Deep Body Core Temperatures in Industrial Workers Under Thermal Stress
Author(s): Derrick John Brake and Graham Peter Bates
Source: *Journal of Occupational and Environmental Medicine*, Vol. 44, No. 2 (February 2002), pp. 125-135
Published by: Lippincott Williams & Wilkins
Stable URL: https://www.jstor.org/stable/44995871
Accessed: 04-06-2025 08:13 UTC

Deep Body Core Temperatures in Industrial Workers Under Thermal Stress

Derrick John Brake, BE (Hons), MBA
Graham Peter Bates, MB, ChB, MPH, PhD

To date, no field study has continuously monitored the deep body core temperatures of industrial workers. A program to continuously measure deep body core temperatures in 36 industrial workers working 10-, 12-, and 12.5-hour day and nightshifts in a hot, deep, underground mine in the Tropics was conducted. No heat illness occurred in these workers during the study. Miniaturized radio-transponders ("pills") taken orally were used to measure temperature during the transit time in the gastrointestinal tract. Commonly recommended limits for industrial hyperthermia are 38.0°C, or an increase of +1°C. The results showed that miners regularly exceeded these limits in terms of maximum deep body core temperature (average, 38.3°C; standard deviation, 0.4°C), maximum temperature rise (1.4°C, 0.4°C), and maximum heat storage (431 kJ, 163 kJ) without reporting any symptoms of heat illness. A significant component of the observed elevated core temperatures was attributable to the normal circadian rhythm, which was measured at 0.9°C (standard deviation, 0.2°C). Evidence was found that workers "self-pace" when under thermal stress. (J Occup Environ Med. *2002; 44:125–135*)

From the School of Public Health, Curtin University of Technology (Mr Brake, Dr Bates); and, formerly, Ventilation and Refrigeration, Mount Isa Mines Limited (Mr Brake); Perth, Australia.

Address correspondence to: Derrick John Brake, 12 Flinders Parade, Sandgate QLD 4017, Australia; rick.brake@mvaust.com.au.

Excessive heat strain in the workplace can lead to a continuum of medical conditions, with symptoms ranging from headache and nausea to vomiting, syncope, and more severe central nervous system disturbances. The most severe form of heat illness is heat stroke, which, if untreated or sufficiently severe, can lead to death and frequently leads to permanent tissue damage. One subclass of heat illness (heat exhaustion) has been shown to have a clear clinical profile[1] and is relatively common in the mining industry. This condition may well have been underreported in other industries during periods of high ambient temperature. The principal pathophysiological factor responsible for heat illness is hyperthermia, due to an extreme environment (high ambient temperatures), high metabolic loads (strenuous physical work), a reduction in heat rejection capability (vapor barrier or heavily insulating protective clothing) or any combination of these. In addition, it can be hypothesized that the rate of increase in deep body core temperature is an additional potential factor in the development of heat illness.[2,3] Circulatory insufficiency, which results from an excessive call on cardiac output to transport heat from the deep body core to the skin, and dehydration due to inadequate replacement of fluids lost in sweat, are factors that frequently lead to hyperthermia and, possibly, heat exhaustion. To date, no major field study has been conducted to continuously document the actual core temperature of workers in hostile environments. Such a study would better define the relationship between environmental heat stress and the physiological strain on the worker. In addition, it would allow the validation of currently recommended limits for the prevention of occupational hyperthermia.

These recommend limits generally fall into one of three categories:

- Limiting (maximum) deep body core temperature, with a typical limit being 38°C or 38.5°C.[4–10]
- Limiting (maximum) increase in deep body core temperature, with a typical limit being 1°C.[4,5]
- Limiting (maximum) heat storage in the body, with a typical limit being 60 watts/hour/meter^2 for acclimatized workers (50 watts/hour/meter^2 for unacclimatized workers).[11,12] These figures translate to 389 kJ and 324 kJ of heat storage, respectively, for "standard" individuals with 1.8 m^2 skin surface area.

Frequently, these governing authorities advise evaluating the thermal stress by using two or more of these criteria and using the most conservative as the relevant limit. Some of these indices are extremely difficult to monitor as prescribed. For example, to administer a workplace using the ISO7933 standard, a range of environmental parameters must be monitored continuously near each worker, an assessment of metabolic rates and clothing ensemble (including personal protection equipment) is required, and exposure limits and times must be calculated and then weighted to find the overall allowable exposure.

Apart from the technical difficulties, there are a number of other complications in measuring and setting limits for industrial hyperthermia.

- In practice, the temperature of the important deep tissues in the body of any particular individual at any given time varies within about a 0.5°C range, even when at rest in thermoneutral conditions (conditions of no heat strain).[13] The temperature can be estimated by a number of methods, including sublingual, tympanic, rectal, esophageal, and gastrointestinal. There is no broad acceptance of a single superior site within the body as defining, from a physiological point of view, a critical "core" temperature.[14–18] However, because of the crucial role of the blood in collecting heat from the core and transmitting it to the skin, where the heat can be rejected, esophageal temperature (measured at about the level of the heart) is considered a very close indicator of the temperature of blood leaving the heart and is, therefore, probably the most valid single indicator of deep body core temperature. Unfortunately, esophageal temperature can be safely measured only in a laboratory.
- Even when unstressed, the "average" temperature of deep body tissues can differ by up to 1°C for different individuals, indicating that a range rather than a single set value exists for humans.[13,19]
- There is a daily (circadian) rhythmicity, which includes temperature, for virtually every organ of the body.[20] The "average" deep body core temperature can vary diurnally by 1°C or more for any individual,[14,18] even when unstressed and in thermoneutral conditions. For resting, thermoneutral conditions, deep body core temperature is at its lowest at about 4 AM and at its highest at about 6 PM. This daily variability has practical consequences when attempting to set limits for night-shift workers or workers on extended shifts.
- There is also a periodic change of about 0.5°C in the overall deep body core temperature associated with menstrual periods.[21,14,18]

In the past, most information about deep body core temperatures has been obtained using rectal thermometers or transducers. For safety reasons associated with manual handling and mobile workers, this has effectively prevented the continuous measurement of core temperatures in actual work environments; the insertion of rectal probes also generally meets with strong resistance from workers. Therefore, the rectal measurements that have been taken intermittently in field studies are unlikely to have captured the full temperature response in the body, particularly when environmental conditions or work rates have varied significantly with time.

