The accuracy of the WBGT heat stress index at low and high humidity levels

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ABSTRACT

The WBGT index is the heat stress index of preference in the Occupational Health and Safety Act, No. 85 of 1993. The purpose of this investigation was to determine if equivalent WBGT values with low and high relative humidity levels would result in similar physiological heat loads. Un-acclimatised subjects were exposed to 24, 28, 30 and 32 WBGT with 30% (LH) and 70% (HH) relative humidity levels respectively using a metabolic rate of 450 watts. Subjects were exposed for five hours using a work:rest cycle of 45 min work:15 min rest. Final core temperature at 30 and 32 WBGT was significantly higher in HH. Final heart rate was at all the experimental conditions significantly higher in HH. Sweat rate increased significantly only at 32 WBGT (HH). Tolerance time decreased significantly at 30 and 32 WBGT with HH. The results indicate that WBGT index values above 30 with HH levels underestimate thermal load and that un-acclimatised employees may be at risk to develop heat illnesses if work schedules are not properly managed.

INTRODUCTION

The Wet-Bulb Globe Temperature (WBGT) index is the heat stress index of preference in the Occupational Health and Safety Act No. of 1993.[1] If an employee needs to perform work in an environment with a WBGT index value higher than 30, the employer needs to take appropriate steps to reduce the thermal load. The Act does, however, not distinguish between work environments with low relative humidity (LH) and high relative humidity (HH) levels. Employers can therefore assume that employees will experience similar heat loads if they need to complete work in environments with equivalent WBGT values with low and high relative humidity levels respectively.

If a heat stress index is to be used in industry, it is important that the index incorporate variables that are related to heat loss mechanisms used by humans to stay in thermal equilibrium.[2] This includes variables such as air temperature (T_a), natural ventilated wet bulb (T_{nwb}), globe temperature (T_g) and air movement ($m.sec^{-1}$). The WBGT heat stress index incorporates all the mentioned variables and is also currently the most user friendly index available in industry. The index proved also to have good correlations with physiological reactions at high temperatures.[3] A question not answered yet is whether the WBGT heat stress index will estimate heat stress accurately at high temperature and humidity levels where humans use mainly evaporative cooling as a heat loss mechanism to stay in thermal equilibrium.[4]

Recent research has, however, indicated that equivalent WBGT heat stress index levels under- or overestimate thermal load in certain conditions. Rastogi *et al*.[5] reported that despite severe environmental heat stress levels in glass bangle and brassware industries in India, workers experienced low physiological strain. They suggested that this might have been due to a high degree of acclimatisation to the work situations and work practices or that the index is not appropriate in environments with high radiant heat load due to the low weighting factor for radiant heat. There is, however, evidence that the WBGT heat stress index might underestimate physiological strain in warm humid environments.[6] McNeill and Parsons[2] also alluded to the fact that the WBGT index values need to be increased in tropical environments due to the underestimation of sweat rate and rate of evaporation. Acclimatisation does however reduce the differences in physiological strain experienced at equivalent WBGT heat stress index levels with different humidity levels.[7]

Increased thermal load that is placed on employees may increase the risk for heat related illnesses. Performance of employees can also be affected due to the relationship that exists between percentage dehydration and performance.[8] It is therefore important that proper guidelines be drafted to allow accurate implementation of the WBGT heat stress index in hot wet conditions to protect the workforce and employers. The guidelines should provide correction factors and threshold temperatures to protect the health of the employees. Other protective approaches that are used are to screen employees for heat intolerance or to implement practices to ensure that employees at risk to develop heat related illnesses, are not allowed in the workplace. Educating the workforce concerning the dangers of heat illnesses, the importance of maintaining optimal hydration status during work and self pacing is still the most effective way to prevent heat illnesses.[9]

> ***"... The WBGT heat stress index underestimates the heat strain placed on un-acclimatised subjects at WBGT values above 30 with a relative humidity level of 70%."***

This study was therefore conducted to determine the influence of two relative humidity levels on a range of equivalent WBGT heat stress index values on physiological responses known to be good indicators of thermal heat strain.

