Ann. Occup. Hyg., Vol. 51, No. 6, pp. 553–561, 2007

doi:10.1093/annhyg/mem035

The Thermal Work Limit Is a Simple Reliable Heat Index for the Protection of Workers in Thermally Stressful Environments

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Received 13 April 2007; in final form 14 June 2007

Background: Workers in many industries are exposed to thermally stressful work environments. Protection of the health of workers without unnecessarily compromising productivity requires the adoption of a heat index that is both reliable and easy to use.

Objectives: To evaluate the Thermal Work Limit (TWL), in a controlled environment and under field conditions, against these criteria.

Methods: Volunteers performed graded work in a controlled thermal environment to determine the limiting workload for the conditions. Core temperature and heart rate were monitored as indicators of thermoregulation. In the field study, outdoor workers were monitored for signs of physiological strain in thermal environments which were characterized using both the traditional Wet Bulb Globe Temperature (WBGT) and the TWL. Abilities of each of these indices to accurately reflect the thermal stress on workers were evaluated.

Results: In the controlled environment, the TWL was found to reliably predict the limiting workload. In the field study, TWL was a more appropriate and realistic index than WBGT, which was found to be excessively conservative.

Conclusions: The results confirm previously published studies evaluating TWL in underground environments, which have led to its widespread adoption in the Australian mining industry. The study extends the applicability of TWL to outdoor environments and generates management guidelines for its implementation.

Keywords: core temperature; heat illness; heat stress index; industry; thermal environment; Thermal Work Limit

INTRODUCTION

In many parts of the world, large numbers of workers in the construction, agriculture and resources industries work long hours in thermally stressful environments, a situation which will be exacerbated by predicted climate change.

Working under conditions of thermal stress has associated risks and consequences. Impairment of mental function and increased fatigue have implications for workplace safety. Heat-related illness ranges from heat cramps and heat exhaustion to the fortunately rare but often fatal condition of heat stroke. Maximizing production without compromising the health and safety of workers requires occupational hygienists and safety officers to be equipped with a simple, robust and reliable index to quantify the degree of stress posed by the thermal environment and unambiguous guidelines for its implementation. Heat stress indices currently in use are either difficult to apply or poorly applicable in many situations, leaving many industries without an effective heat management strategy.

Where the ambient temperature exceeds 35°C, the lack of thermal gradient between the skin and surrounds means effectively that the only avenue for heat loss is the evaporation of water, chiefly from the skin (sweating). At ambient temperatures above 35°C, or where the radiant load is high, the skin is in fact an avenue of heat gain. Under such conditions, or where the effectiveness of sweating is reduced by high ambient humidity, it may not be possible to dissipate metabolic heat; heat storage will occur leading to an increase in core temperature and the risk of heat illness. As the principal factor driving metabolic heat production is muscular activity, those working in hot conditions are at greatest risk. For any set of environmental conditions, there is a maximum rate at which an individual can dissipate heat i.e. a limiting metabolic rate, and therefore a maximum rate at which they can safely work.

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The risk of heat illness is greatly exacerbated by poor hydration. When ambient temperatures are extreme or when high temperatures are combined with high humidity, the fluid losses in sweat may exceed 1 l h^{-1} (Miller and Bates, 2007), predisposing to progressive dehydration.

As sweat is hypotonic to plasma, the volume loss is accompanied by a progressive increase in the osmolality of the extracellular fluid (ECF), so that the reduction in ECF volume is buffered by a fluid shift from the intracellular compartment (Kamijo and Nose, 2006). Continued sweating and failure to adequately replace lost fluid and electrolytes eventually leads to manifestations of heat illness. The biochemical changes (Donoghue *et al.*, 2000; Donoghue, 2003) accompanying cellular dehydration and impaired tissue perfusion contribute to headache, fatigue and other signs of heat exhaustion, while reduction in plasma volume (Jimenez *et al.*, 1999) may result in light-headedness or syncope. Ultimately, the inability to maintain cutaneous circulation and an adequate sweat rate permits core temperature to rise and the individual succumbs to heat stroke.

Clearly, adequate hydration is a critical factor in prevention of heat illness, as is acclimatization, which enhances thermoregulation by increasing plasma volume and sweat response. However, even when heat loss mechanisms are optimized, there is an upper limit to the heat load that can be dissipated. In many situations, workers will self-pace, adjusting either the work rate or the duration of work intervals to maintain thermal balance. The danger is that when the work is externally paced (e.g. by machinery factors, quotas, peer pressure, etc.), or the sustainable level of work is perceived as being unacceptably low, workers will push themselves beyond the safe limit and be at risk of developing heat illness. At most risk are those who are poorly hydrated, unacclimatized or physically unfit.

