

Original Article

Assessment of Heat Stress Exposure among Construction Workers in the Hot Desert Climate of Saudi Arabia

Mohammed Al-Bouwarthan^{1,2,*}, Margaret M. Quinn¹, David Kriebel¹ and David H. Wegman¹

¹Department of Public Health, College of Health Sciences, University of Massachusetts Lowell, Lowell, MA 01854, USA; ²Department of Environmental Health, College of Public Health, Imam Abdulrahman Bin Faisal University, P.O. Box 1982, Dammam 31441, Saudi Arabia

*Author to whom correspondence should be addressed. Tel: +1-978-934-3196; E-mail: mohammed_albouwarthan@student.uml.edu

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Abstract

Objectives: Excessive heat exposure poses significant risks to workers in hot climates. This study assessed the intensity and duration of heat stress exposure among workers performing residential construction in southeastern Saudi Arabia (SA) during the summer, June–September 2016. Objectives were to: identify work factors related to heat stress exposure; measure environmental heat exposure at the construction sites; assess the heat stress risk among workers using the wet bulb globe temperature (WBGT) index; and determine if temperature-humidity indices can be appropriate alternatives to WBGT for managing heat stress risk at the construction sites.

Methods: Worksite walkthrough surveys and environmental monitoring were performed, indoors and outdoors, at 10 construction sites in Al-Ahsa Province. A heat stress exposure assessment was conducted according to the American Conference of Governmental Industrial Hygienists (ACGIH®) guidelines, which uses the WBGT index. WBGT measurements from two instruments were compared. Alternative heat stress indices were compared to the WBGT: the heat index (HI) and humidex (HD) index.

Results: Construction workers were exposed to excessive heat stress, indoors and outdoors over a large part of the work day. Complying with a midday outdoor work ban (12–3 p.m.) was not effective in reducing heat stress risk. The highest intensity of exposure was outdoors from 9 a.m. to 12 p.m.; a period identified with the highest hourly mean WBGT values (31–33°C) and the least allowable working time according to ACGIH® guidelines. Comparison of the alternative indices showed that the HI is more reliable than the HD as a surrogate for the WBGT index in the climate studied.

Conclusion: The extreme heat exposure represents a serious risk. The severity of heat stress and its impact are projected to increase due to climate change, emphasizing the need for immediate

improvement of the current required protective measures and the development of occupational heat stress exposure guidelines in SA.

Keywords: climate change; construction industry; extreme heat; heat stress; heat stress indices

Introduction

Workers in the construction industry are exposed to numerous health and safety hazards leading to the illness and death of thousands of workers every year (Ringen *et al.*, 1995; Snashall, 2005; The Center for Construction Research and Training (CPWR), 2018). Exposure to climatic heat is among the hazards of growing concern in construction work around the globe (Yang, 2017). Like many workers in other industries, construction workers are not in full control of their assigned job activities (Buchholz *et al.*, 1996), nor do they have full control of their work environments (Schulte *et al.*, 2016).

Environmental heat exposure is especially relevant for construction work such as site preparation, construction or demolition of buildings and infrastructure, and building decoration and finishing (Rowlinson and Jia, 2015). These types of activities are classified as physically demanding (Arndt *et al.*, 2005; van der Molen *et al.*, 2007; Chang *et al.*, 2009; Tak *et al.*, 2011) and their execution in a safe and productive manner is affected by many factors including weather conditions (Benjamin and Greenwald, 1973; Moselhi *et al.*, 1997; Li *et al.*, 2016; Liu *et al.*, 2018). Performing these activities under conditions of excessive heat can increase the risk of heat stress (Rowlinson *et al.*, 2014), which is a combination of heat gained from the surrounding work environment, the metabolic cost of the work (workload), and clothing (Krake, 2018). Exposure to an excessive heat load over time causes significant heat strain, which impedes work performance (mentally and physically; Rodahl, 2003; Yi and Chan, 2017; Wittbrodt *et al.*, 2018) and increases the risks of accidents (Sheng *et al.*, 2018), heat-related illness (Wallace *et al.*, 2005), and fatality (Petitti *et al.*, 2013).

The negative impacts of heat stress will likely increase due to climate change (Spector and Sheffield, 2014; Acharya *et al.*, 2018), particularly in countries in arid and tropical zones (Kjellstrom *et al.*, 2009; Andrews *et al.*, 2018). Saudi Arabia (SA) is among these countries; it is one of the hottest, sunniest, and largest arid countries in the world (Alkolibi, 2002; Dargin, 2009; Krishna, 2014). The weather of SA is becoming hotter, with average temperatures increasing 0.72°C per decade since 1990 (Almazroui *et al.*, 2012). Temperatures are projected to rise further, reaching levels incompatible

with human habitation, particularly in the coastal areas along the Arabian Gulf (Husain and Chaudhary, 2008; Pal and Eltahir, 2016). The escalation and persistence of hot weather during the summer currently poses a significant threat to the health and safety of the working population in SA (Jefri *et al.*, 1990; Noweir *et al.*, 1996; Noweir and Bafail, 2008). This is particularly true for the 3.6 million workers employed in the construction sector (39% of the total workforce in the Saudi private sector; General Authority for Statistics of Saudi Arabia, 2018), which has a high reported rate of occupational injuries (Alasamri *et al.*, 2012).

In response to the potential threat of heat stress, in 2010, the Saudi Ministry of Labor and Social Development (MLSD) enacted a regulation that bans outdoor work activities between 12 and 3 p.m. each day during the summer. However, despite the necessity and practicality of this administrative safety measure, empirical data are lacking about the effectiveness of the ban in mitigating heat stress. The lack of empirical data contributes to poor awareness among employers, supervisors, and workers regarding the potential impacts of heat stress exposure and to the absence of appropriate training programs on heat safety and other preventive interventions in the workplace (Saudi Press Agency, 2014, 2015, 2016).

To address these challenges, we conducted an assessment of heat stress exposure among residential construction workers in the province of Al-Ahsa in southeastern SA along the Arabian Gulf, occupying approximately 24% of the country's land area (Abdelatti *et al.*, 2017). It is classified as one of the hottest and driest regions in the country (Al-Jabr, 1984), with an average daily maximum temperature ranging from 44 to 46°C during the summer (Presidency of Meteorology and Environment, 2017). The need for construction in Al-Ahsa has resulted in the growth of many small- and medium-sized construction companies, with approximately 3700 such enterprises employing more than 68 000 construction workers (General Organization for Social Insurance of Saudi Arabia, 2018), the vast majority of whom are expatriate workers (General Authority for Statistics of Saudi Arabia, 2018) from South Asian countries, mainly India, Pakistan, and Bangladesh.

Specific objectives of this study were to: identify work factors related to heat stress exposure for the main construction jobs; measure environmental heat exposure at the construction sites; assess the extent of heat stress risk among workers using the wet bulb globe temperature (WBGT) index; and determine if temperature-humidity indices can be appropriate alternatives to WBGT for managing heat stress risk at the construction sites.

Methods

Study design

Qualitative and quantitative data were obtained via onsite walkthrough surveys and monitoring of work activities and environmental parameters at 10 residential construction sites in Al-Ahsa province during the summer months, June–September 2016. The data were used to calculate the potential for heat stress among workers at these sites and to identify time periods to manage the heat stress. Three heat stress indices were used to calculate the heat stress potential and recommendations for workable hours derived from each index were compared. Each index has different strengths and shortcomings for future use by employers. All study protocols and materials were approved by the University of Massachusetts Lowell Institutional Review Board.

Walkthrough survey

Ten residential construction sites run by four enterprises were surveyed (see [Supplementary Fig. S1](#), available at *Annals of Occupational Hygiene* online). Walkthrough surveys were performed at each site on each day environmental measurements were taken. We gathered qualitative information about heat stress exposure that included: work activities performed by each job title; frequency of worker exposure to direct sun; clothing requirements; and characteristics of onsite lunch and rest facilities. Additionally, appropriate locations for collecting the environmental measurements were identified. Hours of work outdoors and indoors by time intervals and by work effort were estimated based on the sum of all observations over the 81 sample days. The same job (for example, plasterer) was observed to have similar work effort across all of the sites.

Measurement of environmental heat exposure

Indoor and outdoor environmental heat exposure were assessed using WBGT, which integrates into a single empirical index the main environmental parameters (air temperature, humidity, wind speed, and solar radiation) that influence the body's thermal balance ([Macpherson, 1962](#)). It is calculated by combining the measurements

of dry bulb (air) temperature (T_{db}), natural wet bulb temperature (T_{nwb}), and globe temperature (T_g) as follows ([International Organization for Standardization \(ISO\), 2017](#)).

With solar radiation (outdoors):

$$WBGT_{\text{outdoor}} = 0.7 \times T_{nwb} + 0.2 \times T_g + 0.1 \times T_{db} \quad (1)$$

Without solar radiation (indoors):

$$WBGT_{\text{indoor}} = 0.7 \times T_{nwb} + 0.3 T_g \quad (2)$$

Instruments to measure the WBGT vary in cost, ease of use, and durability, features that can impact usability for small enterprises. We compared the performance of two WBGT instruments, the QUESTemp44 (Quest Technologies, WI, USA), an instrument used in previous heat stress studies, and the Kestrel5400 (Nielsen-Kellerman Co., PA, USA), much smaller in size and lower in cost (approximately one-sixth the price of the QUESTemp44 at the time of purchase). Both instruments were equipped with sensors to measure relative humidity (RH), T_g , and T_{db} , which are then utilized to calculate T_{nwb} based on the empirical method developed by [Bernard and Pourmoghani \(1999\)](#). These instruments were validated to measure WBGT and used in heat stress exposure research ([Bernard and Barrow, 2013](#); [Cheuvront et al., 2015](#)).

Prior to full-scale environmental monitoring, a pilot study was conducted at one of the construction sites, outdoors and indoors, to compare the measurements obtained by the two instruments collected over 14 consecutive days (1–14 June 2016). The WBGT measurements were recorded at 5-min intervals during the hottest part of the day, from 7 a.m. to 3 p.m. The first week (7 days), the two instruments were placed side-by-side indoors, and the second week (7 days), they were placed side-by-side outdoors. Each day, the instruments were placed at abdominal level, within 2 m of each other and away from anything that might block or add to radiant heat or air flow. They were allowed to stabilize for approximately 15 min before the measurements were recorded. The measurements were compared with a scatter plot and best-fit linear regression line ([Supplementary Fig. S2](#), available at *Annals of Occupational Hygiene* online). The results showed a strong correlation between the WBGT measurements produced by the two instruments ($r^2 = 0.99$; $P < 0.05$).

Accordingly, both instruments were located in similar fashion at each of the 10 construction sites throughout the study to monitor WBGT. The monitoring was performed simultaneously outdoors and indoors for three consecutive days at each of the 10 sites, starting at site 1; site 2; site 3...; and ending at site 10. This monitoring

approach was implemented repetitively, starting on 15 June through 30 September 2016 excluding Fridays ($n = 15$)—a non-work day—and public holidays ($n = 12$), where the monitoring stopped and resumed thereafter, yielding a total of 81 days of WBGT data (Supplementary Table S1, available at *Annals of Occupational Hygiene* online). The QUESTemp44 was used to measure WBGT outdoors, while the Kestrel5400 was used indoors. Measurements of WBGT were recorded every 15 min from 5 a.m. to 5 p.m.

The possible use of simpler indices that depend on standard meteorological variables rather than measurements from complicated and expensive devices to guide future heat stress management programs in SA was examined by comparing the WBGT estimates of hourly exposure risks to two commonly used temperature-humidity indices: the heat index (HI) and the humidex (HD) using measurements generated from the T_{db} and RH sensors on our WBGT instruments. Since 1905, over 160 heat indices have been proposed each with strengths and limitations depending on purpose, setting, time scale, and health consequences (Gao *et al.*, 2018; Roghanchi and Kocsis, 2018). We selected the HI and HD to compare with the WBGT index because they require only easily available climatic measures and are associated with recommended guidelines for their application in occupational settings.

The HI integrates T_{db} and RH to determine the apparent temperature (Steadman, 1979). Bernard and Iheanacho (2015) provide guidelines for calculating this index for the assessment of occupational heat stress exposure. While calculation of the HI is complex (Anderson *et al.*, 2013), a free software program (Weathermetrics version 1.2.2) readily calculates HI from the T_{db} and RH (Anderson and Peng, 2016).

The HD, based on the combined effects of T_{db} and water vapor pressure (V_p), is commonly used to quantify thermal comfort in the general population (Masterton and Richardson, 1979). It was used by the Occupational Health Clinics for Ontario Workers (OHCOW) to develop a heat response plan for worksite heat stress exposure (OHCOW, 2014). Its calculation is shown in the equation below.

$$HD = T_{db} + 0.555 \times (V_p - 10) \quad (3)$$

where T_{db} is in °C, and V_p is in hPa = $6.11 \times 10^{((7.5T_{db})/(237.7+T_{db}))} \times RH/100$.