For this reason, only modest amounts of reliable information on continuous temperatures are available from field studies. Extrapolation of laboratory work to occupational settings is generally prone to some error and uncertainty because of the very different environments involved, the artificial nature of the laboratory setting, and the interaction of the experimenter with the subject.[22]

Improved information on deep body core temperatures of occupational workers in their work environment would, therefore, assist significantly with the development of appropriate heat stress indices and protocols. The information needed for these decisions can be grouped as follows:

- What upper values of core temperature are reached regularly and safely in a typical thermally stressful workplace where workers are self-pacing?
- What is the time duration over which elevated core temperatures prevail?
- What is the rate at which core temperatures increase and decrease?
- Is heat exhaustion likely to be related to hyperthermia, or to something else, eg, hypohydration?
- What is a safe and realistic core temperature increase for workers on 12-hour shifts when the workday comprises a significant proportion of their overall circadian cycle?

Background and Methods

This article reports a field investigation to measure the deep body core temperatures (hereafter "core temperatures") using gastrointestinal pills with radio-transponders to investigate the above questions and make recommendations.

All subjects were industrial workers habitually exposed to heat stress in a hot, deep underground mine located in the Tropics and were therefore considered to be acclimatized. All in the target group worked 10-, 12-, or 12.5-hour shifts.

The clothing ensemble consisted of long cotton trousers and short or long sleeved shirts, safety boots, safety helmet, and eye protection. Where the environment was dusty or noisy, a face respirator or noise protection was also worn. On occasion, elbow-length impermeable gloves, a rubber apron, and a visor clipped to the safety helmet were worn. However, the workforce was highly mobile, and some work was conducted from within air-conditioned cabins of mobile equipment. Therefore, not all work was performed in hot conditions or was physically strenuous. All lunch breaks were taken in air-conditioned lunchrooms.

Because all workplaces were at a vertical depth of between 1000 m and 1600 m below the surface, and because of the considerable thermal damping effect as air traveled from the surface to the worksites, no significant change in environmental conditions occurred in the workplace between day and night.

The study was conducted over two summers, with a major change to the existing working-in-heat protocols occurring between the summers. The earlier protocol relied heavily on the shortening of the work shift to 6 hours when environmental conditions exceeded approximately 32°C wet bulb globe temperature for more than 2 hours. The shortened shift had been in operation since 1942. The new protocol removed the short shift, increasing exposure times to 12 hours and instituting a graduated management response based on a new thermal stress index called Thermal Work Limit.[23] The experiments were designed, in part, to ensure that the introduction of the new protocols and longer shift lengths did not compromise the workers' health.

The workers were all relatively well informed about the issues related to working in heat, and they worked mostly in self-paced arrangements. No cases of heat stroke had been reported to the 24-hour on-site medical clinic during over 10 million work shifts at temperatures exceeding 28°C wet bulb temperature and 36°C dry bulb temperature from 1966 to 1997.[24] Workers are not generally subject to any regular form of health screen, apart from a preemployment medical and ongoing chest radiographs and blood-lead testing. With self-pacing, the work rate reduces as workplace temperatures increase; therefore, hyperthermia in a self-paced setting is generally due to exposure to extreme thermal environments (exogenous heat) rather than high metabolic loads (endogenous heat). There are significant physiological differences between internal and external heat loads. Internally generated heat loads must be transported by the cardiovascular system to the skin for rejection to the environment, whereas external heat loads can be rejected directly from the skin by evaporation of sweat, with substantially less strain on the cardiovascular system.[17,25,26]

Although mild-to-moderate forms of heat illness do occur in this context,[1,27] none of the participating workers developed heat illness during the course of the study. The fact that such a large number of work shifts have been worked in extreme conditions without a recorded case of heat stroke also indicates that the risk of serious heat illness is low.

Core temperature monitoring equipment consisted of CorTemp temperature-sensing pills (HTI Technologies, St. Petersburg, FL), each with an in-built miniature radio transmitter, and BCTM ambulatory data recorders (PED [Personal Electronic Devices], Inc, Wellesley, MA). The 10-mm-long pills transmit the temperature of the surrounding tissues for their transit time in the gastrointestinal tract, typically 24 to 48 hours, and are not recovered. The manufacturer's reported accuracy of the pill is ± 0.05°C. Each pill is individually calibrated during manufacture and can be set, in the field, to transmit the temperature at an interval between 5 seconds and 1 minute (1 minute in this study). Gastrointestinal temperature is considered to be more closely related to rectal temperature than to esophageal temperature[28] and, therefore, is likely to be about 0.5°C below the temperature of blood leaving the heart and diffusing through the body core.[29] However, rectal temperatures have the advantage of being directly comparable with numerous historical studies, which invariably measured core temperatures rectally.

The study was conducted on 36 male workers, who comprised the target group. All participants gave their written, informed consent to a series of studies that had ethics committee approval. The target group was selected from the rest of the workforce on the basis of highest relative exposures to environmental heat and highest relative work rates.

A control group of six office workers (all male, all day shift), working in the same operation but in sedentary jobs in an air-conditioned office (typically 24°C, 50% relative humidity), was also tested. They were heat-unacclimatized in comparison with the target group.

Because of the travel time required to get from the surface to the workplace and back again, the actual work time on the job was typically 7.5 hours for 10 hour shifts and 9 hours for 12 hour shifts. Workers on 10-hour shifts took one meal break per shift; those on the longer shifts took two meal breaks per shift.

Environmental conditions were measured at each workplace approximately every 60 minutes using a Heat Stress Meter,[30] which provided digital readouts of ventilated wet bulb temperature, dry bulb temperature, wind speed, globe temperature, calculated mean radiant temperature, barometric pressure and wet bulb globe temperature (WBGT). WBGT was evaluated in accordance with the guidelines of the American Conference of Governmental Industrial Hygienists (ACGIH).[4]

Core temperature data were collected on day shift, night shift, and, for some individuals, for work conducted over 2 consecutive day or night shifts, along with "recovery/resting" core temperatures between shifts. For each individual shift, and for the aggregated data, the following was calculated:

- maximum, minimum, and average shift values, and highest 10 and 30 consecutive minute averages
- duration of time spent in the following core temperature zones (°C): 36 to 37, 37 to 37.6, 37.6 to 38.2, 38.2 to 38.8, 38.8 to 39.4, 39.4 to 40
- core temperature rise during the shift (defined as the difference between maximum and minimum temperatures during the shift)
- calculated maximum heat storage in the body (defined as the temperature rise multiplied by the average thermal capacity of body tissue multiplied by the body weight)
- highest 10-, 30-, and 60-minute temperature increase and decrease during the shift, which indicated the rate at which the body underwent thermal strain, and the rate at which the strain attenuated, respectively.

