Estimating Occupational Heat Exposure From Personal Sampling of Public Works Employees in Birmingham, Alabama

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Objective: This study investigated whether using thermometers clipped on workers' shoes would result in different heat exposure estimation and work–rest schedules compared with using area-level meteorological data alone. **Methods:** Alabama workers ($n = 51$) were individually monitored using thermometers on shoes. Wet bulb globe temperature (WBGT) was estimated using thermometer temperatures (WBGT [personal]) or nearby weather station temperatures (WBGT [WS]). Work–rest schedules were determined from WBGT, clothing, and hourly metabolic rates estimated from self-reported tasks and bodyweight. **Results:** The percent of hours exceeding the threshold limit value (TLV®, ACGIH, Cincinnati, OH) were estimated at 47.8% using WBGT (personal) versus 42.1% using WBGT (WS). For work–rest recommendations, more hours fell into the most protective schedule (0 to 15 min work/45 to 60 min rest) using WBGT (personal) versus WBGT (WS) (17.4% vs 14.4%). **Conclusions:** Temperatures from wearable thermometers, together with meteorological data, can serve as an additional method to identify occupational heat stress exposure and recommend work–rest schedules.

Keywords: exposure, heat-related illness, occupational heat stress, outdoor workers, temperature, threshold limit value, wet bulb globe temperature, work–rest schedules

Occupational heat stress puts workers at risk for illnesses such as heat stroke, heat exhaustion, heat cramps, or heat rashes. According to the Bureau of Labor Statistics, overexposure to heat caused 783 deaths and 69,374 serious injuries among US workers between 1992 and 2016.[1] Most of the heat-related deaths and illnesses can be avoided by simply identifying the risks and taking appropriate precautions.[2] In 2016, The National Institute for Occupational Safety and Health (NIOSH) published the Criteria for a Recommended Standard: Occupational Exposure to Heat and Hot Environments, which provides detailed guidance for preventing heat-related illnesses and injuries.[3] In order to implement NIOSH heat stress criteria and initiate robust protective measurements for workers, accurate exposure assessment is required.

Core body temperature measurement is a direct indicator of risk for heat-related illnesses (HRIs). However, the existing core body temperature measurement methods, including oral, rectal, and esophageal temperatures, suffer shortcomings including inaccuracy, invasiveness, inconvenience, and cost.[4] Intestinal temperature via wireless disposable ingestible thermometers (eg, CorTemp Sensor) has been shown to be an acceptable surrogate of core body temperature,[4] and these ingestible thermometers have been used to collect continuous and real-time data in recent occupational epidemiology studies.[5,6] Its limitations include potential measurement disturbance by hot/cold beverage consumption, requirement of a costly separate data recorder, and varied measuring time before being excreted from the body.[5] Moreover, it is not practical to measure core body temperature continuously in a large number of workers who may be at risk of overheating. Therefore, improving methods using environmental conditions to estimate personal heat exposure is needed.

The threshold limit value (TLV®, ACGIH, Cincinnati, OH) is the ambient wet bulb globe temperature (WBGT) at which there is a heat hazard present for an acclimatized worker who has already physiologically adapted to a hot environment through repeated exposures.[7] Once TLV® is reached, controls are needed to prevent heat-related diseases, whether through environmental factors or workload. Controls include work–rest schedules, shade, and hydration.[7] The WBGT index is calculated from air temperature, black globe temperature/solar radiation, dew point temperature/relative humidity, and wind speed.[8,9] All these meteorological data influence heat exposure or the ability of the human body to dissipate heat through sweat evaporation.[2,10] The combination of WBGT, work clothing, and estimated internal generation of heat (metabolic rate) based on the strenuousness of the work task is commonly used to recommend an hourly work–rest schedule to protect workers from HRIs.[3,7]

While current practices use area-level meteorological data to estimate occupational heat stress exposure, these estimates likely do not reflect the actual exposure experienced by workers. Urban workplace conditions can be significantly different from nearby weather stations.[8] It is possible that outdoor workers would move between indoor and outdoor environments, and outdoor workers may move through different neighborhood level microclimates while at work, which would not be captured by a stationary weather station. We hypothesized that thermometers colocated with workers will result in different estimates of heat exposure. To test this hypothesis, we first calculated differences in person-work hours above the TLV® using temperature measurements either from thermometers colocated with outdoor workers or the nearest weather station to the workplace. Next, we calculated differences in the recommended work–rest schedules based on the estimated WBGT index from the nearest weather station or thermometers colocated with workers.

