant during first hour and raised every 10 minutes during second hour					
			1.0	3.2	
3	36	18–40	2.5	4.5	0.7–1.2
			3.3	5.6	

[a]Subject participated also in the first test.

for 3 minutes during which the subject was weighed and given tepid water to replace the weight loss.

Cycling

Thirty minutes of cycling at loads requiring 40 to 50% of the individual's maximal V_{O_2} (range 1.3 to 2.8 liters/min) were administered at each of the following dry-bulb and wet-bulb air temperatures: 24°C (D.B.) and 12°C (W.B.); 44°C (D.B.) and 24°C W.B.); 54°C (D.B.) and 26°C (W.B.).

Measurements

The open-circuit method was used to measure oxygen uptake. Expired air was collected in Douglas bags during the 5th minute of each period for the cycling and load-carrying experiments and directly into a wet spirometer during the 40th and 70th minute of the experiment under increased P_a. For the 30-minute cycling test 1-minute collection was carried out every 5 minutes in separate Douglas bags. The volume in the Douglas bags was measured by use of the wet spirometer (Tissot). Oxygen partial pressure of the room air and expired air was measured with a Beckman C paramagnetic oxygen analyzer.

A cardiotachometer was used to continuously monitor heart rates.

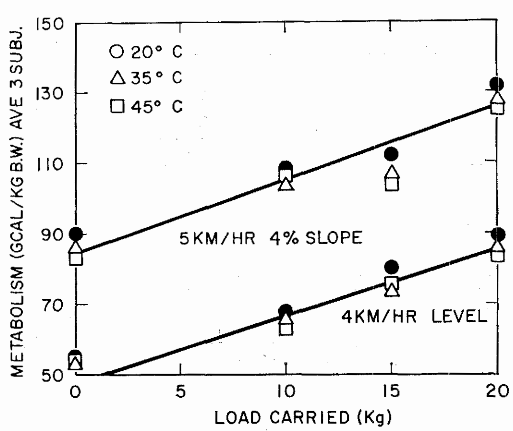

Figure 2. The relationship between load carried and metabolism for two walking speeds and treadmill inclinations.

Results and Discussion

Intermittent Work

Alternating periods of work and rest were scheduled for two experiments: cycling and carrying loads. The data from these tests revealed a linear relationship between the steady-state V_{O_2} (minute oxygen uptake) and work load. Such a relationship was expected, since is was extensively documented for cycling.[1] However, we chose to present in Figure 2 the regression of V_{O_2} on the load carrying for walking at two treadmill settings (speed and inclination). It should be noticed that the V_{O_2} was not affected by ambient temperature. An expected linear relationship was found between heart rate (*HR*) and metabolic rate (V_{O_2}) for any one individual. But, since the *HR* levels differed at the three ambient temperatures (T_a), we chose to show typical examples which were obtained on two subjects during intermittent cycling (Figure 3). Although the lines obtained for experiments at T_a of 45°C were somewhat steeper than those for 20°C and 35°C, practically it

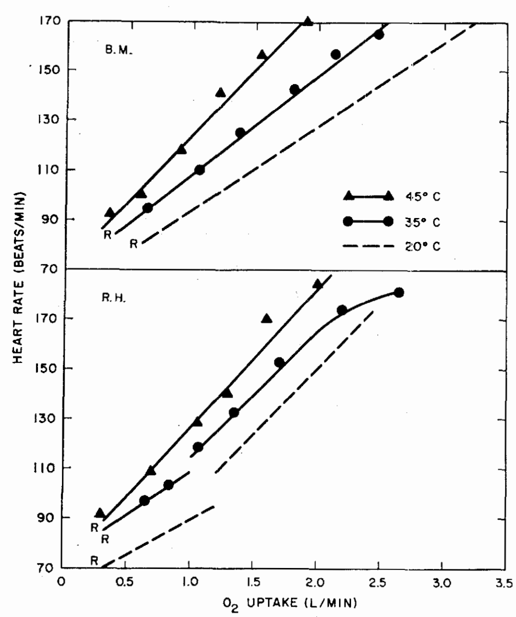

Figure 3. The relationship of heart rate and oxygen intake for progressive cycling under three ambient temperatures shown for two subjects.

can be assumed that the three regressions of *HR* on VO_2 are parallel to each other.

Figure 3 shows that the regression line at lower VO_2 could differ from that at higher VO_2 levels (subject RH). Generally, lines of regression of *HR* on VO_2 should be considered from VO_2 of 1 liter/min and above. At VO_2's lower than that the change in the heart's blood output is due more to an increase in the stroke volume than to a rise in *HR*.

The parallel shift of the regression lines of *HR* on VO_2 for intermittent work at ambient temperatures above "neutral" T_a was also reported by Williams *et al.*[7] for cycling and Rowell[8] for treadmill walking. Our data from the combined tests on cycling and load carrying led us to conclude that the shift was constant for an individual such that, for a given VO_2, values of *HR* at T_a 35°C and T_a 45°C were, respectively, 10 beats/min and 20 beats/min higher than at T_a 20°C. It could be safely assumed that the *HR* prevailing at 20°C will stay the same up to T_a of 25°C, thus allowing an estimate of a rise in *HR*, due to heat, of 1 beat/min per 1°C for a given work load at ambient temperature range between 25°C to 45°C.

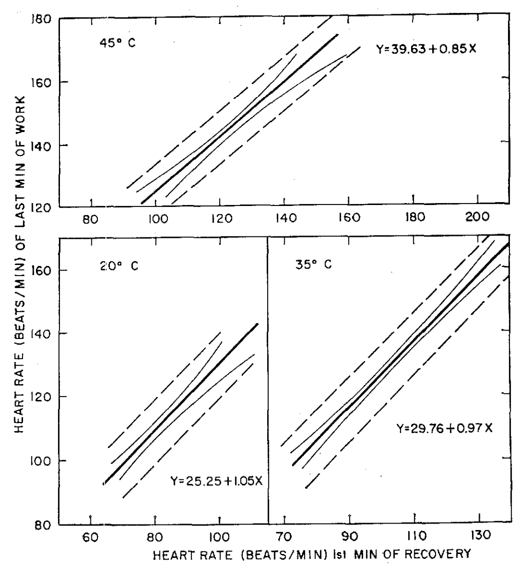

Figure 4. The regressions of heart rate during the last minute of work on the heart rate during the first minute of recovery for three ambient air temperatures: .... standard error of estimate; —— 95% confidence limit.

This information is relevant to the methods used in the prediction of maximal work capacity on the basis of tests at submaximal levels. Since such predictions call for the extrapolation from submaximal values of *HR* and VO_2 to an assumed maximal *HR*,[5,6] tests under warm to hot ambient conditions will underestimate the maximal VO_2 unless corrected for ambient temperature.

Recovery Heart Rates

In practical industrial situatiins it is much more feasible to measure the *HR* during rest than during work; thus, to estimate the strain caused by a particular job it was suggested to use the pulse measured immediately after the task has been stopped.[9] However, since it is still more desirable to have an estimate of the *HR* during the work itself, we tried to see how recovery *HR* correlates with work *HR*. The continuously monitored *HR* during the intermittent task of carrying loads was used to describe the relationship between the *HR* obtained during the first minute of recovery and that obtained during the last minute of work. Figure 4 shows that the relationship between the two was linear but with different regression coefficient at each T_a. It can be seen that, with the increase in ambient temperature, the coefficient becomes smaller, indicating a slower drop in *HR* at the higher T_a. However, it should be noticed that, although the 95% confidence limit of the regression is narrow, the data yielded a wide standard error of estimate. This should be taken to indicate that absolute values cannot be taken from the regression unless it is given for one individual. Nevertheless, the slope of the change is probably common for a wide range of a working population. This is supported by the observations made for work under room temperature on college male and female students, 20 to 30 years old,[10] and on "blue collar" workers, 17 to 63 years old.[11] In the first group the observed linear correlation between 60- to 90-second recovery HR and working HR was high for each individual (correlation coefficient, r = 0.96) but marginal (r = 0.77) for the whole group, thus leading to the conclusion that prediction of working HR from the measured recovery HR (60 to 90 seconds) is satisfactory for an individual but not when applied to a large population. But in the second report when recovery HR was measured 30 to 60 seconds following the work the correlation was found to be satisfactory (r = 0.80) enough for prediction of working HR from recovery HR to the extent that the standard deviation was not more than that yielded when working HR is measured by palpation.

The recovery period at which HR is measured seems important for the correlation with work HR, since when we tried to describe the HR relationship between last minute of work and later recovery periods, such as the 4th minute, the scatter was too high to allow any reliable prediction.

Walking Under Increased Vapor Pressure

Figure 5 represents a typical time course of rectal temperature (T_{re}) and heart rate (HR) for work at T_a 35° to 36°C under either constant vapor pressure (P_a) throughout the 2-hour exposure or increased P_a during the second hour of exposure. Throughout all the experiments (summarized in Table II) it was observed that the rise in HR and T_{re} are parallel except for the first 10 minutes in which there is an initial sharp rise in HR with some lag in the rise of T_{re}. At low P_a, where evaporation was not impaired, both HR and T_{re} leveled off after about 1 hour of exposure. Otherwise both showed gradual rise similar to that described in Figure 5.

The parallel rise in HR and T_{re} suggested a linear correlation between them. To verify such a correlation, the consecutive 10-minute value from all the exposures of each subject to the higher P_e levels (Table II) were subjected to analysis of regression using the least-squares method. The regression equations obtained were in the range of T_{re} = 36 + 0.016 HR to T_{re} = 31.7 + 0.058 HR for work requiring 0.65 to 1.3 liters of oxygen per minute. The pooled data for all the subjects yielded the regression line with standard error of estimate shown in Figure 6. This indicates that, at a work level requiring $\dot{V}o_2$ of about 1 liter/min, the rate of change of T_{re} can be predicted from the change in HR; a rise of 33 beats/min implies

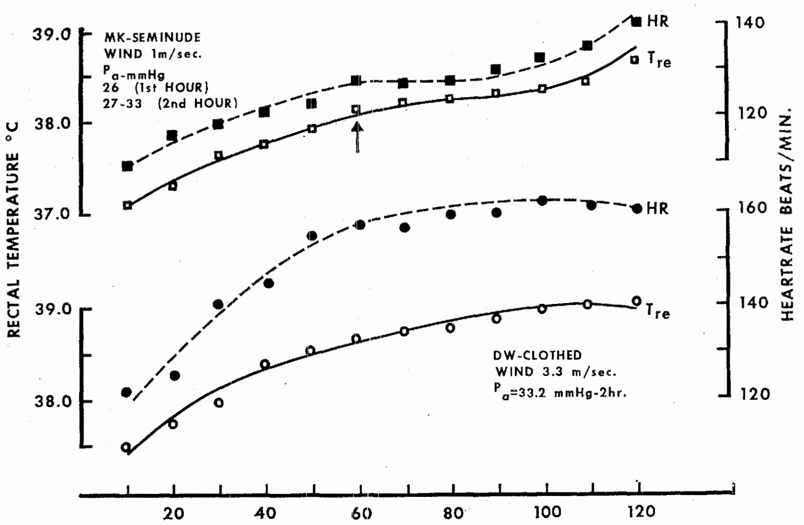

Figure 5. The time course of rectal temperature and heart rate for walking under different vapor pressure at dry bulb temperature of 36°C. Arrow indicates the onset of increasing P_a by 1 mm Hg every 10 minutes.