Radiant heat is a major source of heat exposure for those working outdoors under direct sunlight or indoors in heat-generating manufacturing processes (e.g. foundries, smelters, and bakeries). The WBGT index incorporates radiant heat, while the other two indices do not.

OHCOW (2014) and Bernard and Iheanacho (2015) suggested adding an adjustment factor to HD and HI in the range of 2–3°C to account for the effect of radiant heat. The adjustment factor is dependent on the intensity of radiant heat, which reflects the increase of globe temperature above dry bulb temperature (ΔT_{g-db}) (Bernard and Iheanacho, 2015). In this study, the adjustment was applied as 1°C for $\Delta T_{g-db} < 4^\circ\text{C}$; 2°C for $\Delta T_{g-db} \geq 4^\circ\text{C}$, $< 7^\circ\text{C}$; and 3°C for $\Delta T_{g-db} \geq 7^\circ\text{C}$, reflecting low, moderate, and high radiant heat, respectively. These adjustments to HD and HI indices were applied only for the outdoor setting, given that the hourly ΔT_{g-db} average was 6°C, while indoors, the ΔT_{g-db} was 1°C, indicating that the effect of radiant heat indoors was minimal.

Exposure limits for heat stress

The American Conference of Governmental Industrial Hygienists (ACGIH®) Threshold Limit Value (TLV®) was used to determine the risk of heat stress in the study population. The TLV is calculated for specific heat exposures, as measured by the WBGT, and for specific work intensity levels performed by acclimatized workers (ACGIH, 2009). The construction work activities observed in this study (Supplementary Table S2, available at *Annals of Occupational Hygiene* online, provides details and examples) were classified according to ACGIH guidelines as having workloads (metabolic rates) mainly in the moderate to heavy range (see Table 1). ACGIH guidelines provide a simple qualitative framework to classify workloads (referred to as ‘metabolic work rates’) as: rest, light, moderate, heavy, and very heavy (ACGIH, 2009).

Exposure above the TLV can result in increased core body temperature ($>38^\circ\text{C}$). When this occurs, the ACGIH specifies hourly work limits, an administrative control intended to reduce the heat stress exposure to a safe level (Supplementary Table S3, available at *Annals of Occupational Hygiene* online) (ACGIH, 2009). Both OHCOW (2014) and Bernard and Iheanacho (2015) established similar work limits for the HD and HI indices (Supplementary Tables S4 and S5, available at *Annals of Occupational Hygiene* online). The safe work limits estimated from each of the three indices were compared.

Data analysis

The four environmental heat parameters (T_{db} , T_{nwb} , T_g , and RH) that comprise the WBGT index were recorded over 81 days at the 10 construction sites and summarized as hourly WBGT averages, outdoors and indoors, for daily 12-h periods. Additionally, the four parameters were assessed individually to evaluate the influence of each on the WBGT daily trends. The hourly data were

Table 1. Description of the observed work activities and classification of workload for 10 residential construction sites in Al-Ahsa Province, SA, June–September 2016.

Activity	Location	Jobs	Tasks observed	Classification of workload ^a
Site preparation	Outdoors	Laborers and machine operators	Demolition, excavation, shoveling, pulling, and pushing heavy loaded wheelbarrows; surface leveling	Heavy
Formwork	Outdoors	Carpenters and laborers	Moderate arm and trunk work to assemble and install formwork	Moderate
Steel reinforcement	Outdoors	Steel fixers	Intense hand, arm, and trunk work to modify and shape reinforcing steel bars	Heavy
Pouring and finishing concrete	Outdoors	All workers	Pouring, shoveling, pushing, and leveling of concrete mix at fast pace	Heavy
Masonry work	Outdoors	Block layers	Intense use of hand, arm, and trunk to lay concrete blocks	Heavy
Install insulation	Indoors/outdoors	Insulation workers	Light manual work involving handling and fixing of insulation material	Light
Install utilities	Indoors/outdoors	Electricians and plumbers	Light pushing and pulling, hammering, cutting, and assembly of piping, electric wiring system, and appliances	Moderate
Plastering	Indoors/outdoors	Plasterers	Sustained moderate arm and trunk work to plaster building surfaces	Moderate
Tiling	Indoors/outdoors	Tilers	Sustained moderate hand and arm work to install tiles	Moderate

^aLevels of workload for the observed work task activities were estimated utilizing ACGIH guidelines (ACGIH, 2009).

computed by averaging values measured at each 15 min (i.e. 5:00–5:45 a.m.; 6:00–6:45 a.m....4:00–4:45 p.m.).

The hourly occupational risk of heat stress exposure for light, moderate, and heavy workloads was estimated as the percentage of time when the WBGT value exceeded the TLV during each 60-min interval through the work day. No adjustments to WBGT values were made for clothing because all workers in the study were observed wearing normal summer (light) clothing (see below; ACGIH, 2009).

To analyze the effectiveness of the midday work ban, the number of minutes per hour that work was permitted (hourly workability, HWA) was determined based on the ACGIH guidelines. Then, the mean values of HWA for workers performing moderate and heavy construction work activities outdoors and indoors during four consecutive periods of the day (6–9 a.m.; 9 a.m.–12 p.m.; 12–3 p.m.; and 3–5 p.m.) were estimated to compare HWA during the work ban period with other times in the day. The accumulated proportion of working time spent beyond the HWA was calculated according to two daily work shift scenarios for both outdoor and indoor exposures. The first scenario was a 10-h continuous work shift (5 a.m.–3 p.m.), with two meal breaks (approximately 30 min each), as practiced by some contractors who did not comply

with the afternoon work ban. The second scenario was a 7-h continuous work shift (5 a.m.–12 p.m.), with a 15–20 min break, as practiced by compliant contractors. The impact of the afternoon work ban on reducing exposure risk was estimated as the difference between the accumulated allowable working time in these two scenarios.

Finally, the mean values of the HWA as estimated by the HI and HD were compared to that of the WBGT-based index using Cohen's weighted kappa coefficient (κ_w) with quadratic weight to determine the overall agreement among the indices for workers performing moderate and heavy construction work activities. This statistical test assesses agreement for categorical data on an ordinal scale (Cohen, 1968). The estimated HWA values were assigned ordinal scale values ranging from 1 to 5. These weights corresponded to HWAs of 60, 45, 30, 15, and 0 min, respectively. Agreement between the indices was examined after stratification by outdoor and indoor work. The interpretation of κ_w values was based on the following criteria: ≤ 0.20 = slight agreement, 0.21–0.40 = fair agreement, 0.41–0.60 = moderate agreement, 0.61–0.80 = substantial agreement, and 0.81–1.00 = almost perfect agreement (Landis and Koch, 1977). Data analysis was performed with SPSS Statistics software version 24 (IBM, 2016).