METHODS

Study Populations

Participants ($N = 21$ in 2012 and $N = 32$ in 2017) were recruited by community partner organization Friends of West End via flyers, handouts, and word of mouth at their employment locations, City of Birmingham Parks and Recreation Department, Birmingham, AL. Their typical work schedule was 6 am to 2 pm local time, Monday to Friday, performing general landscape maintenance, such as cutting grass, weeding, and planting. Potential

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participants filled out a screening questionnaire and were invited to come to a recruitment session if they met the screening criteria. Exclusion criteria included having medical conditions or taking medication that could prevent them from spending time outdoors or being out of town or on vacation during the study period. Potential participants attended an informational enrollment session, provided written consent, and filled out demographic and employment questionnaires. Height and weight were collected using a Befour Inc. Model No. PS660 scale and a fold-up height stick and body composition measurements were collected using a Tanita BC-553 portable body composition scale. Participants in 2012 recorded their hourly tasks with the specification of indoors or outdoors in a daily log. Participants in 2017 were asked to record outdoor activities that were over 30 minutes. The protocol for the 2012 or 2017 study was reviewed and approved by the Institutional Review Boards at the University of Alabama at Birmingham (UAB) and Virginia Polytechnic Institute and State University (VT), respectively (UAB Protocol No. X120513012 and VT Protocol No. 15–761).

Temperature Measurement From Thermometers Colocated With Participants

Each participant was instructed to clip a small thermometer to one of his or her shoes for the duration of the 7 days study period. In 2012, HOBO Pendant® (Onset Computer Corp, Bourne, MA) # UA-002–64 temperature/light data loggers were used. These monitors recorded temperature readings every 1 minute for 7 days, 24 hours a day. The HOBO Pendant® monitor records temperatures ranging from 0 to 50 °C with an accuracy of ±0.53 °C.[11] The solar radiation shield was off for all participants in 2012 to capture light intensity measurements. In 2017, iButton® (Maxim Integrated, San Jose, CA) devices (model No. DS1922L) were clipped facing down to avoid direct sunlight. iButton® is a computer chip enclosed in a 16 mm thick stainless steel can. The recording interval was every 5 minutes. iButton® DS1922L has a temperature resolution of ±0.5 °C from −10 to +65 °C with an operating temperature range from −40 to +85 °C.[12] At turn-in sessions, data from HOBO Pendant® and iButton® sensors were downloaded and a printout of individual results was given to participants. Data were stored on password-protected computers for subsequent analysis.

Meteorological Data

The Birmingham International Airport Weather Station is the closest weather station to the workplace of participants. Meteorological data, including air temperature, dew point temperature, and wind speed were collected from this weather station from the National Climate Data Center Surface Data, Hourly Global dataset (DS3505) (http://cdo.ncdc.noaa.gov). Hourly averaged solar radiation was collected from GIOVANNI database at NASA (https://giovanni.gsfc.nasa.gov).

Data Analysis

Data Organization and Inclusion/Exclusion

Because this analysis focuses on occupational heat exposure, only data collected during work hours (between 6 am and 2 pm), Monday to Friday were included. For the 21 HOBO Pendant® devices in 2012, one data logger was lost and another was not readable upon return, leaving 19 devices intact with temperature data. Three 2012 participants (out of a total of 21) had 1 day off between Monday and Friday individually, and temperature data on these 3 days were excluded. Additionally, three participants in 2012 worked on a Saturday, and data on these 3 days were included.

To address the possibility that solar radiation may increase temperatures measured from thermometers clipped to participants' shoes in certain positions and points in time when they were outdoors, upper outliers were identified in the 5-minute interval temperature measurements using median absolute deviation[13] and removed in subsequent analyses (413 out of 8028 in 2012 and 559 out of 13,824 in 2017). The remaining 20,880 temperature measurements were hourly averaged for WBGT index calculation. Analyses with outliers intact were also performed and are presented in supplemental material.