Protection of workers in hot environments requires a means of identifying conditions where excessive thermal stress places their health at risk. International Standard ISO 7933:2004 (ISO, 2004) uses the predicted heat strain index, but the complexity of this index discourages its use. In commoner use is the Wet Bulb Globe Temperature (WBGT), and the ACGIH TLV is in terms of this (ACGIH, 2007). The shortcomings of WBGT are widely recognized (Brake and Bates, 2002b; Taylor, 2006) and include the need to estimate metabolic rates and its relative insensitivity to the cooling effect of air movement. In practice, the WBGT is often seen to be excessively conservative and is largely ignored in many situations where its rigorous implementation would lead to unacceptable and unnecessary losses in productivity.

Advances in instrumentation have led to the publication of a new generation of heat stress indices that address inadequacies in the WBGT. One of the simplest to implement is the Thermal Work Limit (TWL) (Brake and Bates, 2002b,c). TWL uses five environmental parameters (dry bulb, wet bulb and globe temperatures, wind speed and atmospheric pressure) and accommodates for clothing factors to arrive at a prediction of a safe maximum continuously sustainable metabolic rate (W m^{-2}) for the conditions, i.e. the TWL. At high values of TWL, the thermal conditions impose no limits on work. At moderate values, adequately hydrated self-paced workers will be able to accommodate to the thermal stress by adjusting their work rate. At low TWL values, heat storage is likely to occur and TWL can be used to predict safe work rest-cycling schedules, while at very low values, no useful work rate may be sustained. A thermal environment can therefore be classified on the basis of TWL. Recommended management protocols based on TWL (Brake *et al.*, 1998) have been widely adopted and implemented in the underground mining industry in Australia; the resultant reduction in heat illness and lost production (Brake and Bates, 2000) is an endorsement of the index and its validity has been tested under controlled conditions in a small study (Bates and Miller, 2002). To date, TWL has largely been used in the underground environment; however, the algorithm is equally applicable to the outdoor environment where radiant heat forms a significant component of the thermal load.

This paper reports studies reinforcing the ability of the TWL algorithm to accurately predict limiting work rates under controlled conditions and a trial comparing the appropriateness of TWL and WBGT under field conditions in hot outdoor work environments. Management guidelines for the implementation of TWL in outdoor workplaces are provided.

METHODS

The subjects for the controlled environment study were 12 healthy young men accustomed to physical exercise. Prior to the study, the subjects completed a health check and fitness assessment (Table 1). The trials were carried out in late summer to ensure that the subjects were at least partially acclimatized to hot conditions.

Testing of each subject, which followed a similar protocol to the earlier study (Bates and Miller, 2002), was carried out over two consecutive days in a climate-controlled chamber at dry bulb temperature 38–40°C and wet bulb temperature ~28°C (45% relative humidity). For each trial, the subjects remained in the chamber for ~3 h of alternating periods of work (30 min) and rest (10 min). Conditions were monitored with a Heat Stress Monitor (Calor Environmental Instruments, Western Australia) and are summarized in Table 2 together with the computed WBGT and TWL indices for each testing

Table 1. Anthropometric and physiological data for the subjects

Subject	Age	Height (cm)	Weight (kg)	S.A. (m^2)	BMI	WHR	Fat (%)	BP (mm Hg)	RHR (bpm)	FEV1/ FVC%	VO_2 max (ml kg^{-1} min^{-1})
A	20	189	79	2.30	22.1	0.80	10	120/85	56	84	37.9
B	21	180	74.3	1.91	22.9	0.84		115/90	60	77	52.5
C	24	167	68.2	1.76	24.5	0.81	12	108/66	66	80	43.9
D	28	185	86	2.10	25.1	0.79	14.2	115/70	60	86	48
E	22	175	70.8	1.86	23.1	0.85	8.6	124/70	75[b]	86	46.6[b]
F	25	177	66.7	1.81	21.3	0.77	9.5	112/68	60	85	66
G	18	185	78.8	2.02	23.0	0.76	9	140/90[a]	72	75	43
H		174	84	1.98	27.7	0.88	16	125/85	52	82	
I	26	180	71.4	1.90	22.0	0.83	10.3	120/90	60	74	56
J	19	179	84	2.40	26.2	0.87	13	120/80	64	82	42
K	23	181	64	1.82	19.5	0.78		110/85	44	91	78
L	25		75.5				12.1	110/70	54		
Mean	22.82	179.27	75.23	1.99	23.42		11.47		60.25		51.39
SD	3.12	6.05	7.26	0.21	2.33		2.42		8.49		12.36

S.A. = surface area (estimated using the nomogram of Boothby and Sandiford 1921), BMI = body mass index, WHR = waist hip ratio, RHR = resting heart rate, FEV1/FVC% = forced expired volume in one second as a percentage of forced vital capacity.

