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Heat stress assessment during intermittent work under different environmental conditions and clothing combinations of effective wet bulb globe temperature (WBGT)

Yongsuk Seo[a], **Jeffrey Powell**[a], **Amanda Strauch**[a], **Raymond Roberge**[a], **Glen P. Kenny**[b], **Jung-Hyun Kim**[a,c]

[a]Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, National Personal Protective Technology Laboratory, Pittsburgh, Pennsylvania

[b]Human and Environmental Physiological Research Unit, Faculty of Health Sciences, University of Ottawa, Ottawa, Ontario, Canada

[c]Department of Sports Medicine, College of Physical Education, Kyung Hee University, Yongin-si, Gyeonggi-do, South Korea

Abstract

This study examined whether different combinations of ambient temperature and relative humidity for the effective wet bulb globe temperature, in conjunction with two different levels of clothing adjustment factors, elicit a similar level of heat strain consistent with the current threshold limit value guidelines. Twelve healthy, physically active men performed four 15-min sessions of cycling at a fixed rate of metabolic heat production of 350 watts. Each trial was separated by a 15-min recovery period under four conditions: (1) Cotton coveralls + dry condition (WD: 45.5 °C dry-bulb, 15% relative humidity); (2) Cotton coveralls + humid condition (WH: 31 °C dry-bulb, 84% relative humidity); (3) Protective clothing + dry condition (PD: 30 °C dry-bulb, 15% relative humidity); and (4) Protective clothing + humid condition (PH: 20 °C dry-bulb, 80% relative humidity). Gloves (mining or chemical) and headgear (helmet or powered air-purifying respirator) were removed during recovery with hydration *ad libitum*. Rectal temperature (Tre), skin temperature (Tsk), physiological heat strain (PSI), perceptual heat strain (PeSI), and body heat content were calculated. At the end of the 2-hr trials, Tre remained below 38 °C and the magnitude of Tre elevation was not greater than 1 °C in all conditions (WD: 0.9, WH: 0.8, WH: 0.7, and PD:0.6 °C). However, Tsk was significantly increased by approximately 2.1 ± 0.8 °C across all conditions (all $p \leq 0.001$). The increase in Tsk was the highest in WD followed by PD, WH, and PH conditions (all $p \leq 0.001$). Although PSI and PeSI did not indicate severe heat strain during the 2-hr intermittent work period, PSI and PeSI were significantly increased over time ($p \leq 0.001$). This study showed that core temperature and heat strain indices (PSI and PeSI) increased similarly across the four conditions. However, given that core temperature increased continuously during the work session, it is likely that the American Conference of Governmental Industrial Hygienist's

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CONTACT Jung-Hyun Kim junghyun.kim@khu.ac.kr Department of Sports Medicine, College of Physical Education, Kyung Hee University, 1732 Deogyeong-daero, Giheung-gu, Yongin, 17104, South Korea.

TLV® upper limit core temperature of 38.0 °C may be surpassed during extended work periods under all conditions.

Keywords

Heat stress; intermittent work; threshold limit values; wet bulb globe temperature

Introduction

Heat-related injuries are relatively common in workplace injuries and may have an adverse impact on workplace accident rates, worker health, and productivity.[1] According to a recent study, there were 359 occupational heat-related fatalities between 2000 and 2010 in the United States, with the highest prevalence occurring in outdoor workers (e.g., agriculture, construction).[2] Global climate change is shifting weather patterns toward more frequent and severe heat waves, increasing the need for prevention efforts, especially for workers vulnerable to heat stress.[3]

While numerous heat stress indices exist, the American Conference of Governmental Industrial Hygienist (ACGIH®) Threshold Limit Values (TLVs®) are one of the more commonly utilized guidelines to protect workers from occupational heat stress.[4] The goal of TLVs is to limit workers' core temperature (Tc) increase under 1 °C and/or no greater than 38 °C in a standard 8-hr work shift. TLVs are determined based on two main factors: ambient conditions expressed in Wet Bulb Globe Temperature (WBGT; defined by ambient temperature, relative humidity (RH), and radiant heat for outdoor conditions)[4] and estimated metabolic rate of work, with further correction by clothing adjustment factor (CAF). These factors are used to assign a corresponding work and rest allocation (WRA) that ostensibly ensures the prevention of undue thermal strain.

One of the underlying assumptions for use of TLVs is that the level of heat stress is similar for different combinations of ambient temperature and relative humidity when WBGT remains unchanged. However, there remain conflicting results as to whether the level of thermal strain differs between hot/dry and warm/humid conditions when matched for the effective WBGT.[5–7] Noteworthy, a recent report found two different environments with the same WBGT elicited a similar change in body heat content measured by a whole-body direct air calorimeter (a device that can accurately and directly measure the amount of heat dissipated by the human body in a chamber).[8] These findings suggested that there may be a counterbalance between dry heat exchange and evaporative heat loss resulting in a similar net change in body heat content.[7] Workers' Tc response to any thermal condition confirmed that work at the assigned WRAs is presumably the same or, at least, consistent. However, Tc responses to different assigned WRAs following the TLV guidelines were found to be highly variable between different WRAs and individuals.[9] Meade et al.[9] also indicated a change in body heat content was not consistent among the 28 °C, 29 °C, 30 °C, and 31.5 °C of WBGT conditions, and a heat balance was not achieved during 2 hr of heat exposure, resulting in a continuous rise of Tc.

Physiological responses to wearing vapor-barrier protective clothing have been elucidated in previous studies.[10,11] The 2014 Ebola outbreak in West Africa brought attention to heat stress mitigation strategies in healthcare workers who wear protective clothing. An example is the TLV of limited-use vapor-barrier coveralls, which require the use of work-recovery allocations associated with an ambient temperature 11 °C lower than the prevailing WBGT (i.e., CAF of 11 °C).[12,13] It is uncertain whether wearing protective clothing with a CAF of 11 °C will affect heat strain between different ambient conditions of effective WBGT. Since sweat evaporation is impaired by the vapor-barrier layer of protective clothing, regardless of change in ambient vapor pressures, required temperature offsets may not sufficiently influence net body heat content between hot/dry and warm/humid conditions to be physiologically relevant. Additionally, it is not clear how the clothing adjustment factor, determined by human subject trials using a progressive heat stress protocol,[13] affects the wearers' thermal responses during intermittent work in hot ambient conditions. Thus, the purpose of this study was to compare whether work performed under dry and humid heat, for the effective WBGT (30 °C), would elicit a similar level of heat strain under the current TLV guidelines, while participants wore two different clothing ensembles requiring the application of different CAF.

The current study compared thermoregulatory responses and heat strain indices during moderate exercise intensity, while participants wore two different clothing types, cotton coveralls and a chemical protective garment, incorporating ACGIH TLVs recommended adjustment for work duration and clothing adjustment factor.

Methods

Participants

Participants were 12 healthy, physically active, non-smoking men (mean ± standard deviation; age 22.1 ± 1.6 years; height 179.8 ± 7.1 cm; weight 78.8 ± 12.4 kg; and VO_{2peak} 50.8 ± 9.7 ml/kg/min). Each participant completed written and verbal informed consent and passed a health screening by a U.S. licensed physician prior to study participation. All participants were not acclimated to the environmental test conditions prior to trial and were instructed to avoid alcohol, caffeine, and strenuous exercise for at least 24 hr. The study was approved by the National Institute for Occupational Safety and Health Institutional Review Board (protocol #:16-NPPTL-02).

Experimental design

Participants completed four experimental trials performed in a counterbalanced order to minimize order effect using a Latin square and each separated by at least 72 hr. Each trial consisted of four 15-min sessions of cycling at an average rate of 350 watts (W) metabolic heat production, each separated by a 15-min recovery. Prior to cycling, each participant donned work coveralls or protective clothing. Participants performed the exercise under both dry and humid heat equivalent to effective 30 °C WBGT. A fixed rate of heat production of 350 W was chosen to simulate moderate work intensity typical of tasks in mining and electrical utilities industries.[9,14] A work-to-rest allocation of 1:1 (15-min exercise and 15-min recovery × 4 cycles) was chosen based on the TLV guidelines for moderate intensity work in 30 °C WBGT conditions.[4] A 2-hr intermittent work period was used to represent the duration of a typical sustained work period occurring prior to, and following, a mid-morning break.[15] The four conditions were as follows:

1. Cotton coveralls + dry condition (WD): one-piece long-sleeve 100% cotton coverall (CC14PB, Red Kap, Pittsburgh, PA), hardhat (HiViz V-Gard, MSA The Safety Company, Cranberry Township, PA), and mining gloves (Illinois Glove Company, Northbrook, IL): assigned CAF of 0 °C WBGT (effective 30 °C WBGT: 45.5 °C dry-bulb, 15% RH).
2. Cotton coveralls + dry condition (WH): the same clothing and CAF as in condition WD (effective 30 °C WBGT: 31 °C dry-bulb, 84% RH).
3. Protective clothing + dry condition (PD): chemical resistant coverall vapor-barrier ensemble (Tychem QC, DuPont; Wilmington, DE), powered air-purifying respirator (3M Versaflo, 3M, Maplewood, MN), and chemical gloves (Solvex 37–676, Ansell, NJ): assigned CAF of 11 °C WBGT (effective 30 °C WBGT: 30 °C dry-bulb, 15% RH).
4. Protective clothing + humid condition (PH): the same clothing and CAF as in condition PD (effective 30 °C WBGT: 20 °C dry-bulb, 80% RH).

Procedure and Measurements

Upon completion of medical screenings, all participants performed a peak oxygen uptake (VO_{2peak}) test on a cycle ergometer (VIAsprint 150P, CareFusion, Hochberg, Germany) to determine a relative workload for the desired moderate work intensity (i.e., rate of metabolic heat production of 350 W). Participants started cycling at 20 watts and continued cycling through 25 watt increments every min until reaching volitional fatigue. Participants were instructed to maintain between 60 and 80 rotations per min throughout the cycling protocol. VO_{2peak} was measured with a TrueOne 2400 metabolic cart (Parvo Medics, Sandy, UT), while heart rate (HR) was constantly recorded with a Polar heart rate monitor (Polar RS800 CS, Polar Electro Oy, Kempele, Finland).

Volitional fatigue and the end of the VO_{2peak} were reached when the participants were no longer able to maintain pedaling cadence and or stopped cycling. Upon completion, VO_{2peak} was recorded along with maximum heart rate and final power output in Watts(W). Participants initially cycled at the predetermined workload with minute-by-minute intensity adjustments during the first 10 min of exercise to achieve the target metabolic heat production and therefore work intensity during experimental trials. Metabolic heat production was calculated as follows:

$$\frac{VO_2 \times \left(\left(\frac{RER-0.7}{0.3}\right) \times e_c\right) + \left(\left(\frac{1-RER}{0.3}\right) \times e_f\right)}{60} \tag{1}$$

where RER is respiratory exchange ratio, e_c is the caloric equivalent of a liter of oxygen when carbohydrates are oxidized (21.1kj), and e_f is the caloric equivalent of a liter of oxygen when fat is oxidized (19.6 kj).[16]

On the day of an experimental trial, all participants drank tap water (500 mL), inserted a rectal thermistor (REF-4491, YSI Temperature, Dayton, OH) 13 cm into their rectum, and were weighed seminude to the nearest 1.0 gram on a calibrated scale (Electronic scale-4450, GSE, Farmington Hills, MI) before and after exercise. Body mass loss was determined using the change in pre- to post-exercise seminude weight, the weight gained in all absorbent garments (clothing, glove, helmet, HR chest strap, towel, socks, and shoes), and the amount of water intake. Total body water loss (kg) was calculated as (post clothing weight – pre clothing weight) + (pre seminude weight – post seminude weight) + water intake. A heart rate monitor (Zephyr Technology Corporation, Annapolis, MD) and skin thermistors (2.5 diameter T-type copper/constantan; Concept Engineering; Old Saybrook, CT) were affixed with transparent dressing film (Tegaderm, 3M; St. Paul, MN) on the chest, shoulder, thigh, and calf of the left side of body. Weighted mean skin temperature (Tsk) was calculated as follows: chest (0.3) + shoulder (0.3) + thigh (0.2) + calf (0.2).[17] Using Tre and Tsk, mean body temperature (Tb) was calculated as Tb = Tre (0.9) × Tsk (0.1).[18] Body heat storage (S; kj) was calculated as S = ΔTb × m × c to examine the change in body heat content; where ΔTb refers to change in mean body temperature, m is the body mass (kg), and c is the average heat capacity of the body (3.49 kJ/kg/°C).

Following instrumentation with sensors and fully equipped, the participants changed into the assigned clothing (cotton work coverall or chemical protective clothing). Baseline measurements of Tre, Tsk, HR, rating of perceived exertion (RPE; 6 = no exertion at all, 20 = maximal exertion),[19] and thermal sensation (TS; 7 = neutral, 13 = unbearably hot)[20] were recorded while the participants sat for a 15-min stabilization period under a given condition. Using Tre, HR, RPE, and TS, the perceptual heat strain (PeSI) and physiological heat strain (PSI) were calculated as follows:[21]

$$PeSI = \left[5 \times \frac{(\mathrm{TS}_t - 7)}{6} + 5 \times \frac{(\mathrm{RPE}_t - 6)}{14}\right] \tag{2}$$

where $\mathrm{TS_t}$ refers to subjective scale of thermal sensation, 7 represents TS at rest (range from 7 to 13), $\mathrm{RPE_t}$ refers to subjective measurement of perceived exertion at the rating recorded, and 6 is RPE at rest.

$$PSI = \left[5 \times \frac{(\ \mathrm{Tre_t} - \mathrm{Tre_0})}{(39.5 - \mathrm{Tre_0})} + 5 \times \frac{(\mathrm{HR}_t - \mathrm{HR_0})}{(\mathrm{HR}_{max} - \mathrm{HR_0})}\right] \tag{3}$$

where $\mathrm{Tre_t}$ and $\mathrm{HR_t}$ represent values at the time of measurement, $\mathrm{Tre_0}$ and $\mathrm{HR_0}$ were resting Tre and HR, and $\mathrm{HR_{max}}$ is the maximal HR recorded during the $\mathrm{VO_{2peak}}$ test.

Scores of physiological and perceptual strain indices range from 0 to 10, with 0–2: no heat strain; 3–4: low heat strain; 5–6: moderate heat strain; 7–8: high heat strain; and 9–10: very high heat strain.[22]

Following baseline measurements, the participants performed four successive cycling exercise and recovery sessions for a total of 2 hr. Metabolic heat production of 350 W was confirmed during the first and third exercise sessions. The participants were permitted to remove gloves and headgear (hardhat and powered air-purifying respirator) and drink water *ad libitum* during each recovery period. The Tre, Tsk, and HR measures were recorded continuously throughout the trials and averaged for the last min of each time point. The subjective ratings of RPE and TS were assessed simultaneously with physiological measurements at the last min of each stage.

Statistical analysis

All experimental data were analyzed using the Statistical Package for Social Science software (SPSS version 19.0, IBM Corp., Armonk, NY). Two-way (condition by time) repeated measure analysis of variance (ANOVA) was conducted to evaluate the physiological and subjective measurements among four different combinations of ambient and clothing conditions. When ANOVA indicated a significant main effect and interaction, post hoc pair-wise comparison with least significant differences (LSD) was used to identify the difference among conditions at the end of each stage. All data were presented as 1-min average values (mean ± SD) and reported at the 15-min time point of each stage across all conditions. The alpha level was set at $p \leq 0.05$.