Calculating WBGT Index

Outdoor WBGT

The calculation of outdoor WBGT is[3]

$$\mathrm{WBGT_{outdoor}} = 0.7T_{nwb} + 0.2T_g + 0.1T_a$$

where T_a = air temperature, T_{nwb} = natural wet bulb temperature, T_g = globe thermometer temperature. Because T_g measurement requires special equipment which is not used at weather stations, we used the method of Liljegren et al[14] to estimate T_g for outdoor WBGT estimations. A $\mathrm{WBGT_{outdoor}}$ (WS) index for each person-work hour was calculated from meteorological data collected at the Birmingham International Airport weather station (WS) including air temperature, dew point temperature, wind speed from the weather station, and hourly averaged solar radiation from NASA. This was compared with a $\mathrm{WBGT_{outdoor}}$ (personal) index calculated using air temperatures recorded from thermometers clipped to participants' shoes and all other variables from the WS. Since the WBGT index calculation method used in this study requires the ambient air temperature to be greater than dew point temperature, 23 (2012 data) and 27 (2017 data) person-work hours were excluded from analysis. WS temperatures from the same hours were also excluded since our main goal is to compare WBGT (personal) and WBGT (WS) in the same time range. Therefore, temperatures from 813 (2012) and 1122 (2017) person-work hours were used in the final analysis.

The same amount of hourly solar radiation was applied in the $\mathrm{WBGT_{outdoor}}$ (personal) as for $\mathrm{WBGT_{outdoor}}$ (WS) for same person-work hour. In order to examine the effect of the integration of solar radiation into personally measured temperature, WBGT (personal-no solar addition) was calculated, where solar radiation was set to a default value of −99 W/m^2, that is, no solar radiation was added into WBGT calculation, and the black globe temperature was equal to the temperature measured by thermometers colocated with participants. All participants were assumed to be wearing ordinary work clothes during the data collection period, and the clothing adjustment factor for WBGT was 0 °C.[15] The WBGT (WS) or WBGT (personal) discussed in this study is equal to $\mathrm{WBGT_{effective}}$ (WS) or $\mathrm{WBGT_{effective}}$ (personal), respectively.

Indoor WBGT

The calculation of indoor WBGT is[3]

$$\mathrm{WBGT_{indoor}} = 0.7T_{nwb} + 0.3T_g$$

The method by Bernard and Pourmoghani[16] was used for indoor WBGT calculation. A $\mathrm{WBGT_{indoor}}$ (WS) was calculated from air temperature, dew point temperature collected at the Birmingham International Airport WS, and a fixed wind speed of 1 m/s. The 1 m/s wind speed indoor was based on the assumption that body movement indoors generates air flow over the skin so that ''wind speed'' on the skin would never be zero.[9] This was compared with a $\mathrm{WBGT_{indoor}}$ (personal) index calculated using air temperatures from thermometers clipped to participants' shoes. The Excel heat Stress Calculator based on these two methods was used from the Climate CHIP website (http://www.climatechip.org/excel-wbgt-calculator).

$\mathrm{WBGT_{outdoor}}$ (WS) and $\mathrm{WBGT_{indoor}}$ (WS), $\mathrm{WBGT_{outdoor}}$ (personal) and $\mathrm{WBGT_{indoor}}$ (personal) were combined as WBGT (WS) and WBGT (personal), respectively.

Calculating Weight Adjusted Heat Stress TLV® With Estimated Metabolic Rates

A decision tree was created and used to replace missing data and process conflicting data in the self-reported hourly tasks reported in daily logs from 2012 participants (see Figure, Supplementary Digital Content 1, http://links.lww.com/JOM/A537, which presents the decision tree for replacing missing data in the hourly activity log in 2012). An hourly metabolic rate for each person-work hour was estimated based on the self-reported tasks in 2012, the American Conference of Governmental Industrial Hygienists (ACGIH) metabolic rate scale (see Table, Supplementary Digital Content 2, http://links.lww.com/JOM/A538, which presents the study participant's estimated metabolic rates and corresponding codes for activity based on the logs filled out by each participant in 2012)[7,17] and the General Physical Activities Defined by the Level of Intensity documentation by Centers for Disease Control and Prevention.[17] Since there were no hourly logs from participants in 2017, their tasks during work hours were estimated as similar to the tasks performed in 2012. For better comparability between study years, each participant in 2017 was matched to a randomly selected participant in 2012 and adopted the standard human (a representative human with a body weight of 70 kg and a body surface area of 1.8 m^2. Both men and women adapt well to heat exposure, and there are no significant differences between the sexes due to similar physiological capacity to tolerate heat[3]) metabolic rates (Table S1, http://links.lww.com/JOM/A538) and indoor/outdoor conditions from the matched participant on a weekday-match basis.

Metabolic rates were further individually adjusted by multiplying the ratio of the worker's body weight to 70 kg (154 lbs.) of a standard human to determine the weight adjusted metabolic rate[7]:

$$\text{Weight adjusted metabolic rate} = \frac{\text{Standard human metabolic rate (W)} \times \text{Worker bodyweight}}{70\,\text{kg}(154\,\text{lbs})}$$

A weight adjusted heat stress threshold limit value was calculated using the formula[3]:

$$\text{Weight adjusted TLV} = 56.7 - 11.5 \times \text{Log10}\ (\text{weight adjusted metabolic rate})$$

WBGT Index Exceedances of ACGIH TLV® for Each Person-Work Hour

Whether WBGT (WS) and WBGT (personal) index exceeded the ACGIH TLV® for each person-work hour was determined. If the WBGT index exceeds ACGIH TLV® in a given person-work hour, it suggests risk of overexposure in that given hour and a work–rest schedule should be implemented to decrease the risk of HRIs.[3,7] Since different temperature sensors (HOBO Pendant® vs iButton®) were used in 2012 and 2017, and the sex ratio in the two study periods were different, the number of person-work hours that the WBGT index exceeded TLV® in 2012 and 2017 were also analyzed separately and results are shown in supplemental materials.

Recommending Hourly Work–Rest Schedules Based on WBGT Index

Participants in this study were considered acclimatized workers[18] for the purposes of this analysis. Recommended exposure limits (RELs) and recommended work–rest cycles were determined for each person-hour by using either WBGT (WS) and WBGT (personal) indices, based on the criteria by NIOSH, Centers for Disease Control and Prevention[3], and Bernard heat stress screening evaluation document.[19] Participants were approximated to a "standard human" of 1.8 m^2 body surface when determining RELs. Weight adjusted metabolic rates were assigned into different levels of work to use the screening criteria of TLV® to determine work–rest recommendations (see Table column 3, Supplementary Digital Content 2, http://links.lww.com/JOM/A538, which presents weight adjusted metabolic rate categorization criteria for work–rest recommendation).

RESULTS

Participant Demographic Characteristics and Estimated Metabolic Rate Based on Work Tasks

Characteristics of the study population are shown in Table 1. The age median (range) was 44 (24, 57) in 2012 and 39.5 (21, 60) in 2017. In 2012, 84% of participants were men while all participants were women in 2017. The median (range) body mass index (BMI) was 36.1 (25.7, 36.6) among women in 2012 and 29.2 (18.3, 38.4) among men in 2012. In 2017, the median (range) BMI among all female participants was 34.3 (19.3, 52.3). The majority of the participants were African American (89% in 2012 and 94% in 2017).

Estimated Metabolic Rates

The average of estimated hourly metabolic rates of "standard human" during work hours was 252.9 ± 76.1 (mean ± SD) W for participants in 2012 and 253.4 ± 74.9 W in 2017. The average of estimated hourly weight adjusted metabolic rate was 327.1 ± 129.3 (mean ± SD) W for participants in 2012 and 330.0 ± 132.0 (mean ± SD) W in 2017. Estimated hourly metabolic rates or weight adjusted metabolic rates were not different between 2012 and 2017 (P-value = 0.88 or 0.63, respectively).

Environmental Conditions During 2012 and 2017 Study Periods

Temperatures from thermometers clipped to participants' shoes had a wider range compared with temperatures recorded at the nearest weather station (Fig. 1). The daily hour maximum and average temperature during work hours (6 am to 2 pm) were 35.0 and 28.1 ± 3.5 °C in 2012, and 32.2 and 27.9 ± 2.8 °C in 2017, respectively. The average WBGT (WS) during person-work hours was significantly lower in 2012 compared with 2017 (27.1 ± 3.3 °C vs 28.0 ± 4.0 °C, P-value < 0.001).

TABLE 1. Demographics and Body Mass Index for Participants in 2012 and 2017

Parameters	Year 2012	Year 2017
Participant number	19	32
Median age (range), years	44 (24–57)	39.5 (21–60)
Sex-Male	16 (84%)	0 (0%)
Sex-Female	3 (16%)	32 (100%)
% Black or African-American	17 (89%)	30 (94%)
Education		
Less than High School Diploma	4 (21%)	2 (6%)
High School Diploma (or GED or Equivalence)	8 (42%)	16 (50%)
Post-Secondary Certificate and above	7 (37%)	14 (44%)
Income		
Less than $20,000	4 (21%)	10 (31%)
$20,000–$49,999	11 (58%)	18 (56%)
$50,000 and above	4 (21%)	4 (12%)
Body mass index (BMI)		
BMI in female (median, range)	36.1 (25.7–36.6)	34.3 (19.3–52.3)
BMI in male (median, range)	29.2 (18.3–38.4)	N/A
Obese (BMI ≥30.0)	9 (47%)	22 (69%)

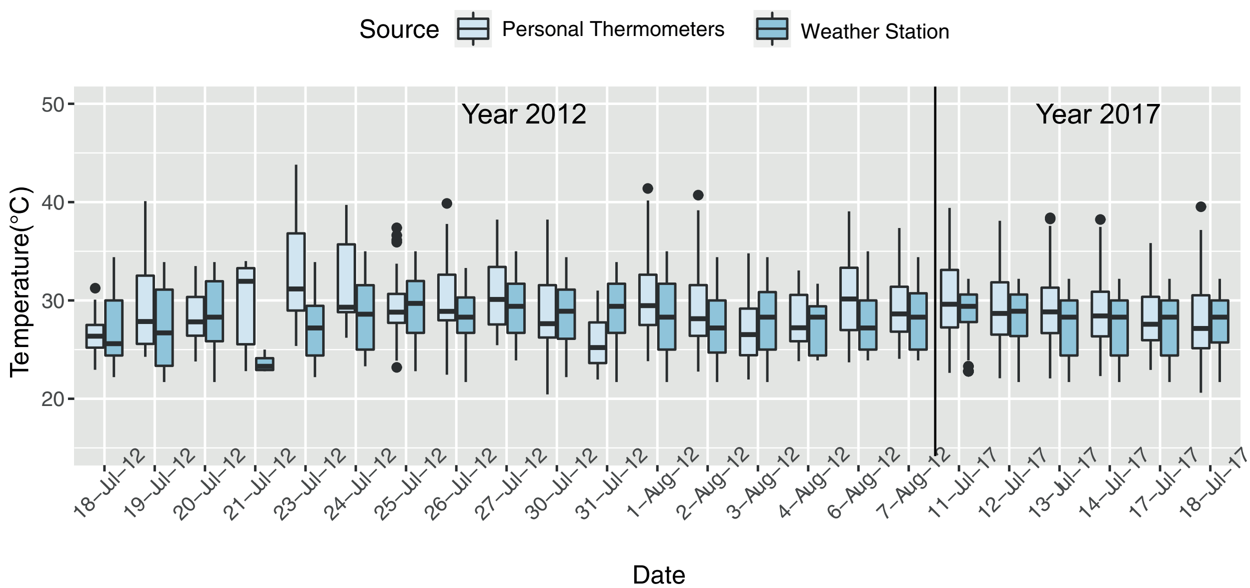

FIGURE 1. Comparison of hourly temperature measurements from personal thermometers and from weather station between 6 am and 2 pm on the days participants worked. Minimal and maximal, 25th and 75th percentiles, median (solid line in the box), and outliers (black circle) were shown.

Person-Work Hours Exceeding TLV®

On average, WBGT (personal) was higher than WBGT (WS) for all the person-work hours in 2012 (27.5 ± 3.4 °C (mean ± SD) vs 27.1 ± 3.3 °C, *P*-value = 0.003) and 2017 (28.6 ± 3.9 °C vs 28.0 ± 4.0 °C, *P*-value = 0.0007), respectively. The 2012 and 2017 datasets were initially analyzed separately, and the trends of the results of person-work hours that exceeds TLV® were similar (see Figure, Supplementary Digital Content 3, http://links.lww.com/JOM/A539, which shows the year effect on person-work hours of WBGT index that exceeds weight adjusted TLV®; also see Figure, Supplementary Digital Content 4, http://links.lww.com/JOM/A540, which shows the year effect on person-work hours in recommended work–rest schedule based on WBGT index). Therefore, results from 2012 and 2017 were combined and presented as one overall dataset. Of the total 1935 person-work hours analyzed, WBGT (personal) estimated 47.8% person-work hours exceeded TLV® while WBGT (WS) estimated 42.1% exceeded TLV®. Percentages of person-work hours of WBGT that exceeds weight adjusted TLV® were calculated for each participant. On average, WBGT (personal) estimated more hours exceeded TLV® at 7 to 11 am and 1 to 2 pm than WBGT (WS) across all participants. There was a significant difference (*P*-value = 2.08E−05) in the percentages between WBGT (personal) and WBGT (WS) at 7 am but not at other hours (Fig. 2).