METHODS

Healthy un-acclimatised young men (N=16) were used. They underwent a medical screening that included a cardiovascular examination, and were declared fit to take part in the study. Informed consent was obtained from each subject and they were aware that they could withdraw from the experiment without any penalty. The physical characteristics of the test subjects are depicted in Table 1.

Test subjects were individually calibrated using open circuit spirometry to complete work at an oxygen consumption of 1.34 L.min^{-1} with the application of a standardised step test protocol. This protocol required subjects to step at a rate of 18 steps.min^{-1} for 9 minutes onto stepping heights of 20, 25, 30 and 35 cm respectively. A linear regression was calculated between oxygen consumption and stepping height to determine required stepping height for each subject that would yield an oxygen consumption of 1.34 L.min^{-1}. The metabolic rate of the subjects was 450 watts, which is representative of activities such as loading a wheelbarrow with stones and mortar, hand moulding medium sized pieces, sawing (40 double pulls.min^{-1}) and stripping of bark.[10]

Subjects were exposed for five hours using a work: rest cycle of 45 min work:15 min rest. During the 45 min work period subjects had to step at a rate of 18 steps.min^{-1}, at their respective predetermined stepping heights, to maintain their metabolic rate at 450 watts. Test subjects were exposed every second day to minimise the effect of acclimatisation. Exposures took place at the same time each day to avoid the influence of circadian variations on the measured physiological variables. No exposures were conducted on Mondays due to the possible influence that social activities during the weekend may have had on thermoregulatory responses. Subjects were instructed to not consume alcohol and refrain from strenuous

Table 1. Anthropometric data of subjects (N = 16)

Variable	Average	Standard deviation
Age (years)	25.6	5.1
Length (cm)	170.3	5.3
Mass (kg)	62.4	5.6
Body surface area (m^2)	1.72	0.08

activities the day before the exposure. Exposures were conducted in a randomised order at different WBGT heat stress index values at the two different humidity levels. The WBGT heat stress index conditions used were 24, 28, 30 and 32 at 30% (LH) and 70% (HH) relative humidity respectively. The dry-bulb, wet-bulb and globe temperature combinations used for the respective WBGT index values for LH and HH are depicted in Table 2. WBGT was recorded with a Tempstress WBGT monitor placed in the climatic chamber. The dry-bulb and wet-bulb temperatures were used to control the climatic conditions in the chamber.

Clothing during exposures consisted of underpants, long trousers (khaki), long sleeve shirt (khaki), socks and light exercise shoes. Exposure of test subjects was stopped if rectal or core temperature exceeded 39.0°C or heart rate exceeded 180 beats.min^{-1}. Water was supplied only during rest periods. The volume of water taken in was noted and used in the determination of sweat rate over the exposure period. The total exposure time was 300 minutes.

All reported temperatures were measured with copper-constantan thermocouples. Core (rectal) temperatures were measured 8 cm beyond the anal sphincter with a copper-constantan thermocouple covered with latex. Heart rate was determined with the placement of four electrodes on the chest. A Helige EK41 ECG monitor was used. Core temperature and heart rate of each test subject was automatically recorded and stored at five minute intervals on a desktop computer. Sweat rate was obtained by the difference in body weight before and after exposure corrected for water intake and urine voided. Subjects were weighed semi-nude, underpants only, on an electronic scale (Toledo Scale, Worthington, OHIO) with an accuracy of 0.02 kg.

Statistical analysis was performed using the Student's t-test. Differences were accepted as being significantly different at the 95% significance level.