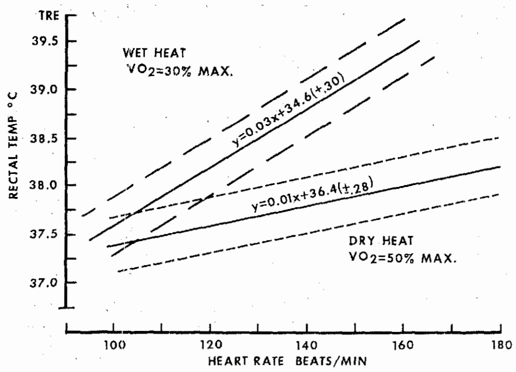

Figure 6. The regression of rectal temperature on heart rate for two ambient air conditions.

a rise of 1°C in T_{re}. It should be noticed that in our study the subjects were acclimatized to heat. However, using the data given by Eichna *et al.*[12] for unacclimatized subjects exposed to walking ($\dot{V}O_2$ at about 1.2 liters/min) at 50°C (R.H. = 15%), we computed an *HR* change of 44 beats/min for a 1.2°C rise in T_{re}. This will be equivalent to a slope of 0.036°C per beat, which is in the range of our data on heat-acclimatized subjects.

Continuous Cycling at moderate to Heavy Work Loads

While the work loads for walking under increased P_a were at about 25% to 30% of the individual's maximal aerobic capacity, the work loads in this series of cycling were at 40% to 60% of the maximum. It can be safely assumed that at levels of 25% to 30% of maximum a day shift (8 hours) can be endured without undue fatigue. However, the higher relative work rates require pauses for recovery. At 50% of maximum the work can be stretched for an hour and only very fit persons can endure it longer than that.[1] Thus in this series of tests the work was performed for 30 minutes.

Similar to the series described previously, the data for all 10 subjects from the tests under the three dry, ambient temperatures were pooled. The consecutive 10-minute values of T_{re} and *HR* were subjected to analysis of linear regression. Figure 6 describes the line and shows the regression equation obtained. It can be seen that the slope coefficient of 0.010°C/beat•min is smaller than the 0.030°C/beat•min yielded for work at 25 to 30% of maximum at the vapor pressure stress.

Principally a rise in *HR* when body temperature rises is not surprising, since the stress due to the excessive heat demands from the circulatory system an increase blood flow to the skin in order to transfer the heat to the periphery. Evidence for an increased peripheral blood flow was brought by Lind,[13] who found that forearm blood flow rises sharply (and in correlation with increased *HR*) beyond the comfort or "prescriptive" zone of corrected effective temperature. We find it of practical importance to equate the rate of change of one parameter with the other, particularly when one of them can be feasibly measured, such as *HR*. Support to such quantification is found in a report of Pirnay *et al.*,[14] who conducted a series of tests on 23 subjects exposed to work loads of 1 liter of oxygen per minute at 46°C wet bulb and 35°C wet bulb for half an hour. They found for 5 minutes of consecutive measured *HR* and T_{re} the same regression coefficient of 0.030 which is shown and given in Figure 6 for this study. But with higher relative work loads where $\dot{V}O_2$ is closer to the maximum, the slope coefficient is not as steep, indicating a rapid rise in *HR* which will reach intolerable values before T_{re} will approach the dangerous limit.

Conclusions

It is felt that, although absolute values of *HR* are subject to individual variations related mainly to fitness and age, they can be used meaningfully if the time course of the apparent change is taken into account.

Thus we proposed to pay attention to the fact that for intermittent work there is an increase of about 1 beat/min per rise of 1°C in ambient temperature (dry heat). This has some implication for work loads for which $\dot{V}O_2$ is known and for the fact that energy cost for a given task is not affected by exposure to heat.

We also find that the rate of the first-minute recovery *HR* is well correlated with the work *HR*, and that temperature requires a measurable correction as given by the regression coefficients shown in Figure 4.

Finally we suggested that the rate of change of *HR* be used to predict the rise in T_{re}. The absolute value of T_{re} would be predictable only if the individual's cardiovascular fitness is known with only $+0.3°C$ standard error of estimate, for work requiring about 1 liter of oxygen per minute. The predictability is somewhat different at higher work levels. Standardization is possible when relative Vo_2 is taken into account.

Acknowledgements

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