Determinants of the prescriptive zone of industrial workers

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KUHLEMEIER, K. V., J. M. MILLER, F. N. DUKES-DOBOS, AND R. JENSEN. *Determinants of the prescriptive zone of industrial workers*. J. Appl. Physiol.: Respirat. Environ. Exercise Physiol. 43(2): 347–351, 1977. —The prescriptive zone is the range of climates in which man's body temperature is independent of climatic conditions. The environmental temperatures which define the upper limit of the prescriptive zone (ULPZ) at different work rates were determined in 46 clothed, healthy, male industrial workers; some of the men were job acclimated to heat and some were not. They performed a total of 653 work bouts of low, medium, or high intensity in environments ranging from 11 to 35°C corrected effective temperature (CET) (8–37°C wet bulb globe temperature). Heart rates (HR) and rectal temperatures (T_{re}) were measured after 1 h of work. The ULPZ was calculated from T_{re} data. HR's showed a similar pattern of response as T_{re}'s except that the inflection point corresponding to the ULPZ occurred at different environmental temperatures at most of the experiment conditions. About one-third of the work bouts were performed in the summer months and the remainder in the winter. The ULPZ decreased with increasing work rates. At high, but not low, work rates, men who were exposed to heat in the performance of their jobs were more heat tolerant than men who were not heat acclimatized. Both groups were found to be more heat tolerant in the summer months than in the winter.

body temperature; pulse rate; heat stress; exercise; acclimatization; work

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INCREASE IN BODY TEMPERATURE during physical activity has long been recognized. Nielsen reported in 1938 (13) and reconfirmed in 1962 (12) that this rise in temperature was independent of ambient temperature over a range from 5 to 30°C. Environments hotter than 30°C result in increases in rectal temperature beyond those reported by Nielsen and Nielsen (12). This finding was used by Lind (9–11) who proposed an objective physiological criterion for establishing environmental limits for everyday work. He found (like Nielsen) that over a wide climatic range, expressed as corrected effective temperatures (CET), the subject's equilibrium core temperature was determined only by his work rate and not by the environmental conditions. Lind designated this range of climatic conditions the "Prescriptive Zone."

The concept of the prescriptive zone is a useful physiological criterion for establishing thermal exposure limits for industrial workers. Rectal temperature is the biological parameter currently used to define the prescriptive zone although heart rates show a similar phenomenon during heat exposure.

In this study we have examined some of the factors that determine the limits of the prescriptive zone. The specific goals of this study were *1*) to examine the functional relationship, including inflection points, between rectal temperatures and heart rates and the CET and wet bulb globe temperature (WBGT) indices of environmental heat in clothed industrial workers; *2*) to determine quantitatively the effect of seasonal changes in the above; *3*) to determine whether there is a response differential between workers who are adapted to heat stress by working in hot jobs and those who are not; and *4*) to determine the effect of work rate on the heart rate- and rectal temperature-environmental index relationship.

METHODS

Subjects

The subjects for this study were healthy men aged 20–50 yr. Subjects were excluded from the study if they exhibited symptoms of hypertension or S-T depression during near-maximal exercise.

The subjects were volunteer workers selected from the following industries.

Hot. Steel (both open-hearth and rolling mill workers), cement manufacture, and aluminum reduction.

Cold. Meat packing.

Neutral. Students, janitors, and hospital orderlies.

In this report, the data of the cold and neutral group were combined to form a "cold-neutral" group since the responses of workers within this group were not different. No subject was tested during or immediately following his vacation.

Experiments were conducted during one summer and two winter seasons. Forty-six workers participated in these experiments. Not all subjects completed a full season's experiments but about 70% of the subjects remained in the study long enough to complete both a full winter and summer test battery. The data from all subjects are included in this report.