[a] Subject aware of having high blood pressure (BP), otherwise healthy.

[b] Subject had jogged 5 km prior to the medical accounting for the relatively high RHR and possibly affecting estimation of VO_2 max.

Table 2. Conditions during the 11 controlled environment sessions

Trial day	Dry bulb (°C)	Wet bulb (°C)	Wind speed (m s^{-1})	WBGT (°C)	TWL (W m^{-2})
1	38.7 ± 1.0	28.6 ± 1.3	0.23 ± 0.05	31.7 ± 1.2	154
2	38.4 ± 0.8	28.7 ± 1.2	0.24 ± 0.05	31.5 ± 1.0	156
3	39.0 ± 0.8	28.1 ± 1.5	0.23 ± 0.06	31.4 ± 1.1	160
4	38.9 ± 0.7	27.6 ± 1.4	0.21 ± 0.04	31.2 ± 1.1	160
5	38.7 ± 1.5	25.0 ± 1.5	0.22 ± 0.04	28.8 ± 1.1	198
6	38.1 ± 0.8	27.9 ± 1.6	0.21 ± 0.03	30.9 ± 1.3	159
7	39.1 ± 1.4	27.3 ± 1.3	0.24 ± 0.04	30.8 ± 1.2	172
8	38.6 ± 0.7	27.3 ± 1.5	0.22 ± 0.05	30.7 ± 1.0	168
9	38.3 ± 1.2	27.2 ± 1.9	0.20 ± 0.03	30.5 ± 1.5	164
10	38.3 ± 0.9	27.6 ± 1.4	0.21 ± 0.05	30.8 ± 1.0	162
11	38.2 ± 0.9	28.4 ± 1.1	0.22 ± 0.04	31.3 ± 0.9	156

Data are means and SDs for readings recorded approximately every 5 min throughout each session. WBGT was automatically calculated at each sampling time. TWL values were computed from the mean environmental data for the session using a clothing insulation value of 0.12 clo (sweat-saturated minimal attire).

day. TWL predicts the limiting metabolic heat load for fully acclimatized subjects; empirical evidence suggests that lack of acclimatization may reduce this by up to 25% (Donoghue *et al.*, 2000; Brake and Bates, 2002b). As our subjects were considered partially acclimatized, it was predicted that their metabolic limit under these conditions (actual TWL) would fall within the range 130–160 W m^{-2}, equivalent to a limiting external work rate of 50–70 W, assuming a resting metabolic rate of 55 W m^{-2} and a work efficiency of 25% (as previously found) and an average surface area (Boothby and Sandiford, 1921) of 2 m^2 (Table 1).

Equivalence was calculated as follows: A work efficiency of 25% implies that 75% of the energy required to perform the work is lost as heat; in other words, the additional heat load is three times the external work rate.

$$\text{Heat load from resting metabolism (RMR)} = 55\,\text{W m}^{-2}$$

$$\text{Heat load from external work (HEW)} = \frac{\text{external workload (W)} \times 3}{2\text{m}^2}$$

$$\text{Total metabolic heat load in W m}^{-2} = \text{RMR} + \text{HEW}$$

The calculation yields total metabolic heat loads for the 40, 50 and 60 W workloads of approximately 115, 130 and 145 W m^{-2}, respectively.

To verify the prediction, external work was performed using Monark cycle ergometres at workloads of 40, 50 and 60 W and the ability of the subjects to maintain heat balance without strain during each work period was assessed by monitoring their core temperature and heart rate. Inability to stabilize these indicates that the subject's limiting metabolic load is exceeded.

Core temperature was recorded using ingested miniature transponders (HTI technologies, Inc.) which transmit a radio signal corresponding to temperature. Each subject wore a Polar 'Sport Tester' heart rate monitor.

To ensure that hydration status would not be a limiting factor to the dissipation of heat, the hydration level of the subjects was monitored throughout each trial by measurement of urine specific gravity (Usg). Subjects could not enter the chamber unless adequately hydrated (Usg $\leq$ 1.015). In the chamber, the subjects maintained hydration by drinking water on schedule at an adequate rate to compensate for the sweat rate predicted by the TWL algorithm ($\sim$1 l h^{-1}).

Locations selected for the outdoor study were mining and mine-related sites in the northwest of Australia where environmental conditions in the summer months typically produce WBGT values in excess of the recommended guidelines (ACGIH, 2007). Environmental parameters and TWL were logged from mid-morning to mid-afternoon for each shift and recorded manually from representative work locations.