Results

Working environment

Nine major jobs and work activities involved in constructing residential buildings were identified based on field observations and onsite discussion with workers and management ([Supplementary Table S2](#), available at *Annals of Occupational Hygiene* online). All construction workers were Indian nationals, while all construction managers were Saudi nationals. These construction activities were performed 6 days per week by teams of 2–10 workers. Depending on arrival time at the site, the typical work day began between 5 a.m. and 6 a.m. and was supposed to end at 12 p.m. as required by the 3-h midday outdoor work ban. Early start times were designed to take advantage of cooler morning hours to maintain productivity while complying with the midday work ban. However, it was observed that four of the worksites (owned by two of the companies) did not comply with the work ban; their onsite work activities, both indoor and outdoor, continued until 3 p.m. Workers at companies that complied with the work ban worked a maximum of 7 h with only a breakfast break (15–20 min). Workers at companies that did not comply with the ban worked 10 h with two meal breaks (30 min each). The latter companies provided workers with breakfast at approximately 8 a.m. and lunch at approximately 1 p.m. At each site, in general, workers were provided access to one 19-l drinking water cooler for a team of 2–4 workers or two water coolers for 5 or more workers. Commonly, we observed two coolers for a team of <10 workers. Water coolers were filled with water once at the start of the work day. On study days, bottles of water kept in a cooler were made available to workers being observed. Access to and consumption of water during the study will be addressed in a separate publication. All the worksites lacked air-conditioned resting facilities, onsite toilets, and nearby sources of water for refilling drinking water containers. The availability of shaded rest areas varied by job and site. Generally, all workers wore the same clothing, consisting of long-sleeved shirts, long pants, work boots or shoes, baseball caps or head scarves, and polyester or rubber gloves.

Environmental conditions

Among the 10 construction sites, the indoor and outdoor WBGT values differed by less than 2.0 and 3.4°C, respectively. Accordingly, subsequent analyses combined the data across all 10 sites, outdoors and indoors. Detailed presentations of WBGT and T_{db} , T_g , T_{nwb} , and RH measured hourly at each site are in [Supplementary](#)

[Table S1](#), available at *Annals of Occupational Hygiene* online.

The hourly mean values of WBGT, for all sites ([Fig. 1](#)) show that the workday started with a relatively low WBGT <26.0°C, both indoors and outdoors, which was sustained for 2 h (5–7 a.m.). Then, the outdoor WBGT values increased, reaching a peak of $33.0 \pm 3.1^\circ\text{C}$ at 9 a.m., after which the measurements decreased until a plateau between 12 and 5 p.m. (measurements end), when the outdoor WBGT was $29.6 \pm 1.8^\circ\text{C}$. Similarly, the indoor WBGT values began to increase at approximately 7 a.m. but at a slower rate, until a peak value of 28.8°C was reached between 9 a.m. and 12 p.m. and remained at that level through the rest of the afternoon before dropping to $27.1 \pm 2.8^\circ\text{C}$ in the last hour (4–5 p.m.; [Fig. 1](#)).

Assessment of heat stress exposure risk

The hourly average WBGT values were compared with heat stress TLVs for the intensity of workload performed (26.6°C = TLV for heavy work; 28.2°C = TLV for moderate work; and 30.8°C = TLV for light work). Then the percentage of each hour that WBGT values exceeded the TLV for a given workload was calculated for outdoors versus indoors ([Fig. 2A,B](#)). During the period from 8 a.m. to 5 p.m., when a heavy workload was performed outdoors, the TLV was exceeded 92–100% of the time. Exceedances with moderate workload outdoors ranged from 77 to 93%, while exceedances at a light workload outdoors ranged between 23 and 71% ([Fig. 2A](#)). Indoor exposures also exceeded the heat stress TLV: for a heavy workload it was exceeded 61–84% of the time; for moderate and light workloads the risk was 34–50% and 9–17%, respectively ([Fig. 2B](#)).

According to the WBGT heat stress exposure limits, the mean values of HWA during the day indicate that the 3-h period ‘prior to the ban’ had the lowest HWA values for both moderate and heavy outdoor work activities (15 and 9 min of allowable work time, respectively; [Table 2](#)). In contrast, for indoor work, the ban period and the periods before and after had similar HWA values for moderate and heavy work (~44 and ~30 min, respectively). Regardless of whether the employer complied with the midday work ban, all workers worked far beyond the HWA for many hours over the summer months. Workers employed by compliant companies worked a total of 548 h compared with 733 h for those employed by non-compliant companies over the study period. The cumulative exceedance of the HWA during these working hours was found to be 60 and 61%, respectively, when performing heavy work activities outdoors and 49 and 47%, respectively, with moderate

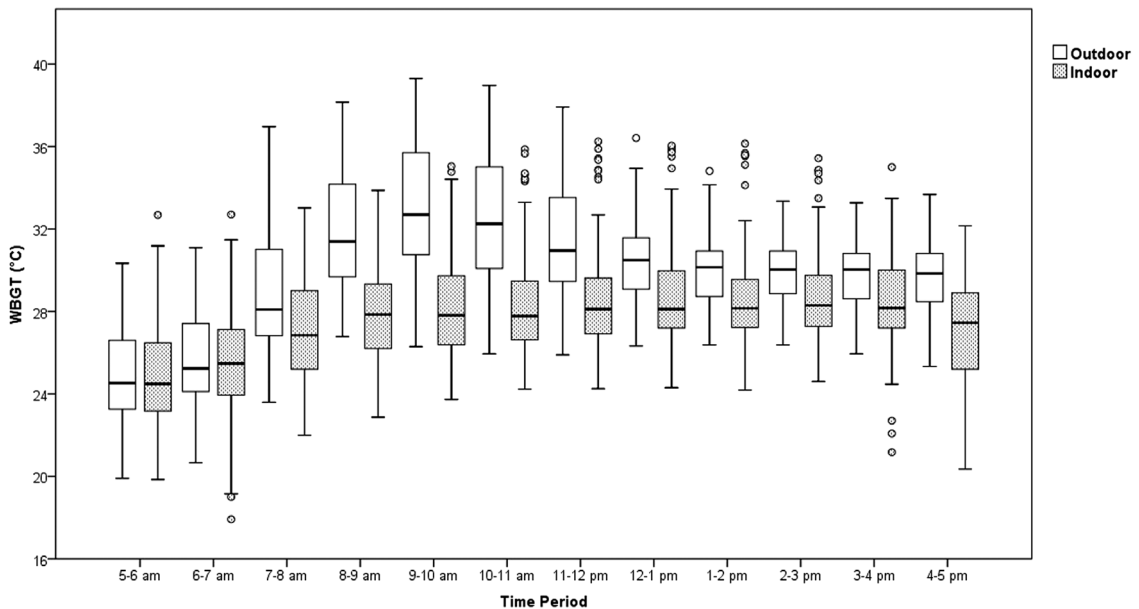


Figure 1. Hourly WBGT averaged for 10 residential construction sites in Al-Ahsa Province, SA, June–September 2016. Grey shading indicates indoor measurements; white indicates outdoor measurements.

work activities. Indoors, the HWA was exceeded for heavy work by 32 and 33%, work ban compliant versus non-compliant companies, respectively, and 17 and 14%, respectively, for moderate work. These exceedances indicate the limited effectiveness of the ban in the prevention of hourly heat stress exposure. However, complying with the ban led to a reduction in total exposure time of 185 h over the summer months for employees who worked for compliant companies.

A comparison of the HWA for moderate and heavy workloads, outdoors and indoors, as determined by the three heat stress indices (WBGT, HI, and HD) showed similarities in the fluctuations in the outdoor HWA, with more consistency in the mean HWA values for heavy workloads than for moderate workloads (Fig. 3A,B). The differences between the HWA based on the WBGT compared to the HI ranged from -6 to $+2$ min, while differences between the WBGT and HD ranged from -3 to $+5$ min (Fig. 3B). Indoors, where the effect of radiant heat was minimized, all indices demonstrated a similar gradual decrease in the mean HWA for a heavy workload until 3 p.m.; for a moderate workload, the HWA values based on the WBGT and HI were in much closer agreement throughout the day than those indicated by the HD (Fig. 4A,B). Overall, all three indices determined that performing continuous moderate or heavy construction work in the summer weather, as characterized in this study, is not advised.

The results of the weighted kappa analysis showed almost perfect agreement between the WBGT and HI in the estimates of the HWA, indoors and outdoors, for both moderate ($\kappa_w = 0.85$ and 0.89 , respectively) and heavy workloads ($\kappa_w = 0.88$ and 0.90 , respectively) (Supplementary Table S6, available at *Annals of Occupational Hygiene* online). The comparison between the HWA using the WBGT and HD indices showed substantial agreement for moderate workloads indoors and outdoors ($\kappa_w = 0.71$ and 0.80 , respectively) and almost perfect agreement for heavy workloads performed both indoors and outdoors ($\kappa_w = 0.88$ and 0.91 , respectively; Supplementary Table S7, available at *Annals of Occupational Hygiene* online).

Discussion

In this study, continuous monitoring of environmental conditions was conducted June–September 2016 to characterize the daily summer heat trends, indoors and outdoors, at 10 residential construction sites in the Al-Ahsa Province, SA, and to assess the corresponding risk of heat stress among the construction workers. The sites selected for this study are typical of construction sites in SA in terms of the onsite work environment and types of construction work activities. Differences from other sites in other parts of SA would be attributed mainly to the size of the construction project and the influence

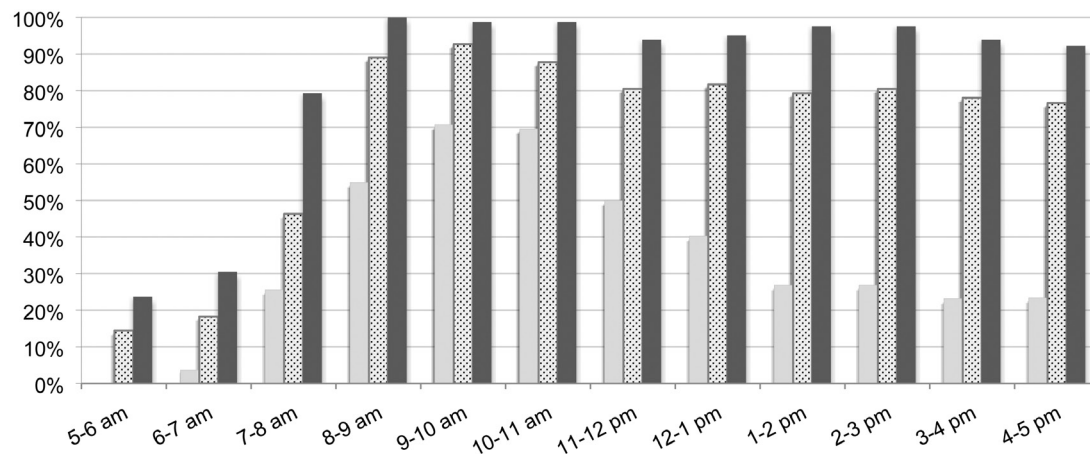
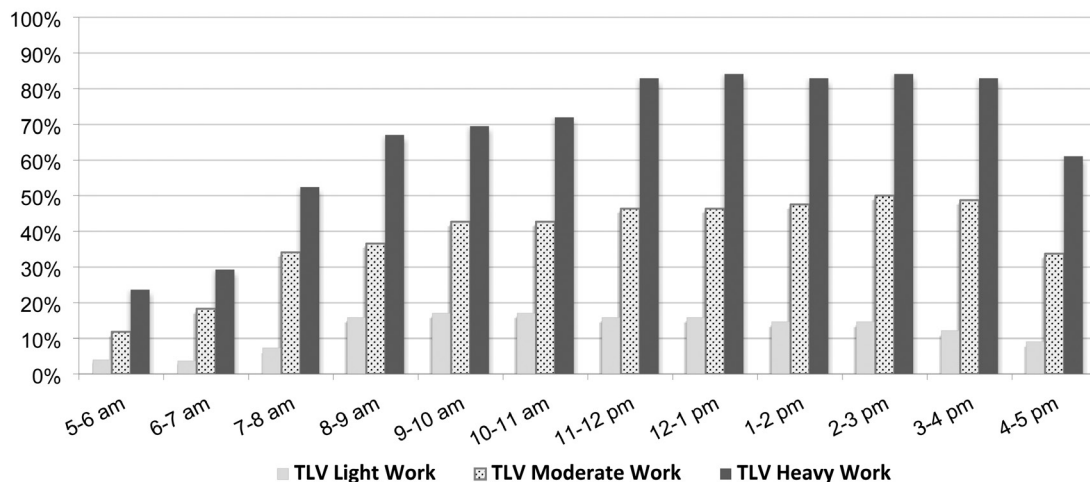
(A) Outdoor Work**(B) Indoor Work**

Figure 2. (A) Outdoor and (B) indoor work: percentage of each work hour that heat stress exposure was exceeded by work intensity, as determined by the WBGT-based TLV, for 10 residential construction sites in Al-Ahsa Province, SA, June–September 2016.