Measurements

The measurements in this study included heart rate and rectal temperature. Each of these was determined before and at the end of each work bout. Heart rates were obtained from ECG tracings. All temperatures were measured with type-T thermocouples and a Honeywell Electronik 112 temperature recorder with an accuracy of 0.1°C. Rectal temperatures were measured 9–11 cm past the anal sphincter. The weight loss incurred during a work period was replaced during each subsequent rest period by salted water. Oxygen uptakes were determined by the open-circuit method with analysis of expired air by a Beckman paramagnetic oxygen analyzer, model E2, and a Beckman infrared carbon dioxide analyzer, model LB-1.

Test Protocol

The subjects entered the laboratory dressed in their normal work clothing after eating their usual breakfast and were fitted with ECG electrodes and a rectal thermocouple. Subjects were instructed to wear their usual working clothes. This consisted of underwear, shirts and trousers, wool or heavy cotton socks, and boots (clo value of 0.7–0.8). The subject was weighed and stood quietly while resting data were acquired. The subjects then walked for 1 h. The tests were terminated before 1 h if *1*) the subject's heart rate exceeded 90% of the predicted maximal heart rate for men of his age; *2*) the rectal temperature exceeded 39.2°C; *3*) the subject's blood pressure exceeded 200 mmHg systolic or 110 mmHg diastolic; *4*) the subject became faint; or *5*) the subject asked that the test be terminated. Subjects completed three or four 1-h tests per day with a 1-h rest between work periods.

In any one series, each subject performed each of three metabolic work loads at up to five ambient temperatures. The low, medium, and high work loads consisted of treadmill walking at 0.8 $m \cdot s^{-1}$ horizontally (average of 142 $W \cdot m^{-2}$), 1.3 $m \cdot s^{-1}$ horizontally (average of 191 $W \cdot m^{-2}$), and 1.3 $m \cdot s^{-1}$ up a 5% incline (average of 273 $W \cdot m^{-2}$), respectively. The ambient conditions ranged from 11.0 to 35°C CET. Relative humidities ranged from 32 to 50% and were chosen so as to keep a constant gradient between the vapor pressure of the atmosphere and the vapor pressure at the skin surface. Two of the ambient conditions were chosen so as to fall below the expected ULPZ and the remainder were chosen to fall above the projected ULPZ.

The subjects were tested during only one day in any 7-day period and progressed sequentially through the three work rates in environments ranging from cool at the beginning of a season's testing to hot at the end of a season.

Natural wet bulb, aspirated wet bulb, dry bulb, and globe temperatures were measured every 6 min and averaged over the duration of the work period. Air velocity was measured at chest level and was usually below 0.3 $m \cdot s^{-1}$. The wet bulb globe temperatures (WBGT's) were calculated as WBGT = 0.3 × globe temperature + 0.7 natural wet bulb temperature. CET's were calculated by the method described by Leithead and Lind (8). The wet and dry bulb temperatures used to obtain a given CET are shown in Fig. 1.

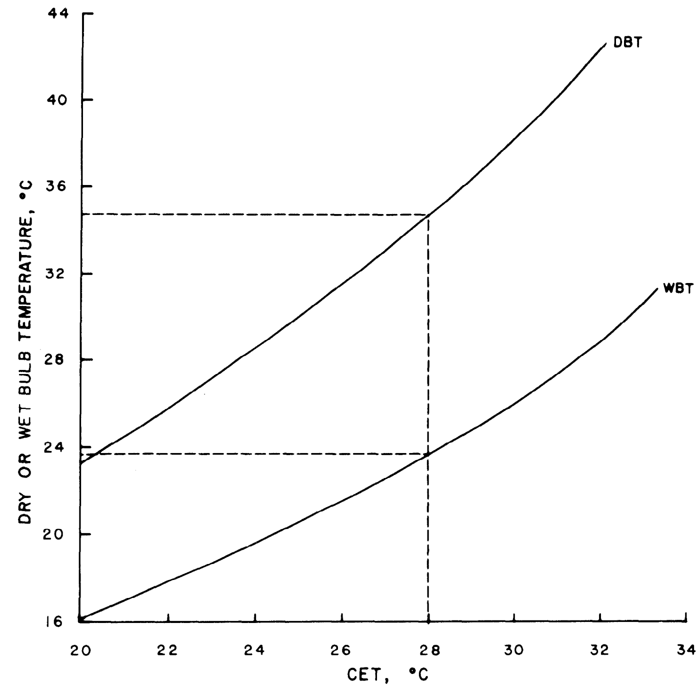

FIG. 1. Dry bulb temperatures (DBT) and wet bulb temperatures (WBT) used to obtain CET's. In the example shown (*dotted lines*) the DBT was 34.7°C and the WBT was 23.7°C for a CET of 28°C.