Participants in the field study were monitored for signs of physiological strain >3 days while continuing with normal work. At the beginning of each shift, each subject was fitted with a Polar S720i heart rate monitor. Tympanic temperatures were recorded at the beginning, middle (lunch break) and end of the shift as an indication of core body temperature. At the same times, subjects were asked to rate their perceived level of fatigue [relative perceived fatigue (RPF)] on a numerical scale ranging from 1 (feeling really good) to 13 (completely exhausted). Urine samples were also obtained at each time to assess hydration status (Miller and Bates, 2007).

All protocols were approved by the Curtin University Human Research Ethics Committee.

RESULTS

Table 3 shows the maximum core temperatures reached by the chamber study subjects in each of their two work trials. In common with other heat stress indices, the TWL algorithm allows for core temperature to reach a maximum of 38.2°C.

In 18 out of the 24 subject sessions, core temperature remained below this level. In the remaining six sessions, the subject's core temperature did exceed 38.2°C indicating that the metabolic heat load exceeded the subject's safe limit under the conditions; however, one of these could be attributed to the subject wearing unsuitably heavy pants thus increasing his clothing insulation (clo) factor and reducing his effective metabolic limit. When the pants were removed, he completed the session without excessive core temperature. Two subjects had to be stopped and allowed to cool down during their first session in the chamber because of rapidly climbing core temperatures. Both returned to the chamber to complete

Table 3. Maximum core temperature reached and limiting workloads for each of the two work trials completed by each subject in the controlled environment study

Day / Subject	1	2	3	4	5	6	7	8	9	10	11	Limiting W/L trial 1 (W)	Limiting W/L trial 2 (W)
A	38.3	38.0										50	60
B	38.2	37.1										50	>60
C	38.2	38.1										40	40
D			38.4[a]	38.1								40	60
E			38.0	38.0								40	60
F			38.1	38.0								50	60
G					37.6	37.7						>60	>60
H						38.4[b]	38.1					40	40
I								38.3[b]	38.1			40	50
J								38.0	38.0			60	60
K										37.8	38.0	50	50
L										37.9	37.6	>50	>60

Shaded cells are those trials in which core temperature exceeded 38.2°C. Limiting W/L = limiting workload i.e. minimum external workload at which core temperature and/or heart rate failed to stabilize at ≤38.2°C/115 bpm.

[a] Had heavy pants on, OK after removed.

[b] Core temperature climbing, exercise stopped.

the remaining work periods and in both cases the temperature again exceeded 38.2°C

The chamber sessions were structured with the first 30-min work period being performed at 40 W followed by a period at 50 W. Most subjects went on to work at 50 W for the third period and then dropped back to 40 W for the fourth. Depending on temperatures and heart rates over the first four periods, the final work period was conducted at 40, 50 or 60 W. By inspection of the core temperature and heart rate records for each trial session, a 'limiting workload' was estimated, this being the external workload which it was judged the subject would not be able to sustain for an extended time under the conditions because either their core temperature had exceeded 38.2°C or was likely to if they continued working or their heart rate had failed to stabilize and had exceeded 115 bpm over the final 10 min of the work period (Fig. 1). Where the core temperature did exceed 38.2°C, reducing the workload in subsequent work periods allowed the temperature to stabilize in some but not all cases (Fig. 2). The limiting external workloads (W/L) for each subject on each day are shown in Table 3.

Assessment of heat strain from heart rate and rectal (core) temperature has a sound physiological basis and has been quantified on a scale of 1–10 in the Physiological Strain Index (PSI) (Moran *et al.*, 1998). According to this index, the subject in Fig. 1 had a PSI of 3 at the completion of the third work period (40 W) and 3.3 at the completion of period 4 (40 W) both indicating a low level of strain. After working at 50 W in period 5, the PSI had risen to 4.6 (moderate), a clear increase in the level of strain at the higher workload. From the heart rate record, it is apparent that if the subject had continued to work at 50 W, the heart rate and PSI would have continued to increase.

Table 4 summarizes the environmental data from the field study. At Sites 1 and 3, the subjects were performing light manual work such as machine operation and were able to be in the shade part of the time. Site 2 was a construction site where the subjects were a crew engaged in laying and tying reinforcing steel, a moderately high level of physical activity, and were exposed to the sun throughout. Physiological data from the subjects are summarized in Table 5. There was no significant change in any of the parameters monitored over the course of the shift. The slight increases in tympanic temperature in all groups were consistent with diurnal rhythm. Subjects also maintained a constant (though not necessarily optimal) level of hydration over the work period (Miller and Bates, 2007). The average heart rate, although differing between groups reflecting differences in the type and intensity of work being performed, was well below levels that would indicate physiological strain and showed no tendency to increase over the shift. Fig. 3 shows the heart rate from one of the construction crew, scheduled rest periods are clearly reflected in the heart rate, which otherwise remains consistently elevated. Heart rates from the other subject groups were much more variable and rest breaks are not clearly evident (Fig. 4).