Only data sets with more than 4 hours of core temperature data were considered in the analyses. All statistical tests were based on the unpaired, two-tailed *t* test, assuming equal variances, unless otherwise noted.

Results

A summary of the anthropometric, body structure, and maximum oxygen consumption ($\dot{V}O_{2max}$) data of the subjects in the target group is shown in Table 1.

A total of 350 environmental observations (Table 2) were taken (excluding observations when workers were inside air-conditioned areas and therefore not under thermal stress). The average workplace WBGT temperature in the first summer with the former protocols was not significantly different (WBGT: $P = 0.38$; Thermal Work Limit: $P = 0.44$) to that of the second summer with the revised protocols. Fifteen observations (4%) exceeded 32° wet bulb temperature.

TABLE 1
Target Group*

	Age (yrs)	Height (cm)	Weight (kg)	BMI	$\dot{V}O_{2max}$ (mL/kg/min)
n	31	31	32	38	19
Max	52	198	125	33	47.4
Min	24	163	65	23	31.1
Avg	35.4	179.4	88.8	27.5	37.7
SD	7.56	8.36	13.96	2.77	4.67

* BMI, body mass index; $\dot{V}O_{2max}$, maximum oxygen consumption, SD, standard deviation.

TABLE 2
Environmental Conditions in the First and Second Summers, After Changes to Working-in-Heat Protocols*

	WBGT (°C)		TWL (watts/meter²)	
	1st Summer	2nd Summer	1st Summer	2nd Summer
n	164	186	164	186
Avg	30.78	30.94	178	174
SD	1.729	2.144	41.7	44.9
Max	36.9	35.2	286	276
Min	26.8	25.7	81	83

* WBGT, wet bulb globe temperature; TWL, Thermal Work Limit; SD, standard deviation.

A total of 38 sets of core temperature data were obtained from the target group, comprising 22 sets from the first summer and 16 from the second summer. The two sets of data were compared on the basis of average and maximum shift values over the two summers.

The average shift value (± standard deviation [SD] and range) for the first summer was 38.4°C (SD, 0.50°C; range, 37.7° to 39.5°C), and for the second summer, 38.2°C (SD, 0.31°C; range, 37.8° to 38.8°C); the difference was not significant ($P = 0.26$).

The maximum shift value for the first summer was 37.65°C (SD, 0.45°C; range, 37.0° to 38.9°C), and for the second summer, 37.58°C (SD, 0.22°C; range, 37.2° to 38.0°C); the difference was not significant ($P = 0.55$).

The total recorded time over the 38 shifts was 413 hours. Gaps in the record set, or invalid data, constituted a total of 35 hours, or 9% of the total elapsed time.

The results for the pooled core temperature data from both summers are summarized in Table 3 for the target group and Table 4 for the control group.

Figures 1 and 2 show core temperature traces for shiftworkers in the target group, whereas Fig 3 shows a trace for an office worker in the control group. Note some examples of gaps in the data set.

Discussion

For clarity, the SDs and ranges of values are listed in either the tables or the text but not both. Neither the WBGT nor the Thermal Work Limit in the workplace changed significantly from one summer to the next; it was concluded that the level of

TABLE 3
Deep Body Core Temperature of 36 Male, Underground Miners (the Target Group) Measured Continuously Over 38 Shifts*

	Max °C†	Min °C	Avg °C	Highest 10 Consecutive Mins (avg, °C)	Highest 30 Consecutive Mins (avg, °C)	Max Temp Increase Over Shift (°C)	Max Heat Storage Over Shift (kJ)	Highest 10-Min Increase (°C)	Highest 10-Min Decrease (°C)	Highest 30-Min Increase (°C)	Highest 30-Min Decrease (°C)	Highest 60-Min Increase (°C)	Highest 60-Min Decrease (°C)	
n	38	35	38	38	38	35	32	35	35	35	35	35	35	
Max	39.5	37.7	38.9	39.4	39.4	2.3	942	1.3	−0.1	1.5	−0.3	1.5	−0.3	
Min	37.7	36.0	37.0	37.7	37.5	0.7	166	0.2	−1.2	0.3	−1.3	0.3	−1.4	
Avg	38.3	36.9	37.6	38.3	38.2	1.4	431	0.5	−0.5	0.8	−0.7	0.9	−0.8	
SD	0.4	0.4	0.4	0.4	0.4	0.5	163	0.2	0.3	0.3	0.3	0.3	0.3	
Temperature range (°C)								36.0–37.0	37.0–37.6	37.6–38.2	38.2–38.8	38.8–39.4	39.4–40.0	>40.0
% of time								29	43	18	5	2	0	0

* The thermal capacity of the body,[12] used to calculate the maximum heat storage, is taken as 3.49 $kJ^{o}C^{-1} \cdot kg^{-1}$.

† For example, the intersection of the Max column and the Max row is the highest core temperature recorded on any shift in the study. The intersection of the Max column and the Avg row indicates the average over all data sets of the maximum individual core temperatures recorded during each shift in the study. The intersection of the Max column and the Min row indicates the lowest single maximum core temperature reached on any shift during the study, etc.

heat stress exposure had not changed.

The maximum and average core temperatures also had not changed significantly from one summer to the next; it was concluded that the new working-in-heat protocols had not changed the level of hyperthermia. The core temperature data was therefore pooled for further analysis.

When recommending safe core temperature limits from this study, it would be misleading to consider only the average upper values measured. For example, some workers were allocated jobs in which they were under little thermal stress for the shift (their upper core temperature was low); this is supported by Table 3, which shows that the highest core temperature recorded by one worker was only 37.7°C. Because no worker reported symptoms of heat illness during the study and environmental conditions included a range of temperatures, not all workers reached their maximum safe individual core temperature during the shift. It is hypothesized that a realistic upper limit from this data is probably about 1 SD above the measured group averages. However, more conservative approaches might be to consider the safe limit as being the value that was *not* exceeded by 95% of workers, or to consider the safe limit to be the value that *was* exceeded by at least (for example) 20 workers. The values based on 1 SD above the average are reported in italics in the following discussion, and comments regarding the alternate approaches are provided when relevant.