Results

Workload and metabolic heat production

The rate of metabolic heat production was not significantly different among conditions ($F = 0.062$, $p = 0.980$). Consequently, there were no differences in workload (76.7 ± 13.5 W, $F = 0.107$, $p = 0.956$).

Water intake and weight loss

Whole-body water loss was significantly lower in PH (0.8 ± 0.3 kg) compared to WH (1.6 ± 0.5 kg), PD (1.7 ± 0.5 kg), and WD (1.8 ± 0.6 kg) (all $p \leq 0.001$). The amount of water intake was greater with greater body water loss. The average amount of water intake was significantly higher in WD (1194 ± 273 mL) than both PD (1028 ± 358 mL, $p = 0.041$) and PH (673 ± 268 mL, $p \leq 0.001$) but not WH (1030 ± 358 mL, $p = 0.219$). Furthermore, water intake was significantly higher in PD than PH ($p = 0.012$). The average rates of water intake over total body water loss were 74 ± 28% (WD), 62 ± 36% (WH), 60 ± 15% (PD), and 91 ± 55% (PH). The average fluid replacement was approximately 70 ± 39% of body fluid loss with large individual variability during the 120-min trials.

Thermoregulatory response

Rectal temperature (Tre) did not differ among conditions ($F = 0.91$, $p = 0.448$), but increased over time ($F = 69.269$, $p \leq 0.001$); although, there was no significant condition by time interaction ($F = 1.35$, $p = 0.146$). The rate of change in Tre did not differ among conditions ($F = 1.73$, $p = 0.182$), but increased over time compared to the prior stage ($F = 18.6$, $p \leq 0.01$). There was no significant condition by time interaction ($F = 0.88$, $p = 0.607$), indicating that Tre was significantly increased throughout the 120 min of trials about 0.8 ± 0.3 °C across all conditions (Table 1 and Figure 1A).

Mean Tsk demonstrated a significant difference among conditions ($F = 60.3$, $p = \leq 0.001$), time ($F = 59.8$, $p \leq 0.001$), and interaction ($F = 23.9$, $p \leq 0.001$). The Tsk also gradually increased throughout the 2-hr trials by an average of 2.1 ± 0.8 °C across all conditions. The Tsk was significantly higher in WD (36.0 ± 0.9 °C) compared to WH (35.0 ± 0.8 °C), PD (35.3 ± 0.8 °C), and PH conditions (33.8 ± 0.9 °C) ($p \leq 0.001$, all) (Figure 1B). The Tsk was significantly higher in PD than WH ($p = 0.004$) and PH ($p \leq 0.001$). In addition, Tsk was significantly higher in WH than PH ($p \leq 0.001$).

The cumulative change in body heat content during each exercise and recovery cycle showed a significant difference among conditions ($F = 3.91$, $p = 0.018$). However, there were no significant changes over time ($F = 0.91$, $p = 0.449$) and no significant condition by time interactions ($F = 0.76$, $p = 0.656$). In particular, change in average body heat content was shown to be lowest in PH (81.0 ± 49.0 kJ) compared to WD (132.0 ± 70.4 kJ), WH (119.2 ± 47.3 kJ), and PD (117.6 ± 58.6 kJ) (all $p \leq 0.05$) (Figure 2).

Heat strain indices

Physiological strain index during recovery did not differ among conditions ($F = 1.83$, $p = 0.164$), but significantly increased over time ($F = 58.2$, $p \leq 0.001$). There was no significant condition by time interaction ($F = 1.75$, $p = 0.09$). PSI during recovery increased through each of the four recovery periods (all $p \leq 0.001$) (Table 2). PSI during exercise was significantly different among conditions ($F = 4.39$, $p = 0.011$), time ($F = 80.2$, $p \leq 0.001$), and condition by time interaction ($F = 3.69$, $p = 0.001$). PSI was greater in WD than WH ($p = 0.008$) and PH ($p = 0.006$). PSI significantly increased over the four successive exercise sessions (all $p \leq 0.001$) (Table 2).

Perceptual strain index during recovery demonstrated a statistically significant difference among conditions ($F = 10.6$, $P \leq 0.001$), time ($F = 12.1$, $p \leq 0.001$), and condition by time interaction ($F = 3.28$, $p \leq 0.001$). The PeSI during recovery was highest in WD, followed by PD ($p = 0.005$), WH ($p = 0.022$), and PH conditions ($p = 0.001$). The PeSI during the first recovery was significantly lower than subsequent recoveries (all $p \leq 0.002$). The PeSI during exercise indicated a significant difference among conditions ($F = 5.90$, $p = 0.003$), time ($F = 20.1$, $p \leq 0.001$), but not interaction ($F = 1.48$, $p =0.167$). The PeSI during exercise was significantly lower in PH than WD ($p = 0.012$), WH ($p = 0.043$), and PD ($p = 0.007$) (Table 3).

Discussion

This study examined the thermoregulatory responses and heat strain indices during moderate intensity, intermittent work, performed in dry and humid heat of equivalent effective WBGT (i.e., 30 °C) while wearing two different types of clothing (common work coveralls and a chemical protective garment) incorporating ACGIH TLVs recommended adjustments for work duration and clothing insulation. This study explored the application of the ACGIH TLV guidelines for these different work scenarios to determine if different clothing would result in similar or different levels of physiological strain and maintain body temperature at or below 38 °C. We showed that the increase in Tre was similar among clothing conditions, such that core temperature did not exceed 38 °C or increase beyond 1 °C during the 120-min intermittent work protocol. However, successively greater increase was seen in the Tre with each exercise/recovery cycle such that the upper limit of 38 °C might likely be exceeded with a longer work period. Indeed, the Tre exceeded TLV upper limits of 38 °C in a number of participants, including two, three, two, and one in the WD, WH, PD, and PH conditions, respectively. Furthermore, the Tre increased beyond 1 °C for four, two, two, and two participants in the WD, WH, PD, and PH conditions, respectively, at the end of 2 hr of intermittent work. While similar responses in PSI, Tre, and Tsk were observed across conditions, a greater increase in PeSI was observed for the high heat (i.e., air temperature) conditions despite the similar levels of heat stress and, therefore, effective WBGT, among conditions.

To limit thermal strain, under the ACGHI TLVs, combinations of work/recovery allocations, environmental conditions for a given work intensity, and clothing design should allow workers to achieve heat balance to maintain a stable core temperature. In the current study, the rate of environmental and/or metabolic heat gain should have been matched by the rate of total heat loss from the body (i.e., heat balance), to stabilize core temperature and prevent heat strain (defined as exceeding 38.0 °C for extended periods). However, we observed a continuous increase in core temperature during the work session that likely would have surpassed the ACGIH TLV upper limit core temperature of 38.0 °C during extended work periods under all conditions. This study employed a fixed rate of metabolic heat production of 350 W, equivalent to a moderate intensity work effort,[23] which is representative of occupations such as the mining and electrical utilities industries.[9,14] Furthermore, as defined by the ACGIH TLV guidelines, under given ambient conditions and work intensity, a 1:1 ratio of work-to-rest allocation (15-min cycling followed by a 15-min recovery) was used. While the average Tc in all conditions was maintained below 38 °C and increased within 1 °C, the study found a positive rate of change in Tre. Tre increased by approximately 0.2 °C between the third and fourth exercise sessions for each of the four conditions (Table 1). Based on this observation, it is likely that, without lowering the work effort or extending the recovery period, core temperature would exceed the TLVs recommended upper limit of 38.0 °C. These results are in agreement with a previous study[9] utilizing various work-rest allocations: continuous cycling (no WRA intervals), WRA of 3:1 (15-min cycling and 5-min resting), WRA of 1:1 (15-min cycling and 15-min resting), and WRA of 1:3 (15-min cycling and 45-min resting) for 120 min in WBGT of 28 °C, 29 °C, 30 °C, and 31.5 °C, respectively, based on the ACGIH TLV recommendations for moderate intensity work. As in the present study, Meade et al. [9] showed that although average Tre did not exceed 38.0 °C, heat balance was not achieved during exercise under all ambient conditions assessed. It was reported that the upper limit core temperature of 38.0 °C would be surpassed in some workers during extended work shifts (i.e., ≥4 hr) performed under these guidelines.[9] Another study evaluating the heat balance during intermittent exercise (six 15-min exercise and 5-min rest) in hot/dry (46 °C, 10% RH) and warm/wet (33 °C, 60% RH) conditions equivalent to 29 °C WBGT, showed similar increases in Tre (and change in body heat content also assessed by direct calorimetry) at the end of a 120-min intermittent exercise protocol in both hot/dry and warm/wet conditions.[7]As defined by the ACGIH TLV,[4] a clothing adjustment factor of 11 °C was applied to effective WBGT for both PD and PH conditions in order to match the level of heat stress of different clothing types, therefore equivalent to the cotton coveralls. However, no adjustment (i.e., 0 °C) was necessary for both WD and WH. These adjustments are supported by prior work.[24,25] For example, previous studies examined the effects of five clothing ensembles at three metabolic rates (low, moderate, and high)[25] and three relative humidity levels (20%, 50%, and 70%)[24] on the clothing adjust factor and concluded that a clothing adjustment factor of 10 °C for garments containing a vapor-barrier is appropriate. Taken together, these findings show that the application of the clothing adjustment factors under the conditions tested (i.e., level of work effort and ambient conditions) elicited the same level of thermal strain. Despite the comparable results, this study suggests that there may be an important shortcoming in the guidelines in that core temperature would likely exceed the ACGIH TLV upper limit of 38.0 °C for extended work periods, placing workers at a greater risk of developing a heat-related injury. As responses were similar across the different clothing conditions, adjustments in the work-rest allocations for moderate intensity work would be necessary to minimize potentially dangerous increases in core temperature during prolonged work in the heat.

Although overall the PSI score indicated a low to moderate heat strain, PSI was significantly increased during both exercise and recovery across all conditions. When the PSI was broken down into components of exercise and recovery, PSI was significantly higher in WD compared to WH and PH conditions during exercise, but did not differ during recovery. This result is in agreement with previous studies, indicating that dry-heat conditions induce higher levels of heat strain under equivalent WBGT of 32 °C due to a greater increase in Tre and HR[5] as well as a greater increase in Tsk and sweat rate.[26] However, other studies did not observe differences in the PSI under different environmental conditions with equivalent WBGT.[6,9] Although WBGT is widely utilized to assess environmental conditions and heat stress, WBGT inadequately reflects humidity and air movement.[27] The differences in air dynamics (velocity and movement) might be responsible for inconsistent results seen in previous studies. In addition to PSI, PeSI scores indicated no heat (0–2) strain to low heat strain (3–4) and PeSI was significantly increased over time during both exercise and recovery. However, it is important to note that the highest score of PeSI was seen in the WD condition compared to WH, PD, and PH, whereas the PH condition indicated the lowest PeSI score.