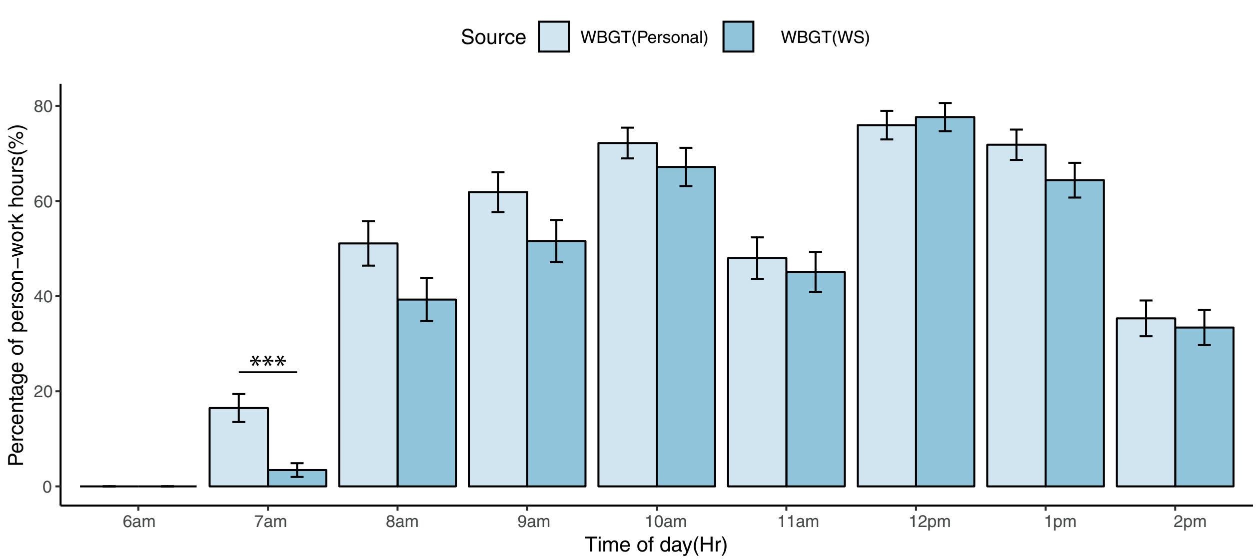

FIGURE 2. Average percentage of person-work hours of WBGT index that exceeds weight adjusted TLV® across all participants (mean ± standard error). Statistical significance symbols: '∗∗∗' denotes *P*-value of 0 to 0.001, ' ' denotes *P*-value > 0.05 and no significant difference.

FIGURE 3. Average percentage of person-work hours in recommended work–rest schedule based on WBGT index across all participants (mean ± standard error). 75% to 100% work is 45 to 60 min work/0 to 15 min rest per hour, 50 to 75% work is 30 to 45 min work/15 to 30 min rest per hour, 25% to 50% work is 15 to 30 min work/30 to 45 min rest per hour, 0% to 25% work is 0 to 15 min work/45 to 60 min rest per hour. Caution category represents WBGT index that exceeds weight adjusted TLV® when participants were at rest (estimated hourly metabolic rate around 115 W) in that person-work hour. Unshown percentage of hours fell into continuous work category. The percentage of person-work hours in continuous work is 55.8% ± 2.3% for WBGT (personal) and 60.9% ± 2.4% for WBGT (WS)(*P*-value = 0.23). Statistical significance symbols: ' ' denotes *P*-value > 0.05 and no significant difference.

Hourly recommended work–rest schedules for each participant were determined using WBGT (personal) or WBGT (WS), and a percentage of person-work hours for each work–rest schedule was calculated (Fig. 3). Across all participants, using WBGT (personal) estimated more person-work hours in the 45 to 60 min work/0 to 15 min rest, 30 to 45 min work/15 to 30 min rest, 15 to 30 min work/30 to 45 min rest, 0 to 15 min work/45 to 60 min rest hourly schedule compared with using WBGT (WS), but the differences were not significant (*P*-value > 0.05). Using WBGT (personal) estimated 17.4% of all person-work hours fall into the 0 to 15 min work/45 to 60 min rest schedule, which is recommended in the highest HRI risk conditions, while WBGT (WS) only estimated 14.4% of person-work hours fall into this high-risk category. We found that WBGT index sometimes exceeded TLV® even when participants were at rest with an estimated hourly metabolic rate around 115 W. These person-work hours fell into the Caution category since no further work–rest schedule could be recommended. WBGT (personal) estimated 1.0% of all person-work hours were in the Caution category while WBGT (WS) estimated 0.8% hours (Fig. 3). All other person-work hours (55.8% ± 2.3% for WBGT [personal] and 60.9% ± 2.4% for WBGT [WS] [*P*-value = 0.23]) did not fall into an HRI risk category, allowing for continuous work.

DISCUSSION

The primary goal for this study was to determine whether the use of a WBGT (personal) index would result in different HRI risk estimates from occupational heat exposure when compared with a WBGT (WS) index. For the same person-work hour, the difference between WBGT (personal) and WBGT (WS) is due to the different temperature measurement from thermometers or WS, which explains the differences in person-work hours above TLV® and different work–rest schedule recommendations. WBGT (personal) estimated that more person-work hours fell into all protective schedule categories than WBGT (WS), indicating using WBGT (personal) may provide more protection for workers from HRIs. If only WBGT (WS) was used, longer work versus rest periods would be recommended, which may result in placing workers at a higher risk of HRIs. While a recent study concluded regional weather station data provides accurate estimates of worksite heat index when compared with individually experienced temperature and humidity,[20] our study suggests additional relatively simple calculations to estimate WBGT using individually experienced temperature, tasks performed, and worker's weight may improve work–rest schedule estimation.

The Universal Thermal Climate Index (UTCI) is an alternative, regression-based metric based on the heat balance mechanism of the human body using the same input variables as WBGT. Since UTCI does not consider metabolic rate, clothing impact, or body movement during real work situations, the WBGT index is considered more comprehensive.[14,21] The Predicted Heat Strain (PHS), which is based on analysis of body heat balance and the required sweat rate for the maintenance of a stable core temperature, is used to calculate the recommended exposure time independent of meteorological conditions.[22] However, it has been demonstrated that the WBGT index provides a more conservative assessment that allows shorter exposure times.[23] An empirical short-term safe exposure time model was proposed using the WBGT index, metabolic rate, and clothing by Bernard and Ashley in 2009.[24] The model was derived from the metabolic rate of 380 W, but not validated against other data.[25] Therefore, the Recommended Exposure Limits (RELs) from NIOSH were used to recommend work–rest schedules in this study.

Limitations of this study include a relatively small sample size; therefore results in this study may not be generalizable to other urban outdoor workers in other locations and sex effects, if any, would be difficult to detect in the current study (see Figure, Supplementary Digital Content 5, http://links.lww.com/JOM/A541, which presents person-work hours of WBGT index that exceeds weight adjusted TLV® for male and female participants; also see Figure, Supplementary Digital Content 6, http://links.lww.com/JOM/A542, which shows person-work hours in recommended work–rest schedule based on WBGT index for male and female participants separately). Second, the participants' metabolic rates were estimated using the hourly self-reported tasks in the daily log in 2012. It is possible that the reported task did not occupy the whole hour for each participant and application of 2012 tasks to the 2017 participants limits our ability to incorporate potential variability in tasks performed. Weight-adjusted metabolic rates were assigned based on the task category without the consideration of all individual differences, including age, basal metabolic rates, and other body measurements. Future research could incorporate biometrics (ie, heart rate monitors) to further evaluate the effect of individual differences in metabolic rate.

Different thermometers colocated with participants were used in the 2012 and 2017 periods of this research. Prior to the 2017 data collection, we tested the temperature measurement precision of three iButton® and six HOBO Pendant® devices placed at the same indoor location for 32 consecutive hours. We found that iButton® had better precision than HOBO Pendant® devices (Onset Computer Corp, Bourne, MA), which lead us to use iButton® in 2017.

The placement of thermometers on the worker (neck or waist) has been previously shown to affect temperature readings,[20] with placement at the waist more accurately capturing mean workplace heat index estimated from regional environmental monitoring data. Our placement on the shoe may have also affected the temperature measurements due to proximity to the ground and depending on the type of surface the participant was on (eg, grass vs pavement); however, the shoe position was chosen based on pilot trials that suggested thermometers attached to other articles of clothing picked up body heat and preference for the shoe position in terms of comfort and discreteness.

Additionally, the impact of solar radiation on temperature measurements from thermometers colocated with participants should be considered in future studies, as also suggested by Mac et al.[20] Since the HOBO Pendant® devices measured temperature without a solar radiation shield and iButton® devices were worn facing down, the amount of solar radiation captured by these devices cannot be quantified at this time. In a sensitivity analysis, the impact of additional solar radiation not captured by HOBO Pendant® and iButton® devices was simplified as negligible (no additional solar radiation) in the $WBGT_{outdoor}$ (personal) calculation. In this analysis, 16.0% of all person-work hours of WBGT (personal-no solar addition) were estimated to exceed TLV® compared with 47.8% of WBGT (personal). There are significant differences (P-value < 0.001) in the average percentage of person-work hours above TLV® by using WBGT (personal) or WBGT (personal-no solar addition) at 7 am to 2 pm (see Figure, Supplementary Digital Content 7, http://links.lww.com/JOM/A543, which presents the effects of solar radiation addition or no-addition on person-work hours of WBGT index that exceeds weight adjusted TLV®). WBGT (personal) recommended more hours than WBGT (personal-no solar addition) in all work–rest regimens (see Figure, Supplementary Digital Content 8, http://links.lww.com/JOM/A544, which presents the effects of solar radiation addition or no-addition on person-work hours in recommended work–rest schedules). While WBGT (personal-no solar addition) is useful to provide a higher bound on the impact of solar radiation possibly captured by the devices, the true value is likely less. Additionally, upper outliers from personal thermometer temperature measurements were removed to address the concern that solar radiation captured by devices elevated personal air temperatures temporarily. There was a minimal effect of upper outlier removal (see Figure, Supplementary Digital Content 9, http://links.lww.com/JOM/A545, which shows the effect of upper outlier removal in WBGT (personal) or WBGT (WS) in person-work hours exceeding weight adjusted TLV®; also see Figure, Supplementary Digital Content 10, http://links.lww.com/JOM/A546, which presents the effects of upper outlier removal on recommended work–rest schedules.) In the future, development of small, wearable thermometers equipped with a solar radiation shield or colocation of a black globe thermometer with participants, which combines the effects of air temperature and solar radiation, could be used to more accurately assess solar radiation effects.

This study suggests consideration of microclimates for outdoor workplaces may result in more precise work–rest schedule recommendations. While the work–rest regimen recommendations in this study were based on post-incidence heat stress estimation and did not provide real-time feedback, employers and workers can still benefit from the results by considering more workplace specific and personal risk factors to prevent HRIs. Additionally, employers could collect real-time meteorological data specific to their workplace or purchase WBGT meters (eg, QUESTemp® QT32/34/36) to place in common work areas. These meters automatically calculate WBGT and display work–rest regimens for each of four metabolic work categories.[26] For example, the NIH Heat Stress Program monitors hourly during work hours at all official NIH facilities.[27]

Placement of a WBGT meter may not be feasible at many workplaces; therefore, implementing work–rest schedules based on heat index from temperature and humidity measurements may be more realistic (eg, BP U.S. Pipelines & Logistics [USPL] Safety Manual).[28] For example, the Heat Safety Tool from OSHA, a smartphone application, reports real-time data from the nearest weather station based on the GPS location of the phone. This information can then be used to develop industry specific work–rest schedules.[28] However, as detailed in this paper, NIOSH recommends an approach that includes solar radiation and wind speed, in addition to temperature and humidity, to determine work–rest schedules.[3]

Workers could also receive training on adjusting the rest time with consideration of their personal risk factors including age, weight, physical fitness, water intake, medical conditions, and medications, etc. To minimize work–rest scheduling effects on productivity, work hours could be adjusted to allow performance of strenuous outdoor work in the early morning hours. Also, sedentary tasks (eg, meetings, paperwork) could be scheduled during rest periods.

Beyond implementation of the more specific work–rest scheduling, engineering controls like installing a form of shade on all mowers to prevent direct radiant heat and UV damage to the skin can be implemented. Cooling stations and personal protective equipment (PPE), such as cooling vests, could be made available for use along with training on proper use. During heat wave days, a daily weigh in and out can be implemented to ensure workers are not losing a dangerous amount of water. Frequent water breaks could be encouraged as part of a hydration protocol.

CONCLUSION

Temperature measurements from thermometers colocated with participants had a wider range than those collected from the nearest weather station. More person-work hours of WBGT (personal) exceeded ACGIH TLV® than when using WBGT (WS) to calculate exceedances (47.8% vs 42.1%). By using WBGT (personal), more person-work hours fell into the 0 to 15 min work/45 to 60 min rest hourly schedules (17.4% vs 14.4%), indicating conditions with the highest risk of HRI. Our findings suggested that using temperature measured by small thermometers clipped to outdoor workers' shoes, together with meteorological data, can serve as a method to identify occupational heat exposure and recommend more protective work–rest scheduling.

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