DISCUSSION

Results from the controlled environment study reinforce the conclusion from earlier work (Bates and Miller, 2002) that TWL does have the ability to

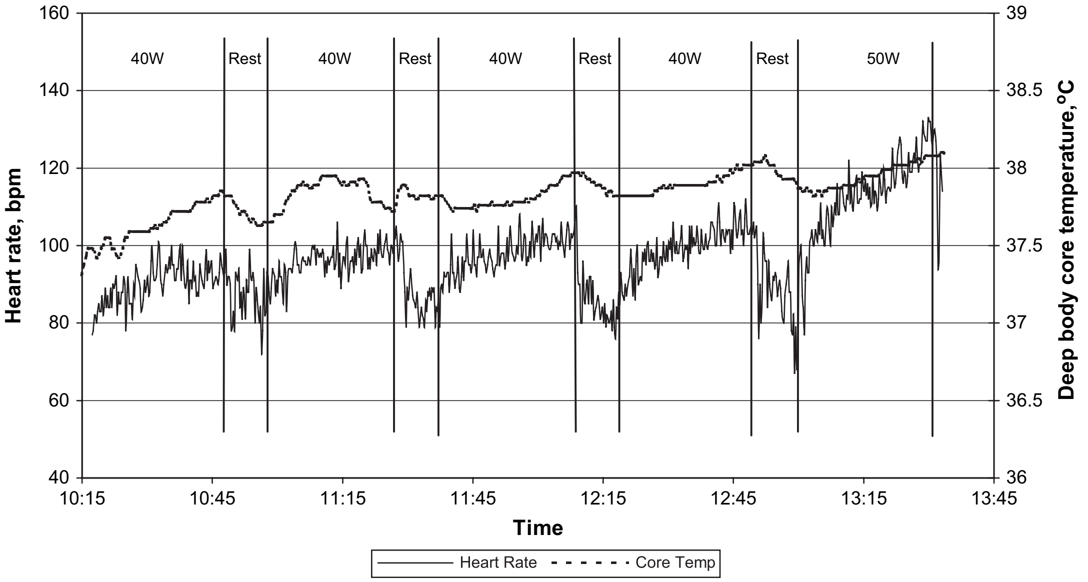

Fig. 1. Heart rate and core temperature records of a subject in the controlled environment trial showing inability to stabilize at 50 W (limiting workload) corresponding to a limiting metabolic heat load (TWL) of ~130 W m^{-2}.

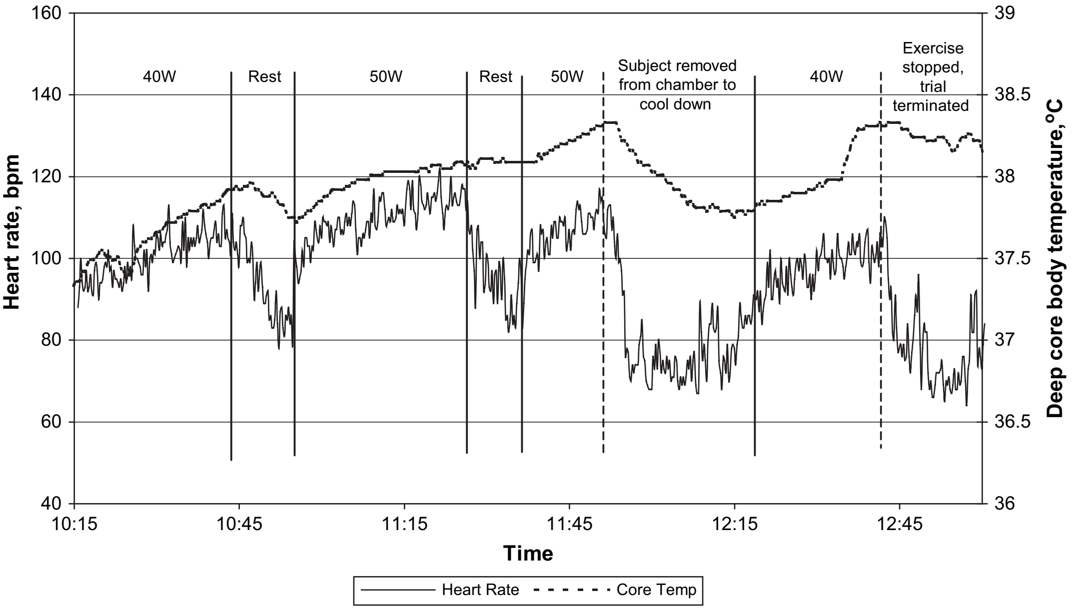

Fig. 2. The subject's temperature exceeded 38.2°C in the third work period. He was unable to stabilize at a subsequent lower workload.

