Thermal Stress in North Western Australian Iron Ore Mining Staff

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Received 18 August 2011; in final form 12 October 2012; Advance Access publication 25 November 2012

Introduction: Demand for Australian mined iron ore has increased employment within this sector, thus exposing increased numbers of workers to the harsh Australian climate. This study examined the influence of hot (>30°C wet bulb globe temperature) environmental temperatures, consistent with working in North Western Australia, on iron ore mining staff.

Methods: Core temperature, hydration status, perceived exertion, mood, and fatigue state were measured in 77 participants at three time points (pre-, mid-, and post-shift) during a normal 12-h shift at an open-cut iron ore mining/processing site (n = 31; Site1) and an iron ore processing/shipping site (n = 46; Site2).

Results: A significant effect for time was observed for core temperature with greater mean core temperatures measured mid-shift (37.5 ± 0.4°C) and post-shift (37.6 ± 0.3°C) compared with pre-shift values (37.0 ± 0.5°C). All mean core temperature measures were lower than ISO7933 thresholds (38°C) for thermal safety. Mean hydration measures [urine-specific gravity (USG)] were greater at Site1 (1.029 ± 0.006) compared with those at Site2 (1.021 ± 0.007). Furthermore, both pre- and post-shift measures from Site1 and the post-shift measures from Site2 were greater than the threshold for dