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PHYSIOLOGICAL RESPONSES TO INTERMITTENT EXERCISE AS MODIFIED BY HEAT STRESS AND PROTECTIVE CLOTHING

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Time-weighted averaging is a method employed in heat stress analyses to consolidate the rate of heat production (M) from complex intermittent exercise patterns into a single continuous level of heat production. Physiological responses during intermittent and continuous exercise were studied in 4 subjects exposed to heat stress in which evaporation was either free or severely restricted. Intermittent work consisted of repeated 10 min exercise/rest patterns. Continuous work was at the time weighted average of intermittent exercise. When heat stress was uncompensable, intermittent work induced more physiological strain than continuous work: endurance time was 14 min less ($p < .05$), core temperature at 60 min was 0.40°C higher ($p < .05$), and the rate of core temperature rise was 33% greater. The difference in the rate of heat storage was not satisfactorily explained by a discrepancy in average M or in the calculated rate of surface heat loss. Alternatively, results may be explained by interruptions in the rate of heat transport via the cutaneous circulation. These interruptions may be associated with postural and workload transitions. While the mechanisms are not totally understood, it is clear that application of the time-weighted averaging method should be applied with discretion.

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by

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EXECUTIVE SUMMARY

Time-weighted averaging is a traditional method employed in heat stress analyses to approximate, in terms of a single continuous level of heat production, the rate of heat production (M) from complex intermittent exercise patterns. The procedure of time-weighted averaging is incorporated into the offical U. S. Army heat stress doctrine, as detailed in TB MED 507. Physiological responses during intermittent and continuous exercise were studied in 4 subjects exposed to heat stress in which evaporation was either free (shorts and tee-shirts) or severely restricted (MOPP4 configuration). Intermittent work consisted of repeated 10 min exercise/rest patterns. Continuous work was at the time weighted average of intermittent exercise: 3.3 mets. When heat stress was uncompensable, intermittent work induced more physiological strain than continuous work: endurance time was 14 min less ($p < .05$), core temperature at 60 min was 0.40°C higher ($p < .05$), and, after 30 min of exposure, the rate of core temperature rise was 33% greater. The difference in the rate of heat storage was not satisfactorily explained by a discrepancy in average M or in the calculated rate of surface heat loss. Alternatively, the results may be partially explained by interruptions in the usual rate of heat transport via the cutaneous circulation. These interruptions may be caused by non-thermal factors associated with postural and workload transitions. While the mechanisms are not totally understood, it is clear that application of the time-weighted averaging method can lead to erroneous overprediction of endurance time and should be applied with discretion.

Keywords

core temperature, skin temperature, heat balance, heat stress,
intermittent exercise, skin blood flow

INTRODUCTION

Common stresses adding to the burden of the ordinary soldier include load carriage, heat stress from climate and from protective clothing, the threat of exposure to chemical and biological warfare agents and the pressure to initiate and complete a mission within a particular time span. Military commanders generally adjust the latter variable to balance the others by interchanging periods of heavy exertion with periods of rest. This tends to forestall excessive heat buildup in protective clothing, but requires rather precise assessment of both mission needs and environmental demands.

Heat stress problems can be differentiated into two types: compensable, in which thermoregulation is effective and a normal person can achieve a thermal steady-state, and uncompensable, in which thermoregulation is thwarted and no one can achieve a thermal steady-state (15). A thermal environment of compensable heat stress can be converted into one of uncompensable heat stress by restricting the evaporation of sweat. Evaporative restriction is associated with several factors: excessive ambient water vapor pressure, insufficient air movement, and impedance by clothing of water vapor diffusing away from skin.

Exercise is classified as either continuous or intermittent. During intermittent work a balance must be struck between the length of work and rest periods. If rest periods are long enough for complete thermal recovery, the demands of the mission may not be met. On the other hand, if rest periods are very short in duration, there may be inadequate recovery to allow completion of the mission.

Both compensable and uncompensable heat stress have been studied extensively during continuous exercise, but relatively few studies have focused on heat stress and intermittent work. Because of the lack of objective data, it has been necessary to presume that intermittent exercise in a hot environment provokes the same level of heat strain as does a single computed workload, calculated as the time-weighted average of the variable exercise pattern, and then extrapolate from studies of continuous work performed at this computed workload. This presumption is supported by studies that used relatively long, moderate exercise and recovery periods (greater than 15 min) and conditions of compensable heat stress (3,14). But work-recovery periods during warfare, emergency work or athletic endeavors are usually much shorter than this, and often are conducted under uncompensable heat stress. We found only two studies that were relevant to this topic and used short (30s) work/recovery periods. These were carried out under moderate compensable environmental conditions and were characterized by opposite results: the first reported that internal temperature rise was higher when an intermittent work pattern was used and the second found no difference in the internal temperature response to intermittent and continuous work modes (5,17). We were able to find no comparative work studies conducted during uncompensable heat stress. Thus, there is no convincing evidence that exercise stress and resulting physiological strain are linearly related when work/recovery periods are short and/or are conducted during uncompensable heat stress. In spite of these uncertainties, time-weighted averaging is incorporated without reservation into the thermal protection doctrine of governmental agencies as the recommended procedure for approximating intermittent work in terms of a single exercise level (1,2).

We suspected that a rapidly changing work pattern performed under severe conditions would elicit a greater degree of physiological strain than time-weighted continuous work. These suspicions arose from two sources. First, as Belding *et al.* suggested, a steady-state will not be achievable and each successive work period might result in an excessive incremental rise in body temperature (3). Second, as cited above, one study has already demonstrated higher rectal temperatures during very short pulses of strenuous exercise than during continuous exercise even when heat stress was classified as compensable (5).

The purpose of the present study was to compare endurance times and physiological responses in the same subjects performing exercise in a continuous or intermittent mode. Two thermal scenarios were provided for each exercise mode: compensable heat stress and uncompensable heat stress. In the former, subjects were lightly clad so that evaporation would be unrestricted and a thermal steady-state could be achieved. In the latter, subjects wore their Battle Dress Uniform (BDU) and Battle Dress Overgarment (BDO) in a modified MOPP4 configuration so that evaporation would be severely restricted and a thermal steady-state could not be achieved. The null hypothesis was that, within the context of each heat stress scenario, intermittent and time-weighted continuous exercise would result in equivalent thermal strain (identical rates of body temperature rise and heat storage) and endurance times. The unique features of this study were (1) the intermittent exercise pattern (walking, jogging, seated rest) and durations (4 min, 2 min and 4 min, respectively) were chosen to mimic patterns of exertion that might occur during exigency or rescue efforts and (2) the effect of work mode was studied during both compensable and uncompensable heat stress.

PROCEDURES AND METHODS

SUBJECTS

Subjects were four healthy, moderately fit, adult male volunteers, 19 to 43 years old. Their average weight was 86 kg and average DuBois surface area was 1.92 m^2. None was acclimated for work in the heat. Before the study candidates became familiar with the experimental procedures, signed an informed consent statement approved by the Institute's Human Use Review Committee, and were examined by a physician and judged able to undertake the study. All experiments were monitored by a physician, who was either on site or within the building, depending on the intensity of the exercise or heat stress.

Before the study, the relationship between metabolic heat production and treadmill work was determined for each subject by measuring oxygen uptake with a metabolic cart (Sensormedics Corp., Anaheim, CA). Two treadmill speeds, 1.3 and 2.2 $m \cdot s^{-1}$, were used and the incline was varied from 0% to 6% grade. Subjects performed these calibration tests in a 23°C environment wearing shorts, tee-shirt, field boots and a weight belt, adjusted to equal the load of semi-permeable overgarments that were to be worn in half of the trials. Calibration curves of heat production rate, corrected for external work, versus percent grade were constructed for each subject. From these curves, treadmill grades were selected for each subject that would approximate rates of heat production equal to 3.0 mets, 3.3 mets and 8.0 mets.

Protocol. Experiments were conducted in a thermal chamber maintained at 30° C and a vapor pressure of 6.3 torr with an air movement of 0.2 $m \cdot sec^{-1}$. All experiments were conducted between the months of January and April and between the hours of 1300 to 1600. Intermittent exercise consisted of repeated 10 minute episodes: 4 min of walking (average M = 201 $W \cdot m^{-2}$), 2 min of jogging (average M = 489 $W \cdot m^{-2}$) and 4 min of seated rest (average M = 67 $W \cdot m^{-2}$). Heat production during continuous mode exercise was the time-weighted average of the above (average M = 204 $W \cdot m^{-2}$). Each subject was tested at all four combinations of compensable heat stress, uncompensable heat stress, intermittent exercise and continuous exercise. In the two compensable heat stress tests, subjects wore tee-shirts, shorts, field boots and the weight belt. In the two uncompensable heat stress tests, subjects wore light-weight work clothing and semi-permeable chemical protective overgarments including respirator masks, protective hood, protective gloves, and leather boots with protective overboots. The chemical canisters and the voice transmitter were removed from the mask to minimize ventilation resistance. Order of the four tests was unique for each subject; tests were separated by at least 48 hr. Subjects were encouraged to take water but, because esophageal temperature (T_{es}) is affected by swallowing liquids, free drinking was allowed only during one minute of each second 10 min cycle during intermittent exercise and at the corresponding time during continuous exercise. Test length was 120 min. Tests were terminated prior to 120 min for any one of the following reasons: (1) the subject chose to withdraw, (2) institutional safety limits were exceeded - a heart rate greater than 180 $beats \cdot min^{-1}$ for 5 min or a rectal temperature exceeding 39.5° C, or (3) the subject exhibited signs of illness, ataxia, disorientation or confusion. Endurance time was taken as the time of test termination.

MEASUREMENTS

Rectal temperature (T_{re}) was measured with a thermistor probe inserted 10 cm beyond the anal sphincter (Model 401, Yellow Springs Instrument Co.). Esophageal temperature (T_{es}) was monitored with a thermocouple sealed in a polyethylene tube and introduced to the approximate level of the right atrium. Skin temperatures were measured with insulated copper-constantan thermocouples at six locations. Thermocouple sensors were secured to the skin and covered with an impermeable waterproof tape to reduce the direct effect of evaporative cooling (Hy-Tape Surgical Products, Yonkers, NY). Mean weighted skin temperature ($\bar{T}_{sk}$) was calculated according to our approximation of regional area distribution using the formula:

$$\bar{T}_{sk} = .04T_{forehead} + .28T_{chest} + .28T_{back} + .10T_{arm} + .20T_{thigh} + .10T_{calf}.$$

Heart rate (HR) was continuously monitored with a cardiotachometer (IBS Corporation, Series 4600 Pulse Rate Monitor). Measurements were sampled at 15 second intervals by a Hewlett Packard data acquisition system (model 3495A scanner, model 3456A digital voltmeter, model 9800 computer; Hewlett Packard Corporation, Fort Collins, CO). The protocol included procedures for systematically effecting the transitions between walking, jogging and seated rest. As a result, timing was precise enough to permit averaging of all 15 second data points across subjects. Statistical comparisons were made with Student's t-test. Null hypotheses were rejected for $p < 0.05$.

RESULTS

ENDURANCE TIMES

When heat stress was compensable, all subjects completed the 120 minute protocols of intermittent and continuous exercise, but during uncompensable heat stress none of the subjects completed either protocol. Average endurance time was 79 min during continuous exercise and 65 min during intermittent exercise. This 14 min difference was statistically significant ($p < 0.05$).

CORE TEMPERATURES

Averaged data for T_{re} and T_{es} are compared in Figure 1. The fidelity of T_{es} data was marred by uncontrolled swallowing, causing moment-to-moment variations of small amplitude, and by water drinking, necessary to maintain subject hydration and allowed at 20 min intervals. The latter drove T_{es} off scale, and for clarity these large excursions were removed from the chart. In spite of these artifacts, the trends in T_{es} are discernable.

When heat stress was compensable, T_{es} was constantly lower than T_{re} by about 0.5°C. Both T_{re} and T_{es} reached steady-state values during continuous exercise by 60 min. During intermittent exercise, the major change in T_{re} was also achieved by 60 min but instead of realizing an authentic steady-state, T_{re} continued to rise very slightly during the remainder of the test.

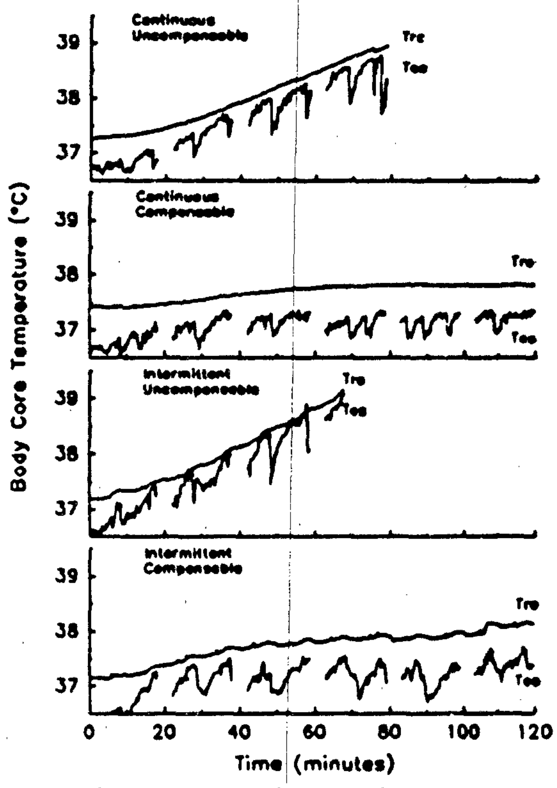

Figure 1. Comparison of T_{es} and T_{re} as measures of core temperature during continuous and intermittent work under compensable and uncompensable heat stress. Ave of 4 subjects.

When heat stress was uncompensable neither T_{re} or T_{es} achieved steady-state values and T_{es}, always the lower of the two temperatures, tended to converge upon T_{re}. After 30 min of uncompensable heat stress, the rate of rise of T_{re} was 33% greater during intermittent exercise than during continuous exercise: 2.16 $C^{\circ}\cdot hr^{1}$ for intermittent exercise versus 1.62 $C^{\circ}\cdot hr^{1}$ for continuous exercise (Figure 2). From inspection of Figure 1, the long-term rates of change in T_{es} appeared to parallel rates of change in T_{re}. At 60 min T_{re} was 38.5°C and 38.9°C for continuous and intermittent work respectively. This 0.4 C° difference was statistically significant ($p<0.05$). In contrast, 60 min values for T_{re} during compensable heat stress were almost identical for both work types.

During intermittent exercise under both heat stress types, T_{re} showed small rhythmic fluctuations (±0.03 C°) corresponding to changes in activity level.

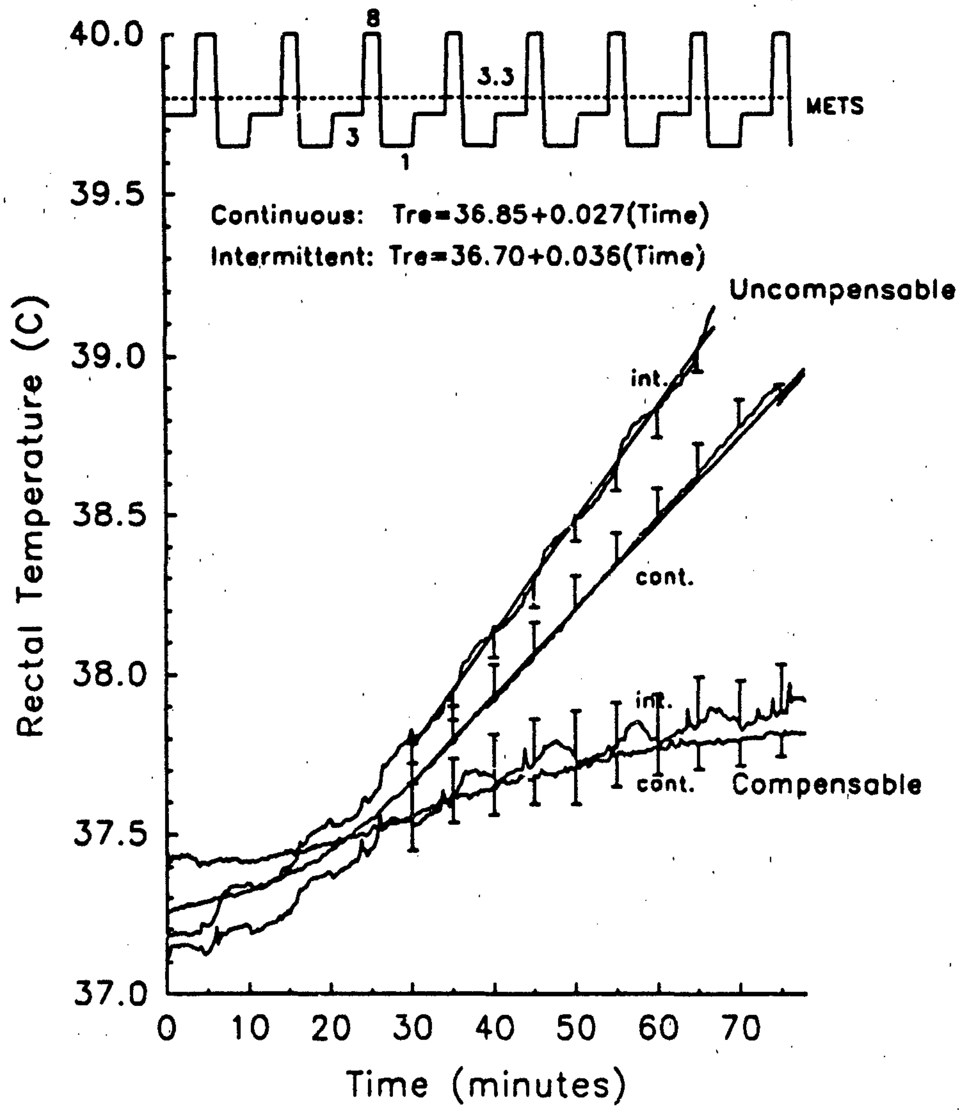

Figure 2. Comparison of ave T_{re} during the 4 protocols. Bars are SEM calculated every 5 min. Dashed linear regression lines calculated from 30 min onward.

SKIN TEMPERATURES AND HEART RATE

Averaged 15s data comparing $\bar{T}_{sk}$ and HR during continuous and intermittent exercise are plotted in Figure 3. During intermittent exercise both HR and $\bar{T}_{sk}$ showed large rhythmic fluctuations corresponding to changes in work intensity. While fluctuations in HR

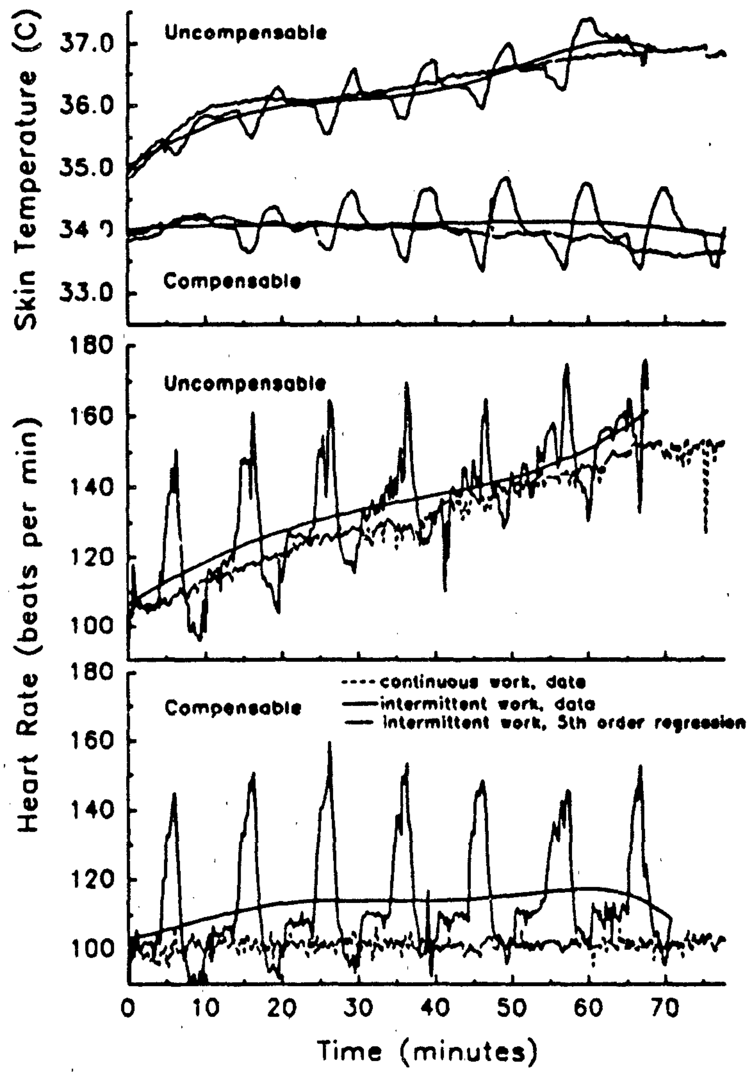

Figure 3. Comparison of average data for $\bar{T}_{sk}$ and HR. Time-weighted averages of periodic responses established by 5th order regression.

were directly related to changes in workload, oscillations in $\bar{T}_{sk}$ were inversely related to changes in workload. Figure 4 is a magnified view showing 2 cycles of intermittent work during uncompensable heat stress from which the slow heating trends were removed and the scale factor was increased to highlight the oscillations in T_{re} and $\bar{T}_{sk}$. $\bar{T}_{sk}$ varied between three distinct levels approximately 0.5 C° apart, the lowest occurring during jogging and the highest occurring during recovery. T_{re} increased during recovery and decreased during exertion, but did not exhibit distinctly different levels during walking and jogging.

To facilitate the process of comparing $\bar{T}_{sk}$ and HR between exercise modes, intermittent exercise values were fitted by least-squares, fifth-order polynomial expressions to dampen oscillations and to highlight the overall trends (Figure 3). These curves are intrinsically time-weighted. As can be seen in Figure 3, there was good agreement between intermittent work trends and continuous work data for both $\bar{T}_{sk}$ and HR during both types of heat stress.

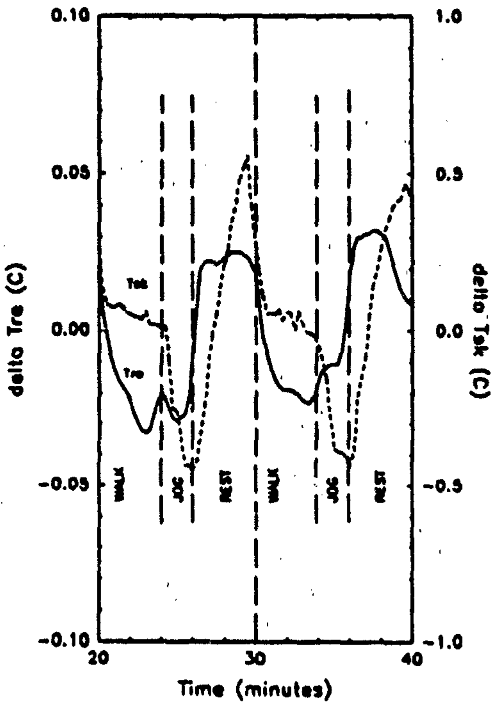

Figure 4. To highlight details of oscillatory behavior, the slow heating trend was estimated by polynomial regressions and subtracted from T_{re} and $\bar{T}_{sk}$ over 2 cycles of intermittent work.

DISCUSSION

Uncompensable heat stress is, by definition, time limited. The results of this study reveal that endurance time for subjects submitting to an intermittent exercise protocol during uncompensable heat stress was significantly less than when they exercised continuously at the same average level of heat production. These abbreviated termination times were not because institutional safety limits were exceeded but actually reflect an earlier onset of physiological failure. Of the 8 tests performed under uncompensable heat stress, 6 were terminated by the investigator because of obvious signs of heat incapacitation: ataxia, confusion, headaches or reports of gastrointestinal distress. In the other two tests, subjects felt they could not continue and voluntarily withdrew. No experiments ended before 60 min or with a T_{re} below 39.0°C. This earlier onset of physiological failure was accompanied by a significantly greater rate of internal temperature rise but not by significantly different values of average $\bar{T}_{sk}$ or average HR.

Similarities and differences in the response of the two measurements of core temperature deserve comment. T_{es} is strongly influenced by the temperature of the heart (16). The temperature of the heart, in turn, is determined largely by the temperature of venous blood that has returned from all body sites, including the skin, and passed through the lungs while T_{re} is influenced by this same blood only after reheating during passage through interior tissues. Rowell et al., in experiments that controlled $\bar{T}_{sk}$ with a water-perfused suit during continuous exercise, showed that changes in the temperature of the right atrium rapidly and dramatically reflected changes in $\bar{T}_{sk}$ (19). In the present study T_{es} was consistently lower than T_{re} during compensable heat stress. This is likely because a significant fraction of the venous return was reduced in temperature during its passage through a cool skin. During the time course of uncompensable heat stress, on the other hand, blood flowing through an increasingly warmer skin returned at an increasingly higher temperature causing T_{es} to gradually converge upon T_{re}.

During uncompensable heat stress the rate of rise of T_{re} was 33% greater from 30 min onward when subjects exercised intermittently. A 33% greater rate of rise in T_{re} implies a similar increase in the rate of deep body heat storage. Physically, this must be accounted for by differences in the rates of heat production, transport or dissipation.

It is possible that during uncompensable heat stress the rate of heat production may have been slightly greater during the jogging phases of intermittent exercise than we anticipated from the subjects' pre-study calibration data. Rowell et al, studying subjects who were continuously exercising at 420 $W \cdot m^{-2}$, reported an increase in $\dot{V}O_2$ but only after 100 min when subjects had become hyperthermic (18). Furthermore, this was a very small change (4%). However, since our subjects spent 20% of their intermittent work time exercising at a similar level (489 $W \cdot m^{-2}$) and also became quite hyperthermic, there may have been a modest increase in heat production during uncompensable heat stress. However, this alone cannot account for a 33% increase in the rate of heat storage.

A second possibility is that, during uncompensable heat stress, the rate of heat loss to the environment by radiation and convection (R+C) and/or by evaporation (E_{sk}) and/or by ventilatory convection and evaporation ($C_{res}+E_{res}$) was less during intermittent exercise than during continuous exercise. We examined this possibility by calculation, using a partitional calorimetry model to estimate heat exchanges and the data values between 50 and 60 min of exposure (7,10).

Table 1. Comparison of rates of skin heat exchange and rates of heat storage ($W \cdot m^{-2}$) after 50-60 min of intermittent or continuous work during uncompensable heat stress as projected by the Gagge-Nishi partitional calorimetry model (7).

Work Mode	*% of Time*	*$\bar{T}_{sk}$ (°C)*	*T_{cl} (°C)*	*Metab (+)*	*(R + C) (-)*	*E_{sk} (-)*	*C_{res} + E_{res} (-)*	*Storage (+ or -)*
Pulsed, Walking	40	36.6	31.7	201	22	80	36	63
Pulsed, Jogging	20	36.4	31.6	489	22	80	86	301
Pulsed, Rest	40	37.1	32.0	67	22	79	12	-46
Time-Weighted Average	**100**	**---**	**---**	**204**	**22**	**80**	**36**	**67**
Continuous Walking	**100**	**36.8**	**31.7**	**204**	**23**	**81**	**36**	**64**

The following values were assumed in these calculations using equations in the Appendix: $T_c = T_r = T_o = 30°C$, $P_a = 6.3$ Torr, $I_{clo} = 1.46$, $i_m = 0.23$, body weight = 86 kg, surface area = 1.92 m^2, $V_{air} = 0.2\ m \cdot s^{-1}$, and $V_{move} = 0$, 1.3 and 2.2 $m \cdot s^{-1}$ for rest, walking and jogging, respectively, duringintermittent work and 1.3 $m \cdot s^{-1}$ during continuous work. Values for $\bar{T}_{sk}$ are averages between 50 - 60 min. Values for T_{cl} were obtained from the outer clothing of a single subject.

The formulas for this model are in the Appendix and the results of calculation are tendered in Table 1. During intermittent work, calculated (R+C) losses remained at 22 $W \cdot m^{-2}$ whether sitting at rest, walking or jogging. Calculated E_{sk} loss also varied little: from 79 $W \cdot m^{-2}$ during rest/recovery to 80 $W \cdot m^{-2}$ while jogging. ($C_{res}+E_{res}$) loss varied the most, from 12 $W \cdot m^{-2}$ while resting to 86 $W \cdot m^{-2}$ while jogging, although one study has shown that Fanger's equations underestimate E_{res} at high work loads (6,9). The calculated increase in ($C_{res}+E_{res}$) loss generally reflects the influence of exercise on ventilation rate. The heat exchange calculations do not support an overall difference in surface heat loss between the two work modes: calculated time-weighted mean values for heat loss by (R+C), E_{sk} and (C_{res}+E_{res}) between 50 and 60 min of intermittent exercise were nearly identical with values calculated at 60 min of continuous exercise. Thus, the partitional calorimetry model predicted that surface heat loss was the same for both work modes during the later stages of work. It is possible that surface heat loss could have been less during intermittent work than during continuous work since the partitional calorimetry model does not account for changes in the convective and evaporative heat transfer coefficients caused by air movement within the clothing or for uncontrolled garment leakage between the internal microclimate and the external environment. Nevertheless, the possibility that differences in leakage or convection within clothing could account for a 33 percent difference in the rate of heat storage seems slight.

The partitional calorimetry model is based on perfect coupling between sources of heat production and sinks for heat loss; that is, it assumes that the rate of heat transport between sources and sinks is never a limiting factor. But, during uncompensable heat stress, a difference in the rate of core-to-skin heat transport during continuous and intermittent exercise might actually account for the greater rate of heat storage. The wide variation in blood flow rate through the cutaneous circulation is of primary benefit to body heat transport processes on command from central thermoregulatory centers. A frequently cited operational model maintains that skin blood flow (SkBF) is a linear function of internal temperature (T_{es}), while $\bar{T}_{sk}$ operates to adjust the T_{es} threshold (4,11). But there are dramatic non-thermal exceptions to this simple paradigm. Large reductions in SkBF, lasting 1-2 min, have been shown to accompany the transition from supine rest or recovery to supine exercise (13). In these cited studies the intensity of vasoconstriction sometimes, but not always, became more conspicuous as subjects become more hyperthermic and there was never any evidence of reactive compensation for this "SkBF debt" during recovery periods. Furthermore, simply assuming an upright posture also tends to reduce the expected levels of SkBF in a heated subject (4,20). Thus, both postural and workload changes have been reported to bring about reductions in the rate of cutaneous heat transport.

While our subjects were not exercising in the supine position, they were moving frequently between exercise and recovery, standing and sitting. The extent to which these postural and exercise maneuvers influenced SkBF in the present study cannot be determined with certainty, but a clue may be uncovered by re-examining $\bar{T}_{sk}$ data in Figures 3 and 4. Our measurements of $\bar{T}_{sk}$ were made with tape-covered thermocouples to minimize effects of evaporation. The progressive reductions in $\bar{T}_{sk}$ observed during the walking and jogging periods and the rebound of $\bar{T}_{sk}$ during recovery, could be related to vasoconstriction during upright exercise and release of vasoconstriction during seated recovery. Postural changes in $\bar{T}_{sk}$ have been reported and attributed to altered circulatory transport of heat, either because of changes in skin blood flow or because of changes in the transit time of blood flow through skin as the result of reflex venous activity (8). To the extent that transient episodes of vasoconstriction or venoconstriction did occur, they most certainly would have been accompanied by interruptions in the rate of heat transport from core to skin. This overall heat transport deficit might in itself be large enough to account for differences in the observed rate of deep body heat storage during the two work modes. In this regard the duration of the exercise and recovery phases may be important (3). Even at ordinary temperatures, Ekblom et al. reported that T_{re} was 0.41 C° higher during intermittent exercise when very short (30s) heavy work/recovery cycles were employed (5).

If one accepts that the problem is one of heat transport and that oscillations in $\bar{T}_{sk}$ reflect alternating imposition and release of cutaneous vasoconstriction and/or venoconstriction during uncompensable heat stress, then the next challenge is to explain why similar oscillations in $\bar{T}_{sk}$ during compensable heat stress were not also accompanied by a similar increase in the rate of observed deep body heat storage. With respect to this paradox, it is worthwhile to scrutinize the time course of temperature difference between core and skin (T_{re} - $\bar{T}_{sk}$) during intermittent work (Figure 5). Recall that skin thermocouples were covered with impermeable tape to minimize the direct effect of evaporation from the skin surface directly beneath them. Thus, changes in $\bar{T}_{sk}$, while reflecting general evaporative influences, were less likely to respond quickly to sudden changes in evaporation rate from surrounding areas, and may be more representative of changes in heat flow from the underlying skin vasculature. In the simplest model of heat transport from core to skin, heat flux is a function of the product of SkBF and the core-to-skin temperature difference (12). During both types of heat stress the observed core-to-skin temperature difference was highest during the jogging phase and lowest during the recovery phase. But over most of the period, the observed core-to-skin

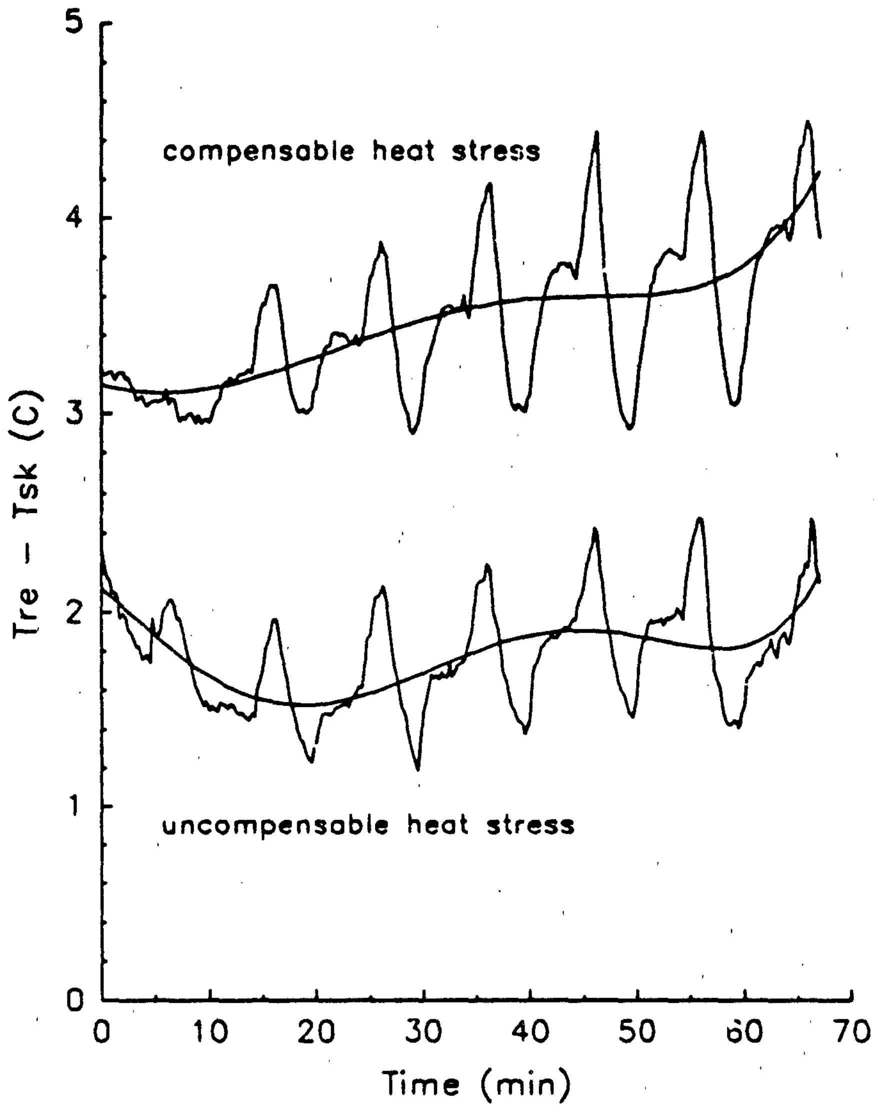

Figure 5. Ave difference between T_{re} and $\bar{T}_{sk}$ and trend lines during intermittent work. Oscillations tend to grow during compensable heat stress but are stationary during uncompensable heat stress.

temperature difference was roughly twice as large for compensable as for uncompensable heat stress. Since heat production was essentially the same in both cases, the above simple heat flow model predicts that required SkBF during compensable heat stress could have been one-half that required during uncompensable heat stress. In addition, during compensable heat stress, the magnitude of the core-to-skin temperature difference enlarged with time nearly 1 C° during walking and jogging phases and remained stationary during recovery. According to the above model, this would further reduce the requirements for SkBF. In contrast, little growth in the core-to-skin temperature difference was seen during uncompensable heat stress, so predicted required blood flow would not change. Thus, it is possible that, during compensable heat stress, growth of the core-to-skin temperature difference provided a mechanism to counteract the effects of transient vasoconstriction but, because of a stationary core-to-skin-temperature difference during uncompensable heat stress, this counteracting mechanism was not available.