Table 2. HWA outdoors and indoors stratified by workload and time of day using WBGT data.

Time interval		6–9 a.m.		9 a.m.–12 p.m.		12–3 p.m. ^a		3–5 p.m.	
HWA (minutes)		Mean ± SD [95% CI]							
Setting	Workload								
Outdoors	Moderate	37 ± 26	[33, 40]	15 ± 21	[13, 18]	27 ± 21	[24, 29]	30 ± 20	[27, 33]
	Heavy	29 ± 25	[26, 32]	9 ± 15	[7, 11]	15 ± 16	[13, 17]	18 ± 17	[15, 20]
Indoors	Moderate	50 ± 19	[47, 52]	44 ± 22	[41, 46]	43 ± 21	[40, 45]	45 ± 21	[41, 48]
	Heavy	42 ± 21	[39, 45]	32 ± 22	[30, 35]	30 ± 20	[27, 32]	33 ± 21	[30, 37]

^aMandatory afternoon outdoor work ban (12–3 p.m.).

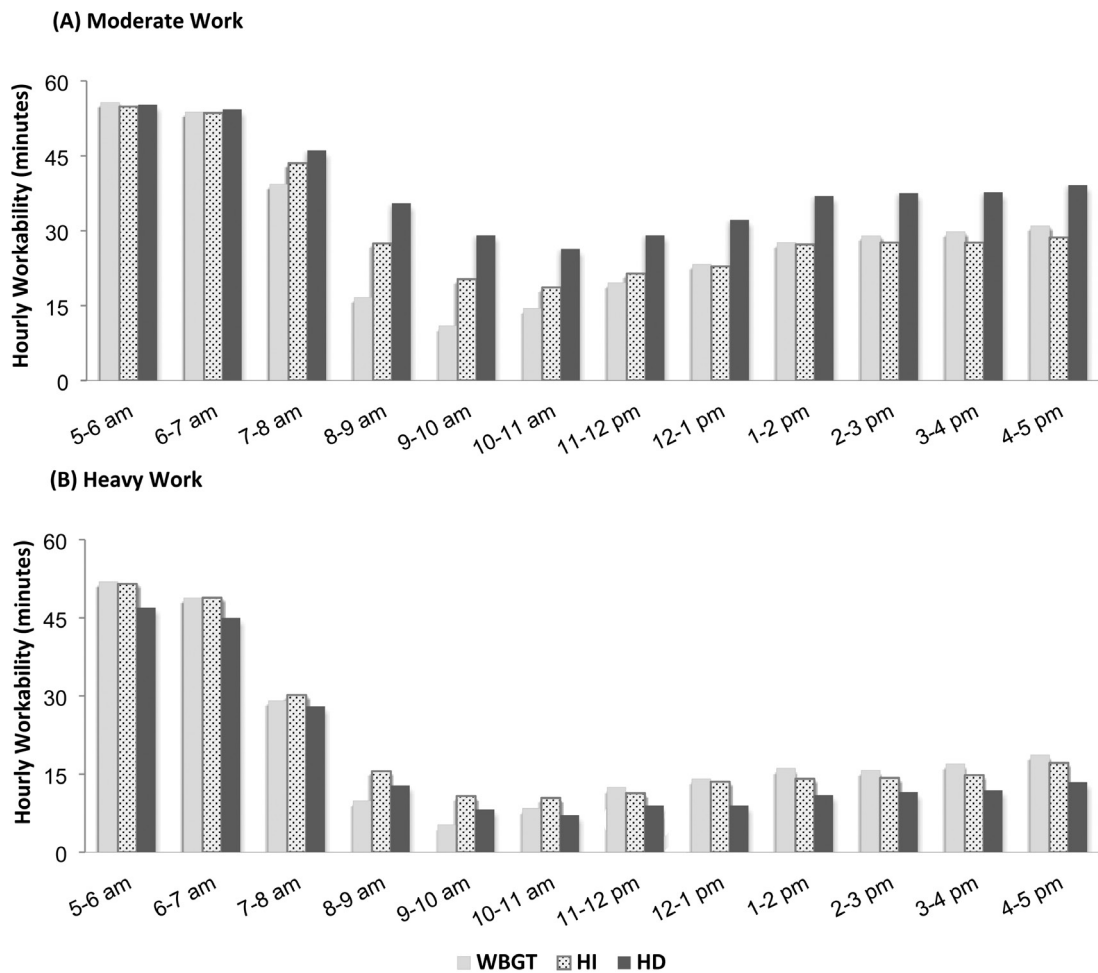


Figure 3. Outdoor work: number of work minutes permitted in each hour of the work day (HWA), a comparison of estimates using the WBGT-based TLV, the HI, and the HD adjusted for radiant heat (ΔT_{g-db}) for (A) moderate and (B) heavy construction work activities for 10 residential construction sites in Al-Ahsa Province, SA, June–September 2016.

of geographical location on climatic conditions. The workers monitored in this study were all of Indian nationality; Indian nationals constitute the majority of the workforce in SA. Accordingly, these workers could be considered representative of the construction workforce in the country.

The WBGT values in the outdoor construction work environment exceeded the ACGIH TLV by high percentages (>75%), indicating a high level of heat stress for both moderate and heavy workloads starting at 7 a.m. and continuing throughout the day and following a distinct daily trend, with the highest exceedances attained during the period before noon. Two earlier summer heat assessment studies conducted outdoors on the western coast of SA reported elevated WBGT values in the range of our findings in the ground service operations area of

King Abdul-Aziz International Airport in Jeddah City (Noweir and Bafail, 2008) and at different locations in Makkah City, where pilgrims perform Islamic rituals during the Hajj season (Noweir *et al.*, 2008). At the global level, our findings are consistent with the level of summer heat exposure (hourly mean WBGT values) reported at outdoor construction sites in other studies in tropical and subtropical countries (Kähkönen *et al.*, 1992; Inaba and Mirbod, 2007; Miller and Bates, 2007; Maiti, 2008; Pérez-Alonso *et al.*, 2011; Rowlinson and Jia, 2014; Venugopal *et al.*, 2016).