Control Group

The most significant feature of the control group is a 0.9°C (1.2°) average core temperature increase during the work shift. Because the control group was sedentary and thermally unstressed, this increase was probably caused by diurnal variation in core temperature over this period. This value was close to the International Labour Organisation[31] recom-

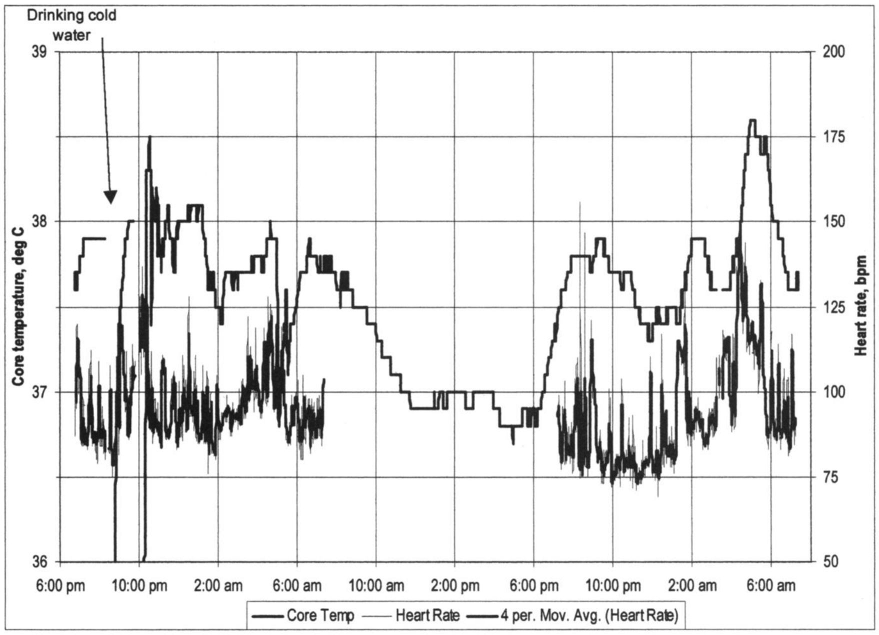

Fig. 1. Core temperature (°C), heart rate (bpm), and (trailing) 4-minute moving average heart rate for subject working two consecutive 12-hour night shifts. Note the drinking of cold water after 8 AM.

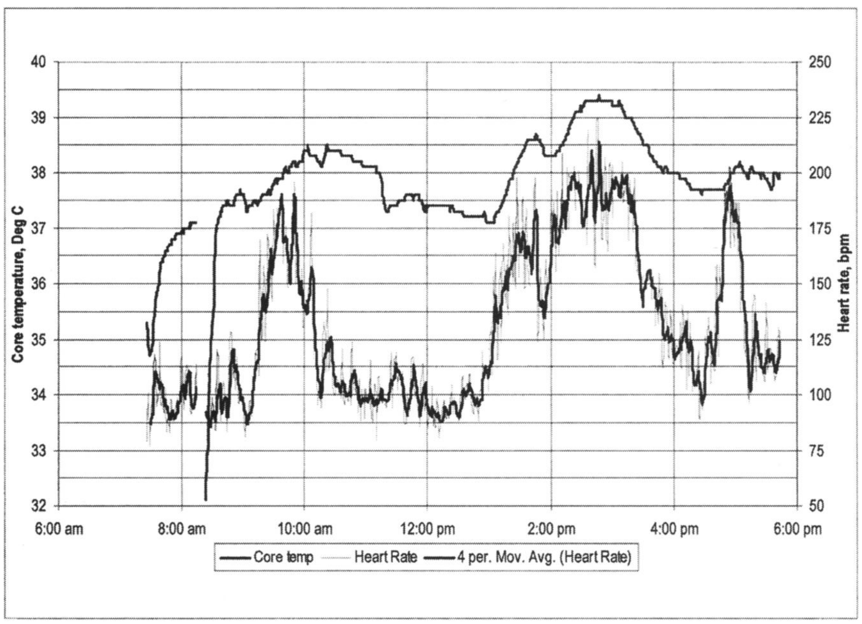

Fig. 2. Core temperature (°C), heart rate (bpm), and (trailing) 4-minute moving average heart rate for subject working 10-hour day shift. Note the drinking of cold water after 8 AM.

mended core temperature rise for acclimatized workers of 1°C, with almost 50% of workers exceeding the International Labour Organisation value without physical exertion or heat stress. Note that these values do not reflect the *full* 24-hour diurnal variation in core temperature (including the sleeping period), but rather only diurnal variation from about 6:30 AM to the end of the workday (typically between 5 PM and 6 PM). The full diurnal variation was found to be larger than this, as can be seen in Figs. 1 and 3. If the 24-hour circadian rhythm increase by itself

TABLE 4

Deep Body Core Temperature of a Control Group of 10 Male Mine Workers, All Employed in Sedentary Work in Air-Conditioned Offices, Measured Continuously*

	Max °C†	Min °C	Avg °C	Highest 10 Consecutive Mins (avg °C)	Highest 30 Consecutive Mins (avg °C)	Max Temp Increase Over Shift (°C)	Highest 10-Min Increase (°C)	Highest 10-Min Decrease (°C)	Highest 30-Min Increase (°C)	Highest 30-Min Decrease (°C)	Highest 60-Min Increase (°C)	Highest 60-Min Decrease (°C)
n	10	10	10	10	10	10	10	10	10	10	10	10
Max	37.9	36.9	37.5	37.8	37.8	1.2	0.7	−0.1	0.8	−0.1	0.8	−0.3
Min	36.9	36.0	36.5	36.8	36.8	0.6	0.2	−0.5	0.3	−0.5	0.4	−0.7
Avg	37.6	36.5	37.1	37.4	37.4	0.9	0.4	−0.3	0.5	−0.4	0.6	−0.4
SD	0.3	0.3	0.3	0.4	0.4	0.2	0.2	0.1	0.2	0.1	0.2	0.1

* This group wore the core temperature monitor day and night for up to 3 days and 2 nights (see Fig. 3). Ten sets of "day shift" results were obtained, comprising six sets on the first day, and four sets on the second day. The control subjects were not weighed, so heat storage figures were not calculated for this group.
† For description of the row and column headings, refer to Table 3.