Table 4. Summary of environmental data from the field study

	Site 1 (Coastal)	Site 2 (Coastal)	Site 3 (Inland)
n	13	8	17
Dry bulb (°C)	35.0 ± 1.9	36.7 ± 1.5	37.6 ± 3.0
RH (%)	58.9 ± 6.2	54.5 ± 10.1	32.3 ± 7.5
Globe temperature (°C)	38.7 ± 3.6	43.1 ± 1.6	43.5 ± 5.2
WS (m s^{-1})	4.1 ± 1.8	2.7 ± 1.5	1.8 ± 1.2
WBGT (°C)	30.6 ± 2.2	32.2 ± 1.1	29.2 ± 2.3
TWL (w m^{-2})	239.1 ± 41.1	199.0 ± 35.2	232.0 ± 37.3

Data are means ± SD of values recorded at various times at representative locations for each site over three or four consecutive days. RH = relative humidity, WS = wind speed, *n* = number of data collections included for each site.

Table 5. Indicators of physiological strain: summary of data from the field study

	Site 1 (Coastal)	Site 2 (Coastal)	Site 3 (Inland)
Tympanic temperature (start)	36.5 ± 0.2 (n = 15)	36.6 ± 0.3 (n = 24)	36.7 ± 0.4 (n = 23)
Tympanic temperature (mid)	36.7 ± 0.2 (n = 11)	37.2 ± 0.3 (n = 24)	37.0 ± 0.4 (n = 21)
Tympanic temperature (end)	36.8 ± 0.2 (n = 15)	37.2 ± 0.3 (n = 24)	37.0 ± 0.3 (n = 23)
RPF (start)	3.0 ± 2.1 (n = 15)	3.7 ± 2.1 (n = 23)	4.7 ± 2.2 (n = 23)
RPF (mid)	2.6 ± 1.0 (n = 14)	4.6 ± 2.2 (n = 24)	5.2 ± 1.7 (n = 21)
RPF (end)	3.7 ± 1.8 (n = 15)	4.5 ± 2.7 (n = 24)	5.7 ± 1.7 (n = 22)
Heart rate (average)	87.9 ± 6.6 (n = 9)	104.2 ± 11.7 (n = 24)	89.8 ± 10.3 (n = 21)

Data are means ± S.D. *n* = number of values in each data set. Tympanic temperature and RPF data were collected at the start, middle and end of the shift.

predict the limiting work rate for a thermal environment. Under milder environmental conditions, the work rates chosen would be well within the capabilities of the subjects, whose predicted VO_2 max averaged 51 ml kg^{-1} min^{-1}, so simple fatigue is unlikely to have affected performance in the chamber. The limiting workloads (W/L) shown in Table 3 are the minimum external workload at which the subject's core temperature and/or heart rate failed to stabilize. In other words, if the subject were required to continue working at this or a higher level, heat exhaustion or fatigue would be expected to result. On