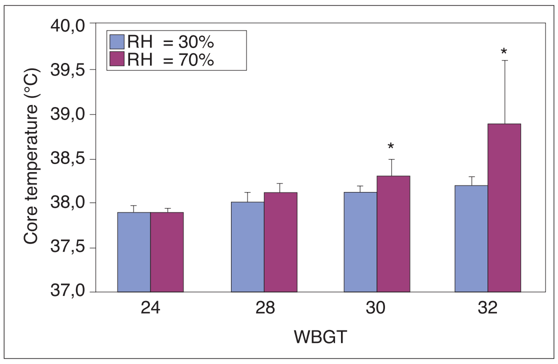

Figure 1. Mean core temperature responses of un-acclimatised subjects completing a block stepping exercise (metabolic rate = 450 watts) using a work: rest schedule of 45 min work: 15 min rest for five hours at 24, 28, 30 and 32 WBGT with 30% and 70% relative humidity levels respectively. (* = p < 0.05 for 30% vs 70% relative humidity exposure conditions). RH = relative humidity

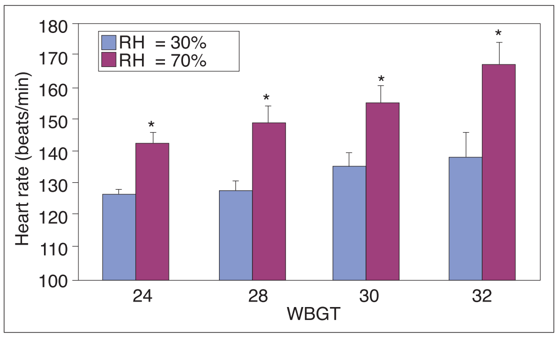

Figure 2. Mean heart rate responses of un-acclimatised subjects completing a block stepping exercise (metabolic rate = 450 watts) using a work: rest schedule of 45 min work: 15 min rest for five hours at 24, 28, 30 and 32 WBGT with 30% and 70% relative humidity levels respectively. (* = p < 0.05 for 30% vs 70% relative humidity exposure conditions). RH = relative humidity

Table 2. Dry-bulb (T_a), natural ventilated wet-bulb (T_{nwb}) and globe (T_g) temperature combinations for 24, 26, 28, 30 and 32 WBGT at 30% and 70% relative humidity levels (altitude = 1440 m)

Relative humidity (%)	T_a (°C)	T_{nwb} (°C)	T_g (°C)	WBGT
30	33.4	19.7	34.4	24.0
	35.9	21.5	36.9	26.0
	38.4	23.3	39.4	28.0
	40.9	25.1	41.9	30.0
	43.3	26.9	44.4	32.0
70	26.9	22.5	27.9	24.0
	29.0	24.5	30.1	26.0
	31.2	26.4	32.2	28.0
	33.3	28.3	34.3	30.0
	35.4	30.3	36.4	32.0

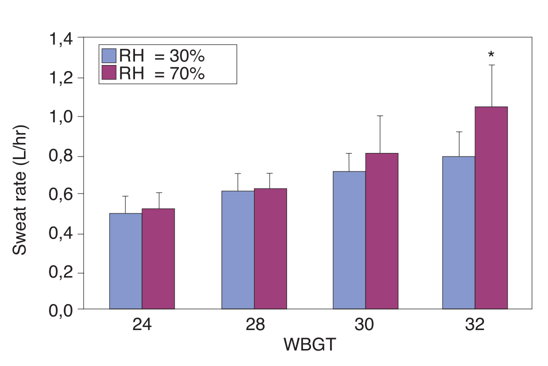

Figure 3. Mean sweat rate responses of unacclimatised subjects completing a block stepping exercise (metabolic rate = 450 watts) using a work: rest schedule of 45 min work: 15 min rest for five hours at 24, 28, 30 and 32 WBGT with 30% and 70% relative humidity levels respectively. (* = p < 0.05 for 30% vs 70% relative humidity exposure conditions). RH = relative humidity

RESULTS

Figures 1 and 2 depict the average core (rectal) temperature and heart rate responses over the exposure period at the end of each 45 min exercise period at the different WBGT values with LH and HH respectively. At 24 and 28 WBGT, no significant differences were measured in rectal temperature responses with LH and HH respectively. At 30 WBGT ($p < 0.05$) and 32 WBGT ($p < 0.001$) a significant increase in core temperature was evident if HH was compared with LH.

Average heart rate at the end of each exercise period in HH was significantly higher at 24 ($p < 0.001$), 28 ($p < 0.001$), 30 ($p < 0.001$) and 32 ($p < 0.005$) WBGT if compared with LH. Heart rate increased with 12.7%, 16.4%, 14.8% and 21.0% beats.min^{-1} at 24, 28, 30 and 32 WBGT respectively with the increase in relative humidity from LH to HH.

Figure 3 depicts sweat rate responses measured with LH and HH at 24, 28, 30 and 32 WBGT. A significant increase of 31.3% was measured in sweat rate ($p < 0.001$) at 32 WBGT with the increase in relative humidity from LH to HH.

Time to reach the set physiological safety criteria, i.e., 39.0°C for core temperature and/or 180 beats.min^{-1} for heart rate, decreased with the

increase in humidity level (Figure 4). Tolerance time decreased significantly with 34.2% ($p < 0.005$) and 81.1% ($p < 0.001$) at 30 and 32 WBGT respectively in HH if compared with LH.

Significant correlations were found between average core temperature and heart rate at the end of each exercise period with an increase in WBGT at LH and HH respectively (Table 3). Utilising the regression equation quoted in Table 3, equivalent core temperature and heart rates for different WBGT values at LH and HH were calculated and are depicted in Table 4.

Discussion

The results of this investigation have shown that the thermal load placed on employees is underestimated in environments with a WBGT index value above 30 if LH and HH conditions are compared. This may have serious implications in terms of risk management and the development of heat management programmes if employees need to perform hard manual labour for extended periods.

According to Ramsey and Chai[11] the increase in T_{nwb} will compensate for the difference in relative humidity levels. The results of the current study do, however, not support their views at all the WBGT index values tested.

At 24 WBGT, the increase in relative humidity level from 30% to 70% did not result in additional physiological heat load if the rectal temperature responses were compared. A significant increase was, however, measured in terms of heart rate. The latter finding may be the result of the metabolic rate used (450 watts). Wenzel and Stratman[12] did report a non-significant increase in heart rate response with an increase in relative humidity from 0 – 100% with a metabolic rate of 116 watts.m^{-2} (about 208 watts) in similar conditions. The non-significant decrease in tolerance time at 24 WBGT with the increase in relative humidity, may be an indication that the total thermal load placed on the subjects with the higher humidity

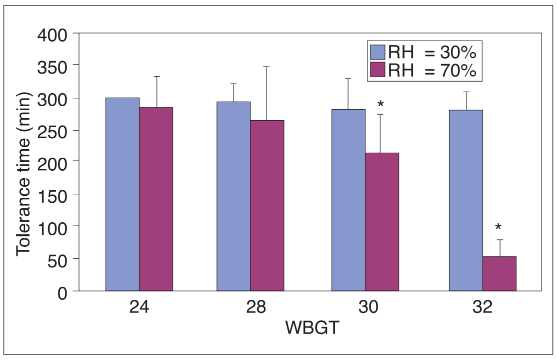

Figure 4. Mean tolerance times of unacclimatised subjects completing a block stepping exercise (metabolic rate = 450 watts) using a work: rest schedule of 45 min work: 15 min rest for five hours at 24, 28, 30 and 32 WBGT with 30% and 70% relative humidity levels respectively. (* = $p < 0.05$ for 30% vs 70% relative humidity exposure conditions). RH = relative humidity.