CONCLUSIONS

The results of this study showed that, under conditions of compensable heat stress, the average time-courses of internal and skin temperatures and heart rate to intermittent work cycles of short duration are approximately the same as those obtained when work is performed continuously at the time-weighted average of the intermittent work pattern. Even under conditions of uncompensable heat stress the average time-course of skin temperature and heart rate during the intermittent work pattern were well approximated by responses during continuous work. However, during uncompensable heat stress, the average time-course of internal temperature during intermittent work was significantly underestimated and the time to physiological failure was significantly overestimated by the continuous work data. Thus, under the uncompensable conditions of our study, relying on the results of trials of time-weighted continuous work to approximate the results of intermittent work patterns results in a significant and perhaps hazardous under-prediction of thermal strain and overprediction of time to physiological failure. This reduction in time to physiological failure was signaled by internal temperature but was not signaled by either average HR or average $\bar{T}_{sk}$.

The mechanisms underlying this non-linearity have not been defined. Clearly, cutaneous blood and heat flow shifts and changes in evaporation rate and in the cutaneous microclimate that may accompany postural and workload transitions are critical factors that deserve additional investigation. Until these basic phenomena are better understood, the time-weighted averaging method should be employed with caution during time-limited exposure to uncompensable heat stress.

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APPENDIX

GAGGE-NISHI PARTITIONAL CALORIMETRY MODEL OF HEAT EXCHANGE (7).

Sensible Heat Loss

(R+C) is given by:

$$(R+C) = F'_{cl} h (T_{sk} - T_o), \qquad [W \cdot m^{-2}]$$

where h is the combined coefficient for heat transfer by radiation and convection, defined as $h = h_r + h_c$. T_o is operative temperature, defined as $T_o = (h_r T_r + h_c T_a)/h$, and F'_{cl} is a dimensionless (*nd*) climatic efficiency factor, defined as $1/(1 + 0.155 \cdot h \cdot I_{clo})$. I_{clo} is the clothing insulation value in Burton's clo units.

h_r is obtained from:

$$h_r = 4\sigma (A/A_D) f_{acl} \left[\frac{(T_{cl} + T_o)}{2} + 273 \right]^3, \quad \textit{where}$$

σ is the Stefan-Boltzman Constant: 5.67×10^{-8} $[W \cdot m^{-2} \cdot K^{-4}]$,

(A/A_D) *is the body fraction exposed to radiation* (0.72), *and*

f_{acl} *is the Breckenridge clothing area factor, defined as* $(1 + 0.15 I_{clo})$ $[nd]$.

Formulas for calculating the convective heat transfer coefficient, h_c, during treadmill walking and rest respectively, are:

$$h_c = 6.5(V_{move})^{.39} + 1.96(V_{air})^{.86}$$
and
$$h_c = 11.6(V_{air})^{.5}$$

V_{move} and V_{air} are velocities of movement by the subject and by air, respectively, in $m \cdot sec^{-1}$.

When T_r and T_a have the same value, as in this study, then T_o also assumes that value.

Insensible Heat Loss

E_{sk} is determined by the rate of sweat production (SR) and the maximal rate of evaporative heat loss from a fully wetted skin surface (E_{max}). E_{max} is a function of the vapor pressure gradient between the fully wetted skin surface and the air ($P_{s,sk} - P_w$), the evaporative heat transfer coefficient (h_e) and i_m, Woodcock's dimensionless factor for water-vapor permeability of clothing. The evaporative heat transfer coefficient, h_e, is directly related to the convective heat transfer coefficient, h_c, by the Lewis Relation. The expression for E_{sk} under conditions where evaporation of sweat is restricted is (10):

$$E_{sk} = E_{max} = h_e\, f_{pcl}\, (P_{s,sk} - P_a), \quad \textit{for } E_{max} \le \frac{40.8\ SR}{A_D} \qquad [W{\cdot}m^{-2}]$$

$$\textit{where} \quad f_{pcl}, \textit{ the Nishi permeation efficiency factor,} = \frac{h}{h_c}\, F_{cl}\, i_m \qquad [nd].$$

$$A_D \textit{ is the Dubois surface area and } \ h_e = 2.2\, h_c \ \ \textit{(at sea level)} \qquad [W{\cdot}m^{-2}{\cdot}Torr^{-1}].$$

$P_{s,sk}$ is related to $\bar{T}_{sk}$ by the Antoine Equation (10):

$$P_{s,sk} = \exp\left(18.6686 - \frac{4030.183}{T_{sk} + 235}\right) \qquad [Torr]$$

Respiratory Heat Loss

($C_{res}+E_{res}$) is directly related to ventilation rate which, in turn, is directly related to aerobic exercise intensity (M_{tot}) up to maximal levels. The combined equation for convective and evaporative respiratory loss is adapted from separate equations of Fanger (6):

$$(C_{res}+E_{res}) = M_{tot}[0.0014(34 - T_a) + 0.0023(44 - P_w)] \qquad [W{\cdot}m^{-2}]$$

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