The unexpected peak in WBGT values in the early morning hours identified in our study resembled the early peak occurring well before noon in a study of heat stress exposure among sugarcane harvesters in Guanacaste, a coastal province in Costa Rica (Crowe

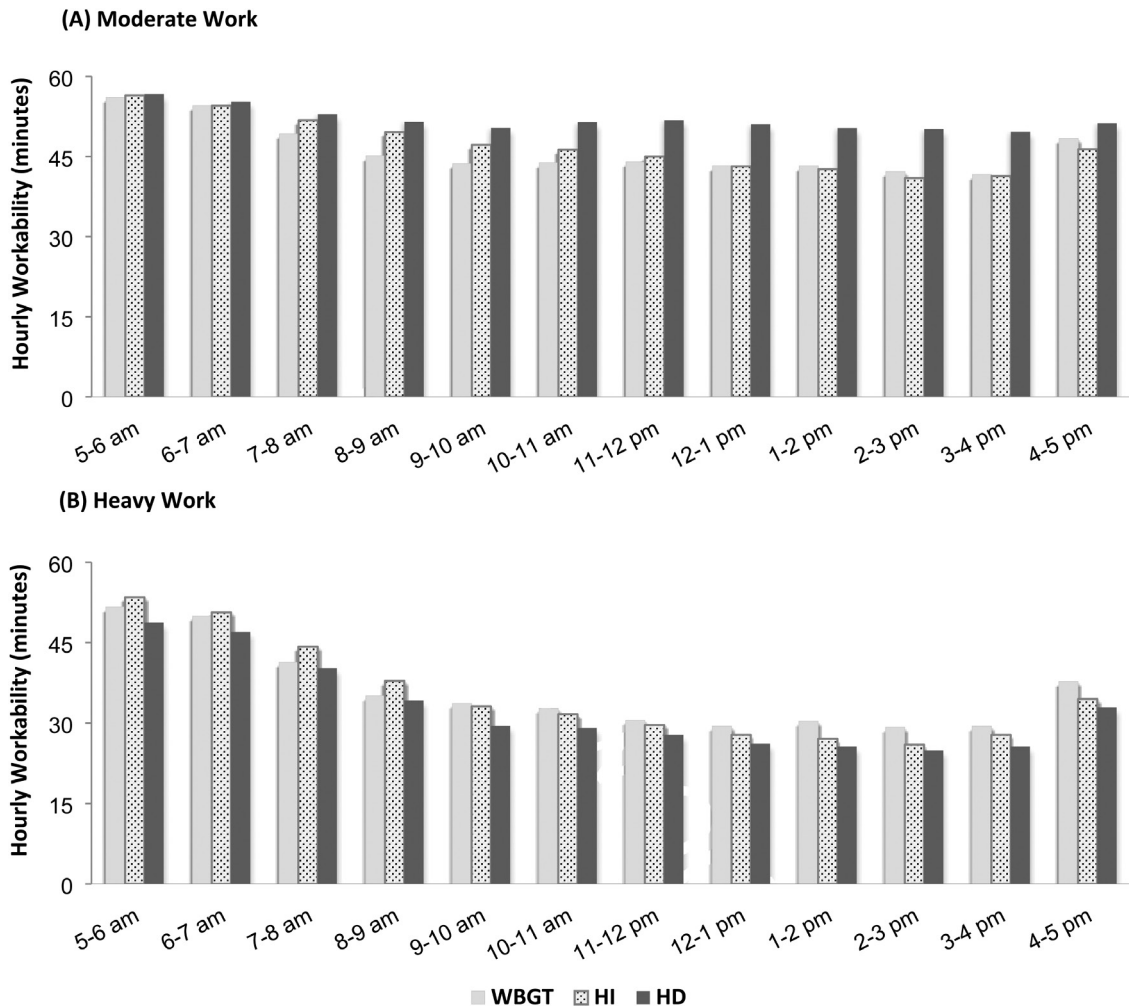


Figure 4. Indoor work: number of work minutes permitted in each hour of the work day (HWA), a comparison of estimates using the WBGT-based TLV, the HI, and the HD for (A) moderate and (B) heavy construction work activities for 10 residential construction sites in Al-Ahsa Province, SA, June–September 2016.

et al., 2013). In our study, the early peak was influenced by the high values of two heat exposure parameters, T_g and T_{nwb} , which account for 90% of the total outdoor WBGT, and reflect the high radiant heat and humidity in the early morning (Supplementary Fig. S3, available at *Annals of Occupational Hygiene* online). Long-term monitoring and analysis of solar radiation trends in SA have indicated that the solar radiation intensity increases with sunrise, reaching its maximum at 12 p.m., then decreases as the elevation of the sun decreases (Al-Dhafiri *et al.*, 2000). Higher RH in the morning than in the afternoon is a result of the lower air temperature during the morning, which in turn decreases the ability of the air to hold water compared to later in the day (Davis

et al., 2016). This phenomenon in the study area is influenced in part by the land and sea breezes, a thermally driven circulation system that develops in coastal areas and is a common characteristic of the regional climate in the Arabian Gulf (Eager *et al.*, 2008).

Although the indoor environment was sheltered from direct sun exposure, this study found that workers with moderate and heavy workloads were at risk of heat stress; the WBGT values exceeded the TLV for moderate and heavy workloads 38 and 66% of the time, respectively. Similar levels of risk were observed for indoor construction workers in India and Japan (Chinnadurai and Venugopal, 2016; Ueno *et al.*, 2018). A possible explanation for the high indoor WBGT values in this study is

that the houses were built from cement blocks, which makes them good conductors of thermal energy, with little ability to maintain cooler indoor temperatures in the absence of mechanical ventilation at this stage of construction. The lack of ventilation is clearly reflected in the difference in RH indoors versus outdoors. The relatively high indoor humidity was partially caused by the indoor construction activities that used water, such as cement mixing. The high RH influences the value of $T_{\text{nw}b}$, which represents 70% of the WBGT calculation.