Table 3. Correlation coefficients and regression equations for average core temperature and heart rate responses for four 45 minute exposures with 15 minutes rest during each hour over a four hour period. (y = predicted physiological variable; x = WBGT heat stress index value)

	Correlation coefficient (r)	Regression equation
Core temperature (°C)		
R.H. = 30%	0.98	$y = 0.037x + 36.991$
R.H. = 70%	0.90	$y = 0.114x + 35.043$
Heart rate (beats.min^{-1})		
R.H. = 30%	0.94	$y = 1.557x + 87.371$
R.H. = 70%	0.95	$y = 2.957x + 68.971$

RH = relative humidity

Table 4. Predicted final core temperatures and heart rates for a four hour exposure with a work rest cycle of 45 minutes work:15 minutes rest in each hour at different WBGT heat stress index values at 30% and 70% relative humidity

WBGT	Core temperature (°C)		Heart rate (beats.min^{-1})	
	RH = 30%	RH = 70%	RH = 30%	RH = 70%
24	37.9	37.8	125	140
26	38.0	38.0	128	146
28	38.0	38.2	131	152
30	38.1	38.5	134	158
32	38.2	38.7	137	164

RH = relative humidity

level could still be tolerated, and that significant heat storage did not occur. The non-significant increase in sweat rate also provided support that heat load did not increase significantly.

A similar tendency in terms of core temperature, heart rate, tolerance time and sweat rate was measured at 28 WBGT. This provided evidence that an increase in relative humidity from 30% to 70% at 28 WBGT also does not have a significant influence on physiological heat loss mechanisms, and that thermal equilibrium was been reached. The 0.2°C increase in final core temperatures at 28 WBGT compared to the final core temperature value at 24 WBGT is also indicative that the thermal heat load did not increase significantly at 28 WBGT and that no significant heat storage occurred in the test subjects over the five hour exposure.[13]

> ***"The recommended WBGT index value of 30 ... needs to be reduced with an index value of 3 in environments with high humidity levels."***

The increase in heart rate measured at 24 and 28 WBGT with the increase in relative humidity is in agreement with the results obtained by Pandolf *et al.*[14] who showed that an increase in relative humidity levels place a higher degree of thermal strain on the cardiovascular system. The increased stress on the cardiovascular system may however also be a factor of metabolic rate. Meese *et al*.[15] found no significant increase in heart rate when light work (230 W) was performed at 29 WBGT.

The increased heat storage due to the increase in relative humidity level was clearly observed in the significant increase in rectal temperature and heart rate responses at 30 WBGT with an increase in relative humidity. This is indicative that increased thermal strain was experienced by the subjects at 30 WBGT with HH, compared to the LH condition.

Tolerance time also decreased significantly at 30 WBGT with the increase in relative humidity level from 30% to 70%. This clearly indicates that at 30 WBGT, an increase in humidity does result in increased heat storage and therefore a significant increase in thermal strain. The higher thermal strain might be due to a reduction in evaporation efficiency of the produced sweat because vapour pressure in the air at 30 WBGT HH approaches water vapour pressure next to the skin. It is therefore likely that thermal strain at 30 WBGT with increased humidity levels may be underestimated, primarily due to a reduction in sweat rate due to hidromeiosis[14] and rate of sweat evaporation.[2]

At 32 WBGT, a further increase in physiological stress was observed with the increase in relative humidity level from 30% to 70%. A significant increase in rectal temperature of 0.6°C ($p < 0.05$) was measured after only 45 minutes of exposure with the increase in relative humidity from 30% to 70%. A similar result was also measured by Kamon *et al.*[16] at 34.5 WBGT HH. In their study acclimatised subjects were used, with effect that an average rectal temperature of 38.3°C was measured after 105 minutes of exposure. In the current study with un-acclimatised subjects, all subjects reached their upper safety physiological criteria (39.0°C) well in advance of 105 minutes. The average rectal temperature at the end of exposure at 32 WBGT HH for the un-acclimatised subjects was 38.9°C. The difference in the core temperature results clearly indicates the protective role of heat acclimatisation to protect a worker against exercise induced hyperthermia.[6,7,17] The additional advantage of self pacing in combination with acclimatisation in an industrial setting can also be considered to protect workers against hyperthermia. Brake and Bates[18] recently illustrated the advantage of self pacing to protect mine workers against heat illnesses.

The reduction in average tolerance time from 279 minutes to 53 minutes with the increase in relative humidity level at 32 WBGT was significant ($p < 0.05$). This clearly indicated that the WBGT heat stress index underestimates the physiological stress at HH if compared to LH for a metabolic rate of 450 watts. To obtain a good estimate of the tolerance time of a population, the minimum tolerance time needs to be reported.[13] The first test subject was removed from exposure after only 30 minutes at 32 WBGT HH. The reason for the removal was a heart rate of 180 beats.min^{-1}, which was in agreement with the results of Iampietro and Goldman.[13] It is therefore a clear indication that 32 WBGT HH was very stressful for the sample used in the study.

The significant increase in sweat rate at 32 WBGT HH placed the test subjects at risk of dehydration as a result of the decreased evaporative capacity.[2,6] A decrease of 1.6% was measured in body mass with the increase in relative humidity from 30% to 70% at 32 WBGT. According to Strydom and Holdsworth[19] a significant reduction in physical work capacity may be evident with a decrease in body mass in excess of 1.5% during exposure to heat. This may result in a decline in productivity if work is to be completed in conditions similar to 32 WBGT HH for an eight hour shift.[8] It is therefore clear that not only the safety of the workers is threatened at 32 WBGT HH, but productivity can also be negatively affected.

The high correlation between rectal temperature and heart rate with the respective WBGT index values at low and high relative humidity is a good indicator that increased physiological strain correlated with an increase in WBGT heat stress index values. The increase in heart rate for 1°C increase in WBGT level was 1.6 and 3.0 beats.min^{-1} for the 30% and 70% relative humidity levels respectively, which accorded with the results of Pandolf *et al.*[14] Rectal temperature increased by 0.037°C and 0.114°C for a 1°C increase in WBGT at LH and HH respectively. The differences in terms of the rate at which rectal temperature increased at the different humidity levels results in the phenomenon that 27 WBGT HH will result in similar heat storage as 30 WBGT LH. The final predicted core temperature of 38.1°C at 30 WBGT LH is, however, in agreement with the ACGIH maximum recommended core temperature of 38.0°C for working in hot environments to prevent heat disorders.[20] Brake and Bates[18] also reported in a recent study that only 7% of mine workers who were allowed to pace themselves reached core temperatures above 38.2°C in similar environmental conditions. It can therefore be stated that 30 WBGT, the current recommended limit in the Environmental Regulations of the OHS Act, Act 85 of 1993[1] for working in hot environments, accurately reflects thermal strain in low humidity conditions but underestimates thermal strain in high humidity conditions. Furthermore, the ACGIH proposed limit of 26.5 WBGT for un-acclimatised workers completing moderate work at a work:rest schedule of 75% work:15% rest,[20] seems to be applicable for humid conditions. Our results indicate, however, that this may be very conservative in value for environments with low humidity levels.

The implication of this for South African industry is that the recommended WBGT index value of 30 as stipulated in the OHS Act, Act 85 of 1993[1], needs to be reduced with an index value of 3 in environments with high humidity levels. This is to correct for the additional heat strain as a result of the decline in evaporative capacity from produced sweat.

CONCLUSIONS

It can, therefore, be concluded that the WBGT heat stress index underestimates the heat strain placed on un-acclimatised subjects at WBGT values above 30 with a relative humidity level of 70%. Correction factors need to be used at such WBGT index values to reduce the thermal strain. A reduction of at least 3 in the WBGT index value is suggested for WBGT index values above 30 with high relative humidity levels.

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