Statistical Analysis

The aim of the statistical analysis was to relate quantitatively the physiological responses of the subjects measured at the end of each test period (equilibrium state) to the heat level of the environment expressed in terms of both CET and WBGT indices. The statistical approach was based on the assumption that our subjects would respond to heat in a manner similar to Lind's subjects, viz., rectal temperature would be independent of the environmental heat load when exposures are below the ULPZ, but when exposures are above the ULPZ, the rectal temperatures would be dependent on environmental heat load. Heart rates were treated statistically the same as the rectal temperatures. The environmental conditions were divided into high and low regions which were expected to be well above or well below the expected ULPZ, respectively. In the high exposure region, a line was fitted to the points representing the equilibrium state by using standard linear regression methods (4). In the low exposure region, it was assumed that the mean physiological response is consistent throughout the region and is, therefore, a horizontal line on a graph relating physiological response to environmental heat index. The inflection point of the rectal temperature (T_{re}) and heart rate (HR) curves is the point where the horizontal line intersects the sloped regression line as illustrated in Fig. 2.

RESULTS

Presentation of Results

The inflection points for each combination of metabolic rate, season, and industry group for the CET and

WBGT indices are given in Table 1 for summer months and in Table 2 for winter months.

Effects of Job Heat Exposure on Inflection Point

The differences between the inflection points for T_{re} and HR of the hot and cold-neutral industry groups are given in Table 3 for each metabolic rate and index of environmental heat level.

When heat stress is expressed as CET, the inflection point for T_{re} is lower in the hot industry group at the low metabolic rate (MR), but at the medium rate is somewhat higher and at the high MR is substantially higher for the hot industry group. The inflection point for HR is higher in the cold-neutral group than in the hot industry group for the low metabolic rate; the inflection points for this parameter at the medium and high metabolic rates are not substantially different for the two groups. When levels of ambient heat stress are expressed as WBGT, the relationships are slightly different. At the low metabolic rate, the infection points for HR and T_{re} are also higher for the cold-neutral group. At the medium metabolic rate, the differences are small. At the high metabolic rate, both the ULPZ for T_{re} and the inflection point for HR are higher for the hot industry group than for the cold-neutral group. Thus, the general picture emerges that inflection points of the hot industry group occur at higher heat exposures, at least at the higher rates of work.

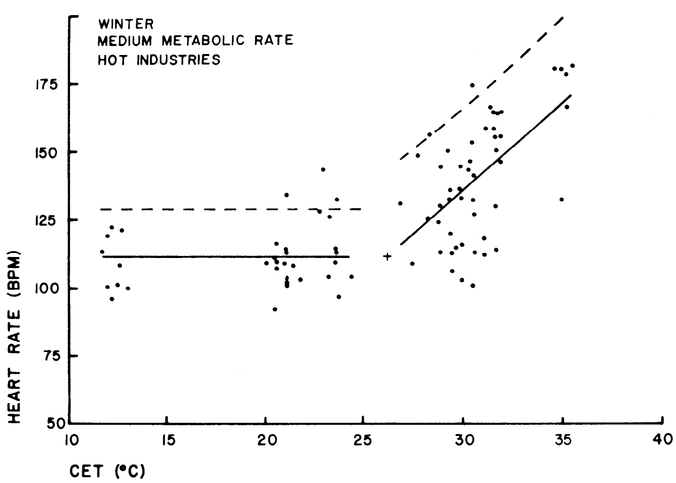

FIG. 2. Graphical representation of method of determining the inflection points. Interrupted lines are upper 90% confidence intervals.