Most of the construction activities observed were judged to require moderate or high workloads according to the reference table in the ACGIH guidelines (ACGIH, 2009). This is consistent with what has been perceived and described by construction workers (Chan and Yang, 2016; Venugopal *et al.*, 2016) and confirmed by observation and measurement (Abdelhamid and Everett, 2002; Maiti, 2008; Rowlinson and Jia, 2014; Chinnadurai and Venugopal, 2016; Meade *et al.*, 2016; Roja *et al.*, 2016). Workers were determined to work far beyond the time allowed by the ACGIH TLV throughout their work shift, particularly outdoors and when performing heavy work activities indoors. The effectiveness of the midday work ban was demonstrated to limit the cumulative exposure risk over the course of the summer, but it does not prevent daily excessive heat stress exposure according to international guidelines. Working in conditions of such long TLV exceedance increases the risk of heat strain, which can lead to acute health effects such as dehydration, heat cramps, heat exhaustion, and heat-stroke (Larrañaga and Bernard, 2011). Cases of these acute health effects are well-documented among workers in construction jobs (Inaba and Mirbod, 2007; Miller and Bates, 2007; Horie, 2013; Montazer *et al.*, 2013; Dutta *et al.*, 2015; Gubernot *et al.*, 2015; Jia *et al.*, 2016; El-Shafei *et al.*, 2018). Additionally, heat stress exposure has been identified as a contributor to chronic health problems, such as psychological distress (Smith *et al.*, 1997; Tawatsupa *et al.*, 2010) and cardiovascular (Vangelova *et al.*, 2006) and kidney diseases (Tawatsupa *et al.*, 2012; Luo *et al.*, 2014).

The short- and long-term health impacts of continuous work during all or part of a 12-h workday (5 a.m.–5 p.m.) were not investigated in this study. A partial explanation for the capability of these workers to sustain their work activities in the extreme heat is that they are heat-acclimated, having been employed in the Saudi construction sector for years. Many were from regions in India, such as Gujarat, Tamil Nadu, and Maharashtra, where mean WBGT values ranging from 28.7 to 34.1°C have been reported for outdoor construction worksites (Maiti, 2008; Dutta *et al.*, 2015; Venugopal *et al.*, 2016).

To some degree, those still working under the studied conditions may be survivors who practice self-pacing to withstand extreme heat and sustain their work activities. The practice of self-pacing by workers through the reduction of their metabolic rate to a safe level has been identified as a protective response to heat stress exposure in construction and other work settings (Mairiaux and Malchaire, 1985; Miller *et al.*, 2011; Nag *et al.*, 2013; Peiffer and Abbiss, 2013; Methner and Eisenberg, 2018). Not accounting for self-pacing could have resulted in an overestimation of the risk. The variability in workload intensity within and between construction work activities and the differences in physiological characteristics among workers are other influential factors of heat stress that have not been accounted for in this study. Without monitoring of workers' physiological response and actual metabolic rate, it is impossible to account for these factors and their impact on workers (Havenith and van Middendorp, 1990; Havenith *et al.*, 1998; Havenith *et al.*, 2002).

The WBGT-based TLV has high sensitivity for detecting unsustainable exposure (an inability to maintain thermal equilibrium) but relatively low specificity (Garzón-Villalba *et al.*, 2017). The TLV has been identified as being overly protective in actual work settings because this measure was developed based on laboratory studies without considering personal factors that might require higher protection (e.g. age, gender, health status, obesity, smoking, alcohol consumption habits, and other unmeasured physiological differences), which affect workers' ability to tolerate heat strain (Chan *et al.*, 2012; Jia *et al.*, 2016; Lamarche *et al.*, 2017). From this perspective, the use of the WBGT-based TLV could have contributed to the overestimation of risk in this study. To evaluate this possibility as well as to explore a convenient, reliable index to manage heat stress risk in construction work, we performed a comparative assessment of the HWA estimated by the WBGT with HWA estimations based on the HI and HD adjusted for radiant heat. This comparison showed that all indices classified the levels of heat exposure corresponding to the summer months as high risk and performing continuous moderate and heavy construction work activities is not advised outdoors. The outdoor mean HWA values based on the WBGT were more constrained than those based on the HI and HD for moderate and heavy workloads during the early and late morning periods, while in the subsequent hours, the WBGT became the least restrictive of the three indices for heavy workloads, and the HD was the least restrictive for moderate workloads. Indoors, where the environmental conditions were more uniform and radiant heat was minimized, the differences

in the mean values of the HWA among all indices were reduced significantly for heavy workloads and for moderate workloads, with the exception of the HD, which had relatively large differences compared to the WBGT.

Our findings demonstrate a high degree of consistency ($\kappa_w \geq 0.85$) between WBGT and the HI in the estimate of the HWA as an indicator of heat exposure risk. The weaker correlation between WBGT and HD aligns with results of a previous study, where HD was found to be less reliable than WBGT in the assessment of heat stress exposure risk with a moderate workload under simulated hot working conditions (D'ambrosio Alfano *et al.*, 2011). We conclude that the HI is reasonably reliable and potentially a practical surrogate for the WBGT index in the climate studied. As demonstrated in this study, the effect of radiant heat has a large influence on the outdoor heat stress exposure level during the day, which makes the adjustment of the HI highly recommended for use in guiding heat stress management programs in Saudi work environments.

Conclusions

The intensity and duration of heat stress exposure among workers in this study were very high throughout the majority of the workday, both indoors and outdoors. These results warrant immediate action, particularly in view of the limited effectiveness of the midday outdoor work ban in preventing heat stress risk and the noticeable absence of other heat stress-preventive measures. The HI, which for most Saudi employers is easier to measure than the WBGT, can be used to identify heat stress exposure risk in construction settings similar to those in this study.

For future research, it would be valuable to expand this study to other regions of SA. Increasing the monitoring period to include all months of the year and 24 h per day will provide an in-depth analysis of occupational heat stress exposure across all work periods. Additionally, it is important to assess the physiologic responses of workers to the measured heat exposures in order to determine their actual heat stress and to improve their capability to withstand extreme heat and sustain work productivity. The short- and long-term health impacts of prolonged heat exposure should be assessed, particularly chronic health problems, which could be a hidden threat to these workers' health and safety. The results obtained from this and future studies can contribute to the development of a threshold based on the WBGT or the HI to guide the management of indoor and outdoor heat stress risk in SA, thus supporting the goal of the National Transformation Program 2020

(Saudi Vision 2030, 2016). However, until such efforts are achieved, the present regulatory midday work ban is a minimum necessity. Shifting it earlier in the day should be considered. Additionally, implementation of other administrative and engineering controls is recommended to reduce heat stress exposure risk in occupational settings, including pre-work heat acclimatization, work organization that promotes worker self-pacing, the provision of cool potable water and toilet facilities, anti-heat stress clothing, portable fans, and onsite shaded resting areas with scheduled rest periods (National Institute for Occupational Safety and Health (NIOSH), 2016).

Supplementary Data

Supplementary data are available at *Annals of Work Exposures and Health* online.

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Conflict of interest

The provision of financial support does not in any way infer or imply endorsement of the research findings by either agency. The authors declare no conflict of interest relating to the material presented in this article. Its contents, including any opinions and/or conclusions expressed, are solely those of the authors.

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