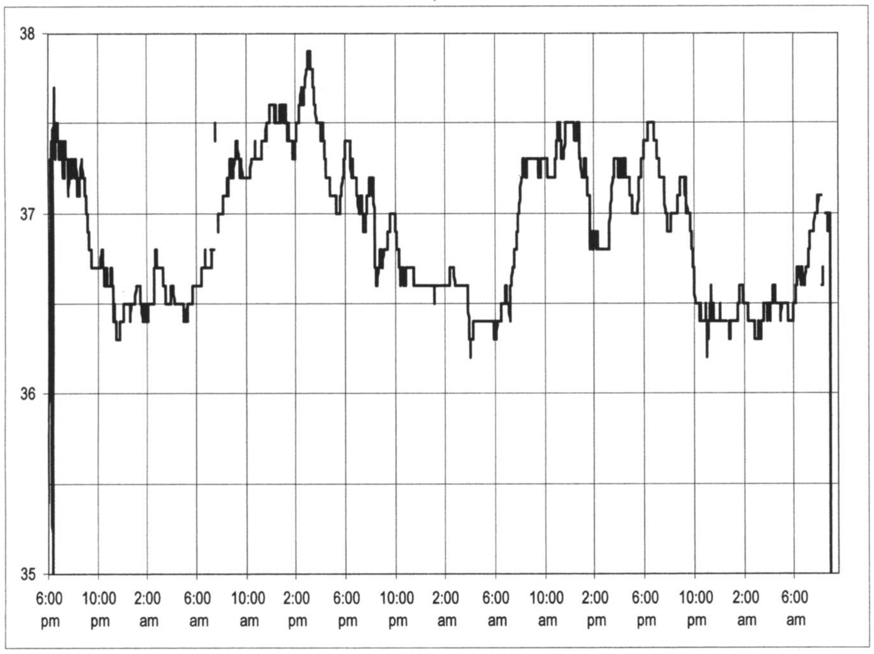

Fig. 3. Core temperature (°C) data for control group (non-stressed) subject. Recording period covers 3 nights and 2 days.

can meet or exceed the allowable core temperature increase due to thermal stress, then it is likely that the recommended allowable increases are too low, certainly for 12-hour shift workers.

Target Group

The average body mass index (27.5) of the target group (Table 1) is in the middle of the "overweight" range of 25 to 30 kg/m^2 as designated by the World Health Organization.[32] The average $\dot{V}O_{2max}$ (37.7 mL/kg/min) is outside the normal range (39 to 48 mL/kg/min) for nonathletes aged 30 to 39 years.[33] The target group was typical of industrial workers in this operation. A test of 469 contract employees joining the organization for project work under similar levels of heat stress during this period had a measured $\dot{V}O_{2max}$ of 39.0 mL/kg/min (SD, 7.8 mL/kg/min) and a body mass index of 25.9 (SD, 5.4).

The average maximum core temperature during the shift was 38.3° (38.7°), which exceeds the ACGIH recommended value of 38.0° (although the 2000 TLVs provide for a core temperature of 38.5° for medically selected, acclimatized workers). Two workers exceeded 39°C (being 39.4° and 39.5°, respectively; one is shown in Fig 2). These figures are broadly in line with the findings of others, who have reported the core temperature limit for moderately fit industrial workers, prior to collapse or withdrawal, as being in the range of 39.0° to 39.5°C[26,32–36] Trained athletes have been found to continue without ill effects at core temperatures in excess of 40°C.[37–39] The fact that these data were measured on workers with a wide range of age, body mass index, and $\dot{V}O_{2max}$ in the ordinary course of their work activities, and who reported no heat illness, questions the validity of using 38.0°C as an absolute limit for industrial workers. However, if a safe limit were to be based on the 5th percentile from this study, the limit would be approximately 37.8°C; if based on the safe level achieved by 20 workers, it would be approximately 38.2°C. Both limits are within the most recently recommended ACGIH limits for screened and acclimatized workers.

The highest 10- and 30-consecutive-minute averages, maximums, and minimums were all very close to the 1-minute (single reading) values. This indicates that workers plateau near the maximum temperature for that shift and remain there for some time.

The average increase in core temperature (or the core temperature *working reserve*, defined here as the maximum reached in the shift minus the minimum reached) was 1.4°C (1.9°C), compared with the ISO recommended maximum of 1.0°C for acclimatized workers. Note that 26 (68%) of the 38 sets were for workers on 12- or 12.5-hour shifts; of these 26 sets, 19 were for the day shift. The average increase of 1.4°C is in accordance with the findings of Rastogi et al,[40] who found an average core temperature increase of 2.2°F (1.2°C) for industrial workers, with one group averaging an increase of 2.5°F (1.4°C).

If gastrointestinal temperatures are, in fact, 0.5°C lower than esophageal temperatures, then the "core" temperatures found in this study, which were already higher than the generally recommended values, would be even higher. This highlights the importance of defining when, where, and how core temperatures are to be defined in setting future occupational limits.

The average heat storage (defined as the calculated maximum minus minimum heat content of the body during the shift) was 431 kJ *(594 kJ)* compared with the ISO recommended value of 389 kJ for acclimatized workers.

The average maximum increase in core temperature was 0.5°C (0.7°C) in 10 minutes, 0.8°C (1.1°C) in 30 minutes, and 0.9°C (1.2°C) in 60 minutes. The average maximum decline in core temperature for the three time periods were 0.5° (0.8°C), 0.7° (1.0°C), and 0.8° (1.1°C), respectively. Individual increases in core temperature of up to 1.3°C in 10 minutes, and up to 1.5°C in 30 minutes, were recorded. The significance of the rate of increase or decrease in core temperature for industrial workers is not known, but it has been speculated that the rate of increase and/or the duration of the hyperthermia may be important factors in developing heat illness, in addition to the actual core temperature reached.[2]

The relatively rapid increase and decrease in core temperature could explain why intermittent rectal temperature measurements in the past during other field studies might not have caught the true maximum temperatures reached. Most laboratory studies, on the other hand, have used "steady-state" or slowly changing heat stress, which is not likely to reflect modern industrial work patterns.

The distribution of temperatures during the work shift indicated that temperatures above 38.2°C were only exceeded about 7% of the time. Temperatures over 38.8°C were infrequent to rare. Acclimatized, self-paced workers are therefore unlikely to voluntarily exceed core temperatures of about 38.8°C. Given the wide range of environmental conditions, body structure, aerobic capacity, and work rates in this study, this is strong evidence that workers are able to self-pace when they are properly trained and supported by their management. The fact that the incidence of heat exhaustion and stroke is more prevalent in the military, in which work is frequently externally paced, also supports this conclusion.

It also seems that authorities charged with responsibility for developing standards or advisory guidelines on occupational heat stress assume that a single measuring site for "deep body core temperature" exists, and that this measure has a single value rather than a range of values. This is certainly the case with the ACGIH TLV and ISO 7933, which refer to, but do not define, "deep body temperature."

One of the reasons several authorities have advised the adoption of the cautious limits of 38°C or an increase of 1°C is that this modest limit is needed to cover the wide range of interindividual variances. However, artificially restrictive limits are created if these limits are then used as ceiling values to trigger withdrawal of personnel under medical surveillance. Where these limits are used to develop heat stress indices and protocols, this study shows that they would lead to unnecessary conservatism for self-paced workers who have, by definition, the ability to reduce their work rate or to withdraw from conditions when they feel unnecessarily stressed.