It has been reported that a higher level of environmental humidity reduces evaporative cooling from sweating and impairs physiological and perceptual responses. This is because evaporative cooling is the primary method of heat transfer from the body to the environment.[28] Previous studies,[29,30] which compared whole-body heat dissipation during moderate intensity work in dry heat vs. humid heat conditions, showed that increasing ambient humidity reduces heat loss capacity resulting in greater heat storage in young adults. However, this response is worse in older adults due to age-related impairments in heat dissipation.[29,30] In the present study, however, the higher PeSI score in WD is attributed to a higher ambient temperature and independent effect of relative humidity since the highest Tsk was observed in WD. These results support those from a previous study indicating that thermal sensation is related to skin and ambient temperature.[5] It is generally accepted that Tsk mostly relies on ambient air temperature and duration of exposure.[31] High Tsk impairs perception of exertion at a given exercise intensity and thermal sensation.[32,33] Indeed, cutaneous thermoreceptors provide thermal information for changes in thermal perception and thermobehavioral adjustments.[33] Along with thermal perception, heat content seems to be influenced by both ambient temperature and Tsk because the body gains heat from the environment when Tsk is lower than ambient air temperature.[34]

Limitations

This study has limitations that should be considered for generalization and interpretation. First, this study utilized a small sample of young, healthy, nonheat-acclimated, young physically active men that may not generalize well to others. Therefore, future studies are needed to explore thermoregulatory responses in larger and more diverse populations, such as older adults or women who represent a growing segment of the workforce.[35] Studies show the actual level of heat strain experienced by an individual in response to a given heat stress may vary remarkably due to interindividual factors (e.g., age, sex, chronic disease) [36,37] and intraindividual factors both within (e.g., caffeine, alcohol and medication use, fitness, acclimation and hydration state)[38–40] and beyond the workers' control (e.g., consecutive work shifts, shift duration, illness).[37] These individual variabilities can lead to over- or under-protection of workers from heat-related illness when employing the ACGIH TLV guidelines. Additionally, it is necessary to consider that a longer duration of exposure would be necessary to verify the time-dependent changes in core temperature and determine appropriate work exposure limits that would be necessary to prevent potentially dangerous increases in core temperature.

Conclusion

This study has indicated that the magnitude of increase in core temperature was similar across all four of the clothing and environmental conditions tested. Core temperature increased significantly with each successive exercise/recovery cycle such that core temperature would have exceeded the safe limit defined by the ACGIH TLV guidelines of 38 °C with a longer work period. Left unchecked, this progressive increase in core temperature could place workers at risk of experiencing potentially dangerous increases in core temperature during a normal 8-hr work shift. Tsk and heat strain indices (PSI and PeSI) were influenced by air temperature rather than WBGT. Therefore, evaluation of WBGT with additional factors (e.g., absolute humidity) would improve WBGT and TLV guidelines and provide better protection for occupational workers in the heat.

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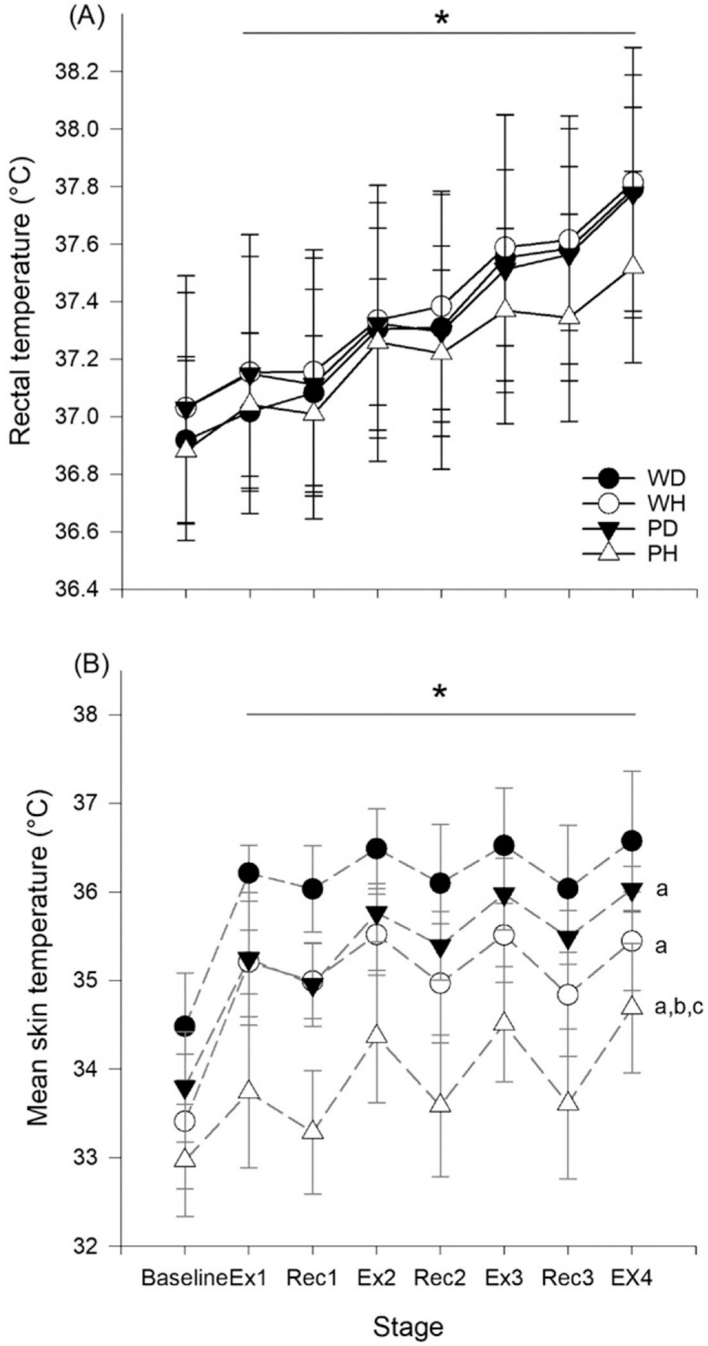