Effects of Season on Inflection Points

The effects of season on inflection points are summarized in Table 4.

The data given in this table are averaged over the hot and cold-neutral industry groups. With one exception, the inflection points are always higher in the summer than in the winter season. The single exception is seen in the inflection point for HR at low metabolic rates when heat stress is expressed as CET. In all other cases,

TABLE 1. *Calculations for determination of ULPZ's and inflection points for summer months*

	Rectal Temperature		Heart Rate	
	A, °C	I, °C	A, beats·min^{-1}	I, °C
Corrected effective temperature				
Cold-neutral industries				
Low metabolic rate	37.43	29.0	94.0	28.1
Medium metabolic rate	37.59	27.8	106.8	28.5
High metabolic rate	37.88	26.5	134.3	26.6
Hot industries				
Low metabolic rate	37.48	26.5	89.2	21.4
Medium metabolic rate	37.70	29.1	102.6	28.6
High metabolic rate	37.98	27.1	127.1	26.5
Wet bulb globe temperature				
Cold-neutral industries				
Low metabolic rate	37.43	29.0	94.0	28.2
Medium metabolic rate	37.59	28.2	106.8	28.5
High metabolic rate	37.88	25.8	134.3	25.2
Hot industries				
Low metabolic rate	37.48	27.1	89.2	22.2
Medium metabolic rate	37.70	28.8	102.6	28.2
High metabolic rate	37.98	26.6	127.1	26.6

A is the average value of rectal temperature (or heart rate) when the environmental temperatures are below the expected ULPZ; I is the environmental temperature (°C) at which the regression line relating rectal temperature (or heart rate) to heat stress equals A, i.e., the inflection point. For the rectal temperature data I is equivalent to the ULPZ.

TABLE 2. *Calculations for determination of ULPZ's and inflection points for winter months*

	Rectal Temperature		Heart Rate	
	A, °C	I, °C	A, beats·min^{-1}	I, °C
Corrected effective temperature				
Cold-neutral industries				
Low metabolic rate	37.48	27.1	96.1	24.7
Medium metabolic rate	37.69	24.6	113.0	25.9
High metabolic rate	38.10	18.0	143.8	23.2
Hot industries				
Low metabolic rate	37.57	27.5	95.6	27.6
Medium metabolic rate	37.78	26.5	110.7	26.2
High metabolic rate	38.13	23.6	137.7	22.7
Wet bulb globe temperature				
Cold-neutral industries				
Low metabolic rate	37.48	25.6	96.1	21.5
Medium metabolic rate	37.69	22.4	113.0	24.3
High metabolic rate	38.10	15.8	143.8	19.8
Hot industries				
Low metabolic rate	37.57	26.2	95.6	26.4
Medium metabolic rate	37.78	25.5	110.7	24.3
High metabolic rate	38.13	21.4	137.7	19.8

See Table 1 for explanation of terms.

TABLE 3. *Differences between ULPZ's and inflection points for workers from hot and cold-neutral industries averaged over both seasons*

	CET, °C		WBGT, °C	
	T_{re}	HR	T_{re}	HR
Low MR	−1.0	−1.9	−0.6	−0.6
Med MR	1.6	0.2	1.8	0.1
High MR	3.1	−0.3	3.2	1.5

A negative value indicates that the ULPZ or the inflection point is lower for the hot group.

TABLE 4. *Seasonal differences in ULPZ for T_{re} and inflection points of HR averaged over hot and cold-neutral groups*

	CET, °C		WBGT, °C	
	T_{re}	HR	T_{re}	HR
Low MR	0.4	−1.4	2.2	1.2
Med MR	2.9	2.5	4.6	3.8
High MR	6.0	3.6	7.6	5.3

A negative value indicates that the inflection point is higher in the winter season.

the inflection points for T_{re} and HR for summer months are higher than the inflection points for the winter months for all metabolic rates whether expressed on the CET or WBGT index of heat stress. The difference in inflection points for both HR and T_{re} between the summer and winter months increases as the work rate increases so that summer-winter differences are magnified at the high work rate. A multivariate regression analysis described elsewhere (7) revealed that job industry classification and season had a significant ($P < 0.01$) effect on the HR and T_{re} responses.