Given the exposure to very hot conditions in this workforce of about 2000 underground miners over a period of at least 50 years, it is perhaps surprising that there have been no recorded incidents of heat stroke, a conclusion that can be made with reasonable confidence, as a 24-hour medical clinic with attending occupational physicians is on-site. The most likely reasons for this record include the following:

- The workforce, especially the target group that habitually works in the heat, is reasonably well-educated about the affects of working in heat.
- The surface climate is hot, and workers are at least partly acclimatized by living in this climate.
- Workers typically work by themselves or with one, or at most two, regular coworkers. Older workers typically "mentor" new workers with advice about suitable work paces and breaks. This situation differs from occupational settings in which the work rate is externally paced.
- Because of the geographical spread of workers, work is typically conducted with no on-the-job supervision. Supervisors usually visit each workplace twice each shift, for about 10 minutes each visit.
- The workforce is relatively unfit (compared with athletes). Others have found that relatively unfit workers are likely to suffer heat exhaustion that is self-limiting, resulting in voluntary withdrawal or collapse, before serious hyperthermia is incurred.[41–43]

It should not be concluded from the above that this industrial operation is inefficient. Productivity is within good practice levels of other similar operations in the Western world. Workers are well paid, and there is a production-based incentive component (typically about 25%) in their earnings.

Indications of the impact of lower core temperatures experienced by workers on night shift (due to normal circadian rhythm) can be seen Fig. 1. This additional core temperature reserve at night compared with daytime work could help explain why Donoghue et al[1] and Cabanac[44] found that workers exposed to heat stress on day shifts were statistically more likely to develop heat illness than workers on night shifts. The threshold for sweat onset is also lower at night than during the day.[45]

Note that 26 of the 38 data sets from the target group were from workers on 12- or 12.5-hour shifts. This roster requires only two 12-hour night shifts to be worked, so that the resetting of the circadian clock would not occur to any significant extent over the course of this roster.[46] If subjects worked long rosters of consecutive night shifts, then the circadian clock would reset and the natural increase in core temperature working reserve at night would no longer exist.

The close correlation between heart rate and core temperature, when under thermal stress, can be seen in the Figs. 1 and 2. This confirms what others[16,47,48] have found as to heart rate being a reasonable indicator of overall physiological and psychological strain, and it opens the possibility of using widely available ambulatory heart rate monitors to continually assess hyperthermia in industrial workers.

It should be noted that the widespread adoption of WBGT as an index of thermal stress was historically driven by two important factors:

- It was seen as a proxy for Corrected Effective Temperature, which at its inception (1957) was the most widely used heat stress index for occupational use.[17]
- It could be measured directly by an instrument that could be made sufficiently small and robust to be used in the field.

Neither of these assumptions is now true, with widespread recognition of weaknesses in both Corrected Effective Temperature and WBGT as indices of thermal stress,[40,48–51] and the development of microprocessor-based instruments that can measure and compute more complex physiological models than the WBGT instruments.[30]

Note that the principal source of heat strain for these workers is the environmental heat load rather than an internally produced heat load due to heavy metabolic rates. As discussed earlier, this follows from the nature of self-pacing; a cool environment can allow higher work rates and therefore a higher proportion of the heat strain to be generated by internal (endogenous) loads, but as the environmental heat stress increases, self-paced workers reduce their work rates and the balance shifts, with the environmental (exogenous) load now creating most of the heat strain. Internally generated heat loads must be transported by the cardiovascular system to the skin for rejection to the environment, whereas external heat loads can be rejected directly from the skin by evaporation of sweat with substantially less strain on the cardiovascular system,[2,18,26,52] although the same sweat gland response is required as the overall heat rejection requirement from the surface of the skin is unchanged.

Conclusions and Recommendations

The gastrointestinal temperature-sensing radio-transmitting pill is an effective method of profiling the core temperature of workers in difficult occupational settings.

The rapid increase and decrease in core temperatures suggests that previous data collected in occupational settings, which are almost always from intermittent measurements taken rectally, have probably failed to give a true picture of the maximum limits reached.

The range of core temperatures measured highlights problems in existing guidelines in which neither the location nor method of measuring core temperature is specified. Moreover, current guidelines do not adequately account for circadian variability.

The current limits advocated by ISO, ACGIH, and others are possibly conservative compared with those actually experienced in heat acclimatized workers in this operation. In particular, the suggestion that a 1°C limit on the rise of core temperature due to exposure to heat is unlikely to be practical, especially for workers on 12-hour shifts, in which increases of 1°C in core temperature can be due to normal circadian rhythms alone. This is in accordance with the findings of others.[18,53]

The proposed revised upper limit of 38.5 recommended by ACGIH for medically screened, acclimatized workers seems to be endorsed by this study, with workers in the target group spending very little time at temperatures exceeding this figure, although some brief excursions did occur. However, given that no worker developed heat illness during these exposures, the need for continuous medical surveillance during the exposure, as recommended by ACGIH, is unlikely to be warranted, at least for self-paced, well-informed workers.

Workers can self-pace, as seen by the fact that this environment was frequently very stressful, with an average WBGT of 31.9°C. Nevertheless, only 7% of the time was spent with core temperatures above 38.2°C.

When workers are both educated and encouraged to self-pace, it is likely that a higher upper limit on core temperature would not result in significant heat illness problems. When workers are unable or not permitted to self-pace (eg, some military personnel), limits based on much more conservative values may be required to account for interindividual differences.

The current ACGIH limits of a 26.7°C WBGT for moderate work rates and 30.0°C WBGT for light work rates are not supported by this study, with average workplace environmental conditions being substantially above these recommended values.

Shortening the working shift to avoid hyperthermia is unlikely to be necessary for self-paced workers.

Further work is required to determine whether it is the peak core temperature reached, the rate of increase in core temperature, or the duration of the temperature excursion that results in heat exhaustion and heat illness.

It is important to recognize that this study was conducted on acclimatized workers who were reasonably well educated about the affects of working in heat and had a measure of control over their pace of work during their work shifts. Moreover, the principal source of heat stress for these workers was generally environmental heat load rather than an internally produced heat load due to sustained strenuous metabolic rates.