Figure 1.

(A) Rectal temperature and (B) mean skin temperature during intermittent exercise (Ex) and recovery (Rec) under four different conditions. Values are mean ± standard deviation. WD: standard work clothing + dry condition; WH: standard work clothing + humid condition; PD: protective clothing + dry condition; PH: protective clothing + humid condition. $^*p \leq 0.05$ vs. Baseline; $^a p \leq 0.05$ vs. WD; $^b p \leq 0.05$ vs. WH; $^c p \leq 0.05$ vs. PD.

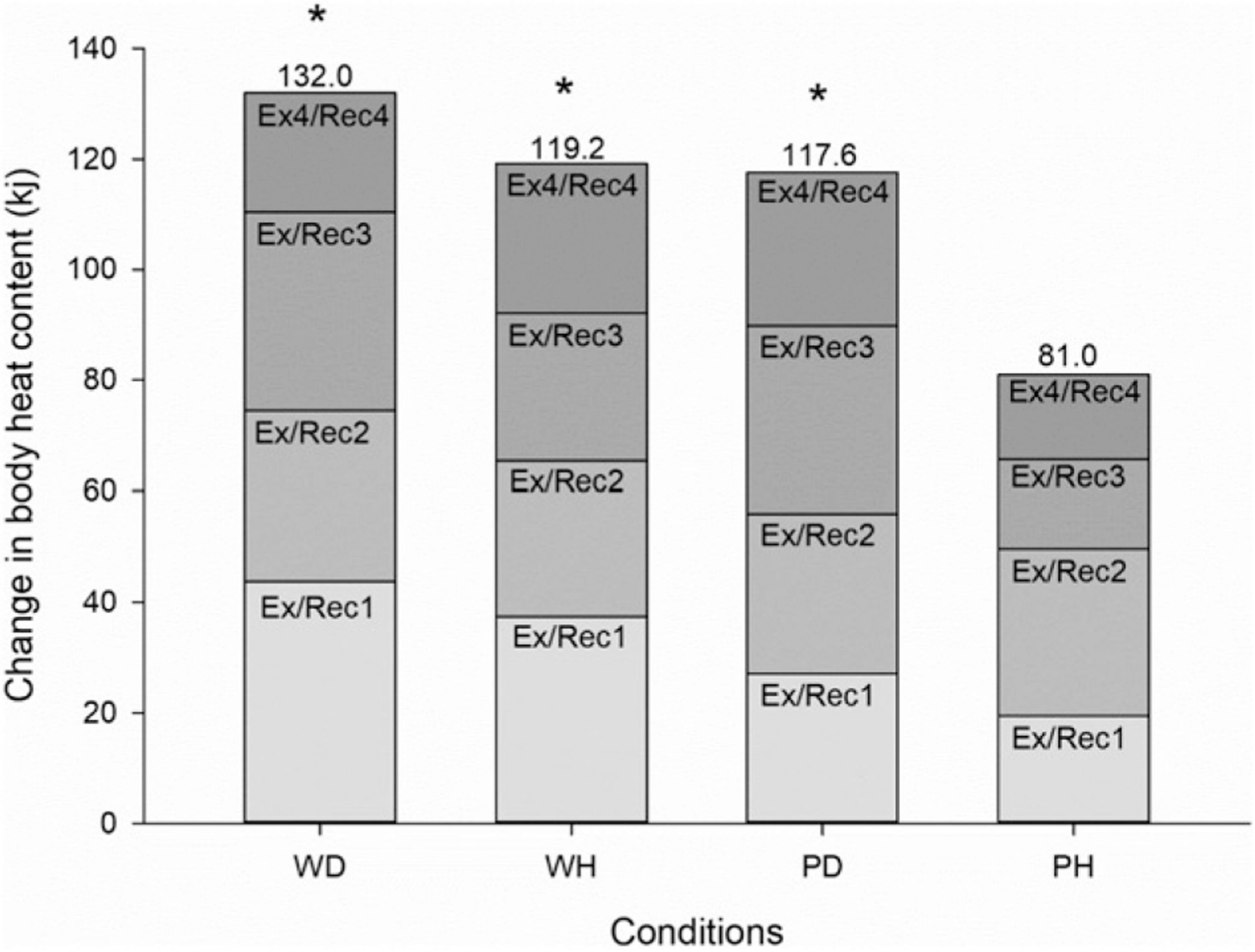

Figure 2.

Cumulative change in body heat content during four exercise (Ex)/recovery (Rec) cycles. The period of each Ex/Rec cycle is 30 min (a work-to-rest ratio of 1:1) for 120 min. Values are mean ± standard deviation. WD: standard work clothing + dry condition; WH: standard work clothing + humid condition; PD: protective clothing + dry condition; PH: protective clothing + humid condition. $*p \leq 0.05$ vs. PH.

Table 1.

Rate of change in rectal temperature during four exercise (Ex)/recovery (Rec) cycles under four different conditions (°C).

	Ex1	Rec1	Ex2	Rec2	Ex3	Rec3	Ex4
WD	0.1±0.1	0.1±0.2	0.2±0.1*	0.0±0.2	0.2±0.1*	0.0±0.2	0.2±0.1*
WH	0.1±0.1	0.0±0.1*	0.2±0.1	0.0±0.1*	0.2±0.1*	0.0±0.1*	0.2±0.0*
PD	0.1±01	0.0±0.1*	0.2±0.1	0.0±0.1*	0.2±0.2	0.1±0.2	0.2±0.1
PH	0.2±0.2	0.0±0.1*	0.2±0.2	0.0±0.1*	0.1±0.1	0.0±0.1*	0.2±0.1

Values are mean ± standard deviation.

WD: standard work clothing + dry condition; WH: standard work clothing + humid condition; PD: protective clothing + dry condition; PH: protective clothing + humid condition.

[*] Significant difference compared to prior stage ($p \leq 0.05$).

Table 2.

Physiological strain index during intermittent exercise and recovery under four different conditions.

	Baseline	Rec1	Rec2	Rec3
WD	0.0 ± 0.0	0.9 ±0.5[*]	1.4 ±0.5[*]	2.2 ± 0.6[*]
WH	0.0 ±0.0	0.6 ±0.4[*]	1.2 ± 0.7[*]	1.6 ± 0.8[*]
PD	0.0 ±0.0	0.4 ± 0.9	1.0 ± 1.3[*]	1.7 ± 3.8[*]
PH	0.0 ±0.0	0.5 ± 0.7[*]	0.8 ±0.8[*]	1.3± 1.0[*]
	Ex1	**Ex2**	**Ex3**	**Ex4**
WD	1.9 ±0.9	2.8±0.9[†]	3.5 ± 0.9[†]	4.1 ± 0.9[†]
WH	1.5 ±0.9[‡]	2.3 ± 0.9[†,‡]	2.9 ± 1.3[†,‡]	3.8 ± 1.1[†]
PD	1.9 ± 0.9[§]	2.5 ± 1.1[†]	3.1 ± 1.3[†]	3.8 ± 1.3[†]
PH	1.8 ±0.9	2.2 ± 0.9[†]	2.5 ± 1.0[†,‡,‖]	3.1 ± 1.0[†,‡,§,‖]

Values are mean ± SD. WD: standard work clothing + dry condition; WH: standard work clothing + humid condition; PD: protective clothing + dry condition; PH: protective clothing + humid condition.

[*] p ≤ 0.05 vs. Baseline at each condition;

[†] p ≤ 0.05 vs. Ex1 at each conditions;

[‡] p ≤ 0.05 vs. WD;

[§] p ≤ 0.05 vs. WH;

[‖] p ≤ 0.05 vs. PD.

Table 3.

Perceptual heat strain index during intermittent exercise and recovery under four different conditions.

	Baseline	Rec1	Rec2	Rec3
WD	0.2 ± 0.5	1.3 ± 1.0[*]	1.6 ± 0.8[†]	1.8 ± 0.9[†]
WH	0.3 ± 0.4	1.0 ± 0.6[†,‡]	1.1 ± 0.9[†,‡]	1.1 ± 0.8[†]
PD	0.4 ± 0.6	0.8 ±0.7	1.1 ± 0.8[†,‡]	1.2 ± 1.3[†]
PH	0.2 ±0.5	0.5 ± 0.7[†]	0.8±0.9[†,‡]	0.8 ± 0.9[†,‡]
	Ex1	**Ex2**	**Ex3**	**Ex4**
WD	2.9 ±0.4[*]	3.6 ±0.7[*]	3.9 ±0.9[*]	4.3 ±0.9[*]
WH	2.7 ±0.8[*,§]	3.5 ± 0.7[*,§]	3.8±0.8[*,§]	3.8 ±0.9[*]
PD	3.0 ± 0.8[*,‖]	3.4 ± 1.0[*]	4.2 ± 1.0[*]	4.4 ± 1.4[*]
PH	2.1 ± 1.0[*,§,#]	2.6 ± 1.4[*,§]	2.9 ± 1.5[*,§,#]	3.1 ± 1.5[†,§,‖,#]

Values are mean ± SD. WD: standard work clothing + dry condition; WH: standard work clothing + humid condition; PD: protective clothing + dry condition; PH: protective clothing + humid condition.

[*] p ≤ 0.05 vs. Baseline;

[†] p ≤ 0.05 vs. Baseline at each conditions;

[‡] p ≤ 0.05 vs. WD,

[§] p ≤ 0.05 vs. WD;

[‖] p ≤ 0.05 vs. WH;

[#] p ≤ 0.05 vs. PD.