DISCUSSION

In these studies, the tests were terminated a total of 51 times out of 653 work bouts because one or more of the safety limits were reached. Forty-six were terminated for excessive heart rates, three for excessive T_{re}'s, and two for simultaneous excessive HR's and T_{re}'s. In many industries, men in very hot jobs may work very vigorously for relatively short periods of time. In these circumstances heart rates may reach high levels, while the thermal inertia is such that rectal temperatures may rise only slightly. For example, one of our subjects was a 41-yr-old male who had a heart rate of 180 after 24 min of work at the high metabolic rate; yet his rectal temperature was only 37.7°C.

Although there are several differences between this study and those of Lind (9) and Wyndham and his colleagues (15, 16), a comparison is informative. The major differences, include the following.

Clothing. Our subjects wore their normal work clothing, Lind's wore only shorts and shoes and Wyndham's were nude.

Number of subjects. Lind studied three subjects extensively (9) and many subjects less extensively (11). We had 46 workers participate in our study and Wyndham used over 300 subjects who performed only one test each.

Climate of residence. Lind's subjects resided in a temperate climatic region and were unacclimatized to heat. Wyndham's subjects and ours lived in a semitropical zone and some were acclimatized to work in hot environments. The ULPZ's for these studies are outlined in Table 5.

The average physiological responses after prolonged exposures to environments below the ULPZ are in general agreement with those reported by Lind. The subject grouping which had T_{re} values closest to Lind's subjects was the hot group during the summer. Since these

TABLE 5. *ULPZ's in °C CET as found by Lind and Wyndham et al. and as found in this study (based on T_{re} data)*

	Hot Group		Cold-Neutral Group		Lind	Wyndham et al.	
	Summer	Winter	Summer	Winter		Unacclimatized	Acclimatized
Low MR	26.5	27.5	29.0	27.1	30.2	31.3	31.2
Med MR	29.1	26.5	27.8	24.6	27.4	31.0	30.1
High MR	27.1	23.6	26.5	18.0	26.9	28.7	28.1

subjects were acclimatized and clothed while Lind's subjects were unacclimatized and almost nude, the explanation which appears most probable is that the effect of clothing and acclimatization tend to cancel each other (1, 5). Wyndham's unacclimatized subjects had higher T_{re}'s in the prescriptive zone than the acclimatized subjects at all metabolic rates.

At the low metabolic rate the ULPZ's found in this study were lower than those reported by either of the other investigators, suggesting a lower heat tolerance of our subjects.

At the medium metabolic rate, the ULPZ's found in this study were somewhat different from those reported by Lind and Wyndham. However, it appears that at least some of the differences are attributable to climate of residence and/or degree of acclimatization. Our ULPZ's and those of Lind were consistently lower than those of Wyndham.

At the high metabolic rate, the ULPZ for the hot industry subjects is 0.2°C CET higher during the summer than Lind's and 3.3°C CET lower during the winter. The ULPZ for the cold-neutral industry subjects during the summer is 0.4°C CET lower than Lind's findings. Again Wyndham reported higher ULPZ's than those observed in this study and Lind's study. The ULPZ for the cold-neutral subjects during the winter was calculated to be 8.9°C CET lower than Lind's ULPZ and 10.1°C CET less than Wyndham's. Such large differences were quite unexpected, and if confirmed would mean that the heat tolerance of workers not employed in hot jobs is extremely low during the winter. However, this conclusion may be biased by the fact that we were unable to get adequate data at the higher levels of heat stress since the subjects' responses frequently exceeded the safety levels and the experiment had to be terminated. This resulted in a calculated ULPZ which might be lower than the ULPZ would have been if the experiments had been continued for a full hour.