References

1. Donoghue AM, Sinclair MJ, Bates GP. Heat exhaustion in a deep, underground, metalliferous mine. *Occup Environ Med.* 2000;57:165–174.
2. Hales JRS, Richards DAB. Present controversies in heat stress: prefacing comments. In: Hales JRS, Richards DAB, eds. Heat stress—physical exertion and environment. In: *Proceedings of the 1st World Conference on Heat Stress: Physical Exertion and Environment, Sydney, Australia.* Amsterdam: Elsevier Science; 1988:xii.
3. Febbraio MA. Heat stress and exercise metabolism. In: Lau WM, ed. *Proceedings of the International Conference on*

Physiological and Cognitive Performance in Extreme Environments, Canberra, Australia. Canberra: Defence Scientific and Technology Organisation, Australian Department of Defence; 2000: 12–16.

4. American Conference of Governmental Industrial Hygienists. Heat stress TLV. In: *TLVs and BEIs: Threshold Limit Values for Chemical Substances and Physical Agents*. Cincinnati: ACHIH; 1998: 170–182.
5. Dukos-Dobos FN. Rationale and provisions of the work practices standard for work in hot environments. In: Horvath SM, Jensen RC, eds. *Proceedings of Symposium: Standards for Occupational Exposures to Hot Environments*. Cincinnati: National Institute for Occupational Safety and Health; 1973:27–42.
6. Richards CRB, Richards DAB. Medical management of fun-runs. In: Hales JRS, Richards DAB, eds. *Heat Stress—Physical Exertion And Environment, Proceedings of the 1st World Conference on Heat Stress: Physical Exertion and Environment, Sydney, Australia*. Amsterdam: Elsevier Science; 1988:513–526.
7. Coyle EF, Montain SJ. Thermal and cardiovascular responses to fluid replacement during exercise. In: Gisolfi CV, Lamb DR, Nadel ER, eds. *Perspectives in Exercise Science and Sports Medicine*. vol 6: Exercise, heat and thermoregulation. Dubuque, IA: Brown Publishers; 1993:214.
8. Pandolf KB, Stroschein LA, Drolet LL, Gonzalez, RR, Sawka MN. Prediction modelling of physiological responses and human performance in the hat. *Comput. Biol. Med.* 1986;6:319–329.
9. Bell CR, Crowder MJ, Walters JD. Durations of safe exposure for men at work in high temperature environments. *Ergonomics*. 1971;14:733–757.
10. Wyndham CH, Strydom NB, Williams CG, Morrison JF, Bredell GAG. The heat reactions of bantu males in various states of acclimatisation. *Int Z Angew Physiol Einschl Arbeitsphysiol*. 1966;23:79–92.
11. International Organization for Standardization. *Hot Environments—Analytical Determination and Interpretation of Thermal Stress Using Calculation of Required Sweat Rate*. Geneva: IOS; 1989. ISO7933.
12. American Society of Heating, Refrigeration, and Air-Conditioning Engineers. *ASHRAE Fundamentals*. SI ed. Atlanta: ASHRAE; 1997:8:1–8.28.
13. Leithead CS, Lind AR. *Heat Stress and Heat Disorders*. London: Cassell; 1964: 29.
14. Sawka MN, Wenger CB, Pandolf KB. Thermoregulatory responses to acute exercise-heat stress and heat acclimation. In: Fregly MJ, Blatteis CM, eds. *Handbook of Physiology Section 4 Environmental Physiology*. vol 1. New York/Oxford: Oxford University Press; 1996: 157.
15. Stewart JM, Van Rensburg AJ. *Heat Stress Limits for Men Working in the Gold Mining Industry*. Chamber of Mines of SA Research Organization. Project no. GY6H21 1976.
16. International Organization for Standardization. *Evaluation of Thermal Strain by Physiological Measurements*. Geneva: IOS; 1992. ISO9886.
17. Parsons KC. *Human Thermal Environments*. London: Taylor & Francis; 1993: 87.
18. Stitt JT. Central regulation of body temperature. In: Gisolfi, CV, Lamb DR, Nadel ER, eds. *Perspectives in Exercise Science and Sports Medicine*. vol 6: Exercise, heat and thermoregulation. Dubuque, IA: Brown & Benchmark; 1993:1–48.
19. Hoyt RW, Young AJ, Matthew WT, Buller MJ. *Warfighter Physiological Status Monitoring (WPSM). Body Core Temperature During 96 h of Swamp Phase Ranger Training*. Natick, MA: US Army Research Institute of Environmental Medicine; 1997. USARIEM technical report no. T 97–4.
20. Campbell SS. Effects of sleep and circadian rhythms on performance. In: Smith AP, Jones DM, eds. *State and Trait of Handbook of Human Performance*. vol 3. San Diego: Academic Press; 1992:195–216.
21. Fortney SM. Hormonal control of fluid balance in women during exercise. In: Buskirk ER, Phul SM, eds. *Body Fluid Balance—Exercise and Sport*. Orlando, FL: CRC Press; 1996:231–258.
22. Peacock FL. Practical Problems of Implementation of the NIOSH Proposed Standard for Occupational Exposure to Hot Work Environments. In: Horvath SM, Jensen RC, eds. *Proceedings of Symposium: Standards for Occupational Exposures to Hot Environments*. Cincinnati: National Institute for Occupational Safety and Health; 1973:27–42.
23. Brake DJ, Bates GP. Limiting metabolic rate (thermal work limit) as an index of thermal stress. *Appl Occup Environ Hyg*. In press.
24. Howes M, Nixon C. Development of procedures for safe working in hot conditions. In: Ramani RV, ed. *Proceedings of the 6th International Mine Ventilation Congress*. Littleton, CO: Society of Mining Engineers, American Institute of Mining, Metals and Petroleum Engineering; 1997:191–198.
25. Hales JRS, Hubbard RW, Gaffin SL. Limitation of heat tolerance. In: Fregly MJ, Blatteis CM, eds. *Handbook of Physiology Section 4 Environmental Physiology*. vol 1. New York/Oxford: Oxford University Press; 1996:285–355.
26. Nielson B. The implications of endogenous versus exogenous heat loads in stress tolerance. In: Hales JRS, Richards DAB, eds. *Proceedings of the 1st World Conference on Heat Stress: Physical Exertion and Environment, Sydney, Australia*. Amsterdam: Elsevier Science; 1988: 337–354.
27. Brake DJ, Bates GP. Occupational illness: an interventional study. In: Lau WM, ed. *Proceedings of the International Conference on Physiological and Cognitive Performance in Extreme Environments*. Canberra, Australia: Defence Scientific and Technology Organisation, Australian Department of Defence; 2000: 170–172.
28. Cotter JD, Roberts WS, Amos D, Lau WM, Prigg SK. Heat strain during combat fitness assessment of soldiers in Northern Australia. In: Lau WM, ed. *Proceedings of the International Conference on Physiological and Cognitive Performance in Extreme Environments*. Canberra, Australia: Defence Scientific and Technology Organisation, Australian Department of Defence; 2000:176–178.
29. Gagge AP, Gonzalez RR. Mechanisms of heat exchange: biophysics and physiology. In: Fregly MJ, Blatteis CM, eds. *Handbook of Physiology*. sect 4, vol 1. New York/Oxford: Oxford University Press; 1996:191.
30. Bates G, Matthew B. A new approach to measuring heat stress in the workplace. In: *Occuptional Hygiene Solutions. Proceedings of the 15th Annual Conference of the Australian Institute of Occupational Hygiene, Perth, Australia, Nov 30–Dec 4, 1996*. Perth: AIOH; 1996: 265–267.
31. Vogt JJ. Heat and cold. In: Stellman JM, ed. *Encyclopaedia of Occupational Health and Safety*. Chapter 42. Geneva: International Labour Organisation; 1998.
32. World Health Organisation Expert Committee on Physical Status. The use and interpretation of anthropometry 1995. In: *Physical Status: The Use and Interpretation of Anthropometry: Report of a WHO Expert Committee*. Geneva: WHO; 1995. Technical report series 854.
33. Wilmore JH, Costill DL. *Physiology of Sport and Exercise*. Champaign: Human Kinetics; 1994.
34. Brinnel H, Cabanac M, Hales JRS. Critical upper levels of body temperature, tissue thermosensitivity and selective brain cooling in hyperthermia. In: Hales JRS, Richards DAB, eds. *Proceedings of the 1st World Conference on Heat Stress: Physical Exertion and Environment, Sydney, Australia*. Amsterdam: Elsevier Science; 1988:209–240.
35. Weiner JS. Extremes of temperature. In: Roghan JM, ed. *Medicine in the Mining Industry*. William Heinemann Medical Books; 1972:215.
36. Tranter M, Abt GA. The assessment of metabolic rate, core body temperature and hydration status during underground coal mining. In: *Proceedings of the 1998 Safety Institute of Australia Annual Con-*