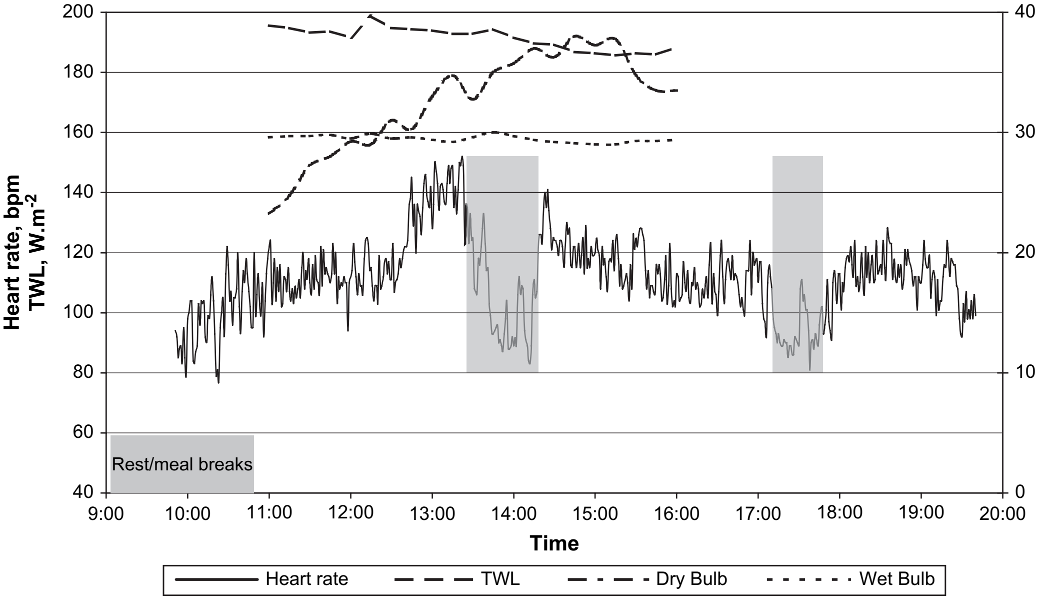

Fig. 3. Heart rate record from subject at Site 2 performing continuous manual labour. Dry and wet bulb temperature and TWL records superimposed.

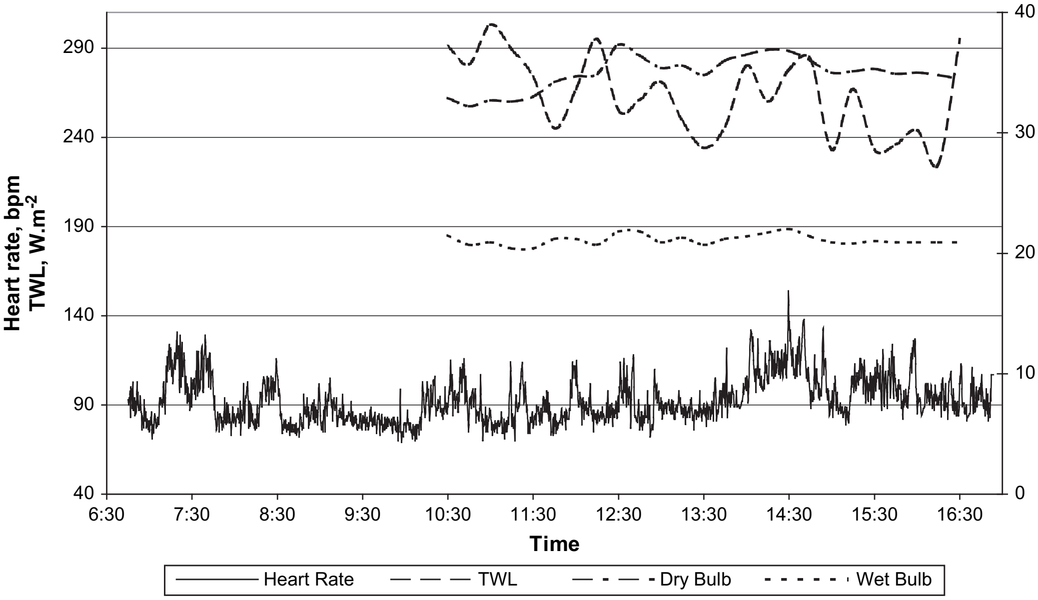

Fig. 4. Heart rate recording from subject at Site 3 performing varied tasks. Dry and wet bulb temperature and TWL records superimposed.

their second day in the chamber, eight of the 12 subjects were able to complete the work periods at $\geq$50 W without evidence of heat storage or physiological strain. A further two were able to stabilize at 40 W but not at 50W, in other words, 10 out of the 12 subjects had limiting workloads in the range predicted by the algorithm. The remaining two showed heat storage at all workloads on both days probably reflecting lack of acclimatization (or in one case, the highest body mass index and body fat per cent of the group). In a self-paced work situation, these two would have voluntarily reduced their work rate to a level where they could cope.

Conditions for the outdoor study were generally less thermally challenging than for the chamber study as shown by higher TWL values (mean TWL across the three outdoor sites $\geq$200 W m^{-2} versus $\sim$160 W m^{-2} in the chamber), although WBGT

Table 6. Recommended management protocols for the implementation of TWL in the aboveground workplace

TWL limit (W m^{-2})	Interventions
Restricted access TWL $<$ 115 or dry bulb $>$ 44°C or wet bulb $>$ 32°C	Limited to essential maintenance or rescue operations
	No person to work alone
	No unacclimatized person to work[a]
	Job description to specify requirement to work in hostile thermal conditions
	Specific induction required emphasizing hydration and identifying signs of heat strain
	TWL prescribes work/rest cycling and fluid intakes appropriate for type of work and conditions
	Regular dehydration testing at end of shift
	Personal water bottle (4 l capacity) must be on the job at all times
Buffer TWL = 115 to 140	Zone exists to identify situations in which environmental conditions may be limiting
	Any practicable intervention to reduce heat stress should be implemented e.g. provide shade, improve ventilation, etc.
	Working alone to be avoided if possible
	Unacclimatized[a] workers not to work in this zone
Acclimatization TWL = 140 to 220	Workers with uncertain acclimatization status should not work alone in this zone
Unrestricted TWL $>$ 220	No limits on self-paced work for educated, hydrated workers

[a] Unacclimatized workers are defined as new workers or those who have been off work for $>$14 days due to illness or leave (outside the tropics).

values were similar [mean WBGT ranged from 29 .2 to 32.2 °C at outdoor sites and (excluding Day 5) from 30.5 to 31.7°C in the chamber]. One reason for this is that TWL reflects wind speed to a far greater degree than WBGT. Although conditions at each site varied from day to day, and to a lesser extent throughout the day, TWL seldom went $<$150 W m^{-2} indicating that the index predicted no limitation to work of a light to moderate intensity ($<$150 W m^{-2} represents light work, MVA, 2005). The physiological data support this, despite the fact that on the majority of days WBGT values of $>$30°C were consistently recorded, a level at which this index predicts an increased risk of thermal strain. Until 2006, the ACGIH TLV for acclimatized workers wearing long sleeved summer work uniform was WBGT values of 29.5, 27.5 and 26.0°C, for light, moderate and heavy work, respectively (ACGIH, 2006), and they are now slightly higher (ACGIH, 2007). Mean average heart rates for the subjects at Site 2 were higher than for the other groups reflecting both a higher work intensity and more consistent exposure to the higher environmental heat load; however, even in this group, there was no evidence of thermal strain, individual heart rates remained relatively steady during work periods with clear reductions during rest periods. There was no noticeable influence on the heart rates of any measured or computed environmental parameter. Other parameters also showed no evidence of physiological strain. The highest recorded tympanic temperature was 37.6°C with means generally ~37°C. Mean values for RPF were generally ~5 (feeling OK); the highest reported value was 11, recorded at the end of the shift by one of the construction crew on a particularly hot day when his Usg values indicated that he was poorly hydrated, emphasizing the role of hydration in protecting against heat strain.

WBGT values at the three sites ranged from 27.1 to 34.7°C with values $>$30°C being consistently recorded, particularly at Site 2. For much of the time, these values exceeded the acceptable limit for acclimatized persons to perform even light work without work/rest cycling, let alone the manual labour carried out by the construction workers. These observations confirm that TWL is a more appropriate, realistic and reliable index than the WBGT in this environment. In an aboveground environment where the convective and evaporative effect of air movement contributes significantly to cooling, the WBGT is an excessively conservative index of environmental heat stress. Although WBGT is the nominal standard for many industries, it is often not in fact used, particularly in industries where heat stress is a significant issue, as its implementation would lead to too much lost production. The need is for an index which does reliably quantify the environmental heat stress in a meaningful way and which can be used to manage work in outdoor environments.

Individuals who are able to self-pace will adjust their work rate to the conditions and thereby avoid physiological strain (Brake and Bates, 2002a). Our observations from this and other studies suggest that self-paced workers will seldom maintain a work rate that elevates their average heart rate >110–115 bpm. In the chamber study where the subjects were required to maintain a set workload, those subjects whose heart rates were not stabilized below this level were deemed to have reached their limiting workload. For well-hydrated individuals who are able to self-pace, provided that the environmental conditions permit an adequate workload to maintain productivity, work may safely continue. TWL is an index of this maximum safe work rate. A TWL of >140 W m^{-2} indicates that self-pacing, acclimatized, hydrated individuals may safely perform light to moderate work. Higher TWL values correspond to higher levels of work with a TWL of >220 W m^{-2} corresponding to unrestricted work at any level. In the study, on even the hottest days, the air movement was sufficient to keep the TWL >140 W m^{-2} and for the most part >200 W m^{-2}. The TWLs recorded in the vicinity of the construction workers at Site 2 were generally the lowest, and even these workers were able to perform continuous manual labour while fully exposed to the sun without any indication of heat strain. WBGT values computed for the same locations would have imposed severe and unnecessary limitations on their work.

On the basis of this study, TWL has been shown to perform better than WBGT as a predictor of the impact of environmental heat stress in outdoor work environments. The introduction of TWL and associated protocols (Table 6) provides management with a workable strategy for minimizing the risk to workers posed by environmental heat stress.

KEY POINTS

- WBGT is not a practical indicator of thermal stress in many situations
- TWL is a realistic and valid index of heat stress
- TWL provides a workable strategy for managing heat stress

FUNDING

Rio Tinto Iron Ore

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