Lind's paper shows a graph of HR's for the medium metabolic rate only. The mean HR below the ULPZ appears to be about 120. Our average HR's ranged from 103 to 113 beats$\cdot$min^{-1} depending on the season and industry group. Mean HR's were about 95 and 130 for the acclimatized and unacclimatized men, respectively, in South Africa. At the same exercise level as Lind's subjects the HR inflection point we found in our "winter, cold-neutral industries" group was 25.9°C CET and Wyndham found 27.8 and 28.4 for his two groups. Lind's subjects had a HR inflection point of about 25°C CET.

Although there are some minor inconsistencies it is clear that increasing the degree of acclimatization raises the point at which physiological responses become dependent on environmental heat stress. This can be seen by comparing the inflection points for summer and winter or for the hot and cold-neutral groups. Surprisingly the summer-winter differences are larger than industry group differences, implying that normal daily summer activities have a greater effect on acclimation than working in hot industries.

At low work rates there is little difference between the industrial groups in the inflection points for either T_{re} or HR. At medium and high work rates the T_{re} inflection points for the hot group are clearly higher than for the cold-neutral in this study. Thus at low stress levels the results from unacclimatized men compare favorably with those from acclimatized subjects; but in more severe environments the increased tolerance to heat stress of the acclimatized men becomes apparent. Similarly the differences in inflection points between the two seasons are smaller at the lower rates of work than at higher work levels.

When Wyndham's data are plotted in a format similar to Fig. 2 (see (2)), the difference in ULPZ between acclimatized and unacclimatized Africans is about 0.2°C at the low metabolic rate (205 W) and about 0.6°C at the high metabolic rate (469 W). Similarly within the prescriptive zone the equilibrium rectal temperature is about 0.5°C lower for the acclimatized men at the low work rate and 1.0°C lower at the high work rate.

The smaller differences at low work rates may be due to the fact that the cardiovascular requirements of the working muscles are relatively modest so that the necessary increases in blood flow are easily met. However, during hard work the cardiovascular reserves are smaller so that the increased heat production cannot be readily dissipated. During high work rates the acclimatization process, which increases the cardiac reserves, lends a greater degree of protection than during work rates when the cardiovascular reserves are larger. The acclimatization process increases cardiac reserves by several mechanisms. Senay (14) found that the process of heat acclimatization reversed the hemoconcentration and loss of protein from the vascular volume during work in the heat that is normally seen in unacclimatized subjects. Presumably the increased blood volume could result in increased ventricular filling and a larger stroke volume, allowing the heart to maintain cardiac output at a reduced heart rate. Skin blood flows increase after passive acclimatization to heat (6). Increased skin blood flow is one of the major mechanisms for dissipating internally produced heat.

The changes in inflection points with acclimation are smaller for the HR than for T_{re} as shown in Tables 3 and 4. Also, the trend for larger differences at higher work rates is less pronounced for HR than for T_{re}.

While it is true that the type of clothing worn (not highly standardized in this study) can alter the ULPZ (3), it was not the purpose of this study to examine clothing effects. Rather we have tried to determine the ULPZ of industrial workers wearing their usual work attire.

Due to the large inter- and intraindividual variability, we urge caution in using the data as presented here. It would not be prudent to assume the inflection point for an individual is the same as the inflection point calculated from mean responses of many individuals.

We gratefully acknowledge the assistance of Mr. J. Carrigan and Ms. S. Bell in conducting these experiments and the aid of Ms. J. Amberson, Ms. L. Atchley, and Mr. T. Wood in data analysis. We also are indebted to Drs. A. Henschel, A. R. Lind, and J. A. J. Stolwijk for their assistance in the design of these experiments.

This research was supported by National Institute for Occupational Safety and Health Contract HSM-99-72-45.

Mention of trade names or commercial products does not constitute endorsement or recommendation by the National Institute for Occupational Safety and Health.

Received for publication 30 August 1976.

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