ference, Gold Coast. Gold Coast: SIA; 1998:293–303.

37. Gisolfi CV. Influence of acclimatization and training on heat tolerance and physical endurance. In: Hales JRS, Richards DAB, eds. *Proceedings of the 1st World Conference on Heat Stress: Physical Exertion and Environment, Sydney, Australia.* Amsterdam: Elsevier Science; 1988: 355–366.
38. Sato, K. The Mechanism of Eccrine Sweat Secretion. In: Gisolfi CV, Lamb DR, Nadel ER, eds. *Perspectives in Exercise Science and Sports Medicine.* vol 6: Exercise, heat and thermoregulation. Dubuque, IA: Brown & Benchmark; 1993:85–118.
39. McLellan, TM. The importance of aerobic fitness in determining tolerance to uncompensable heat stress. In: Lau WM, ed. *Proceedings of the International Conference on Physiological and Cognitive Performance in Extreme Environments, Canberra, Australia.* Canberra: Defence Scientific and Technology Organisation, Australian Department of Defence; 2000: 68–71.
40. Rastogi SK, Gupta BN, Tanveer H, Mathur N. Physiological responses to thermal stress in a glass bangle factory. *J Soc Occup Med.* 1988;38:137–142.
41. Holdsworth R, Crowe M. The thermoregulatory strain produced by protective PVC suits during simulated chemical spill clean-up operations in a hot environment is not reduced by passive cooling vests. In: Lau WM, ed. *Proceedings of the International Conference on Physiological and Cognitive Performance in Extreme Environments, Canberra, Australia.* Canberra: Defence Scientific and Technology Organisation, Australian Department of Defence; 2000:61–64.
42. Atkinson SE, Coles GV. The contribution of solar radiation to heat stress and heat strain during work in encapsulating protective suits. In: Lau W M, ed. *Proceedings of the International Conference on Physiological and Cognitive Performance in Extreme Environments, Canberra, Australia.* Canberra: Defence Scientific and Technology Organisation, Australian Department of Defence; 2000: 163–166.
43. Soule RG, Pandolf KB, Goldman RF. Voluntary march rate as a measure of work output in the heat. *Ergonomics.* 1978;21:455–462.
44. Cabanac M. Heat stress and behaviour. In: Fregly MJ, Blatteis CM eds. *Handbook of Physiology.* sect 4, vol 1: Environmental physiology. New York/Oxford: Oxford University Press; 1996:261–278.
45. Nadel ER, Mack GW, Takamata A. Thermoregulation, exercise, and thirst: interrelationships in humans. In: Gisolfi CV, Lamb DR, Nadel ER, eds. *Perspectives in Exercise Science and Sports Medicine.* vol 6: Exercise, heat and thermoregulation. Dubuque, IA: Brown & Benchmark; 1993:235.
46. Knauth P. Hours of work. In: Stellman JM, ed. *Encyclopaedia of Occupational Health and Safety.* Geneva: International Labour Organisation; 1998.
47. Shvartz ES, Shibolet A, Meroz A, Magazanik A, Sharpiro Y. Prediction of heat tolerance from heart rate and rectal temperature in a temperature environment. *J Appl Physiol.* 43:684–688.
48. Rodahl K, Guthe T. Physiological limitations of human performance in hot environments, with particular reference to work in heat-exposed industry. In: Mekjavic IB, Banister EW, Morrison JB, eds. *Environmental Ergonomics—Sustaining Human Performance in Harsh Environments.* London: Taylor & Francis; 1988: 37.
49. Rastogi SK, Gupta BN, Husain T. Wetbulb globe temperature index: a predictor of physiological strain in hot environments. *J Occup Med.* 1992;42:93–97.
50. Horvath SM. Heat stress studies in aluminium reduction plants. In: Horvath SM, Jensen RC, eds. *Proceedings of Symposium: Standards for Occupational Exposures to Hot Environments.* Cincinnati: National Institute for Occupational Safety and Health; 1972:91–100.
51. Kerslake DM. *The Stress of Hot Environments.* Cambridge: Cambridge University Press; 1972.
52. Minard D. Heat disorders: a tabular presentation. In: Horvath SM, Jensen RC, eds. *Proceedings of Symposium: Standards for Occupational Exposures to Hot Environments.* Cincinnati: National Institute for Occupational Safety and Health; 1973:21–26.
53. Werner J. Temperature regulation during exercise: an overview. In: Gisolfi CV, Lamb DR, Nadel ER, eds. *Perspectives in Exercise Science and Sports Medicine* vol 6: Exercise, heat and thermoregulation. Dubuque, IA: Brown & Benchmark; 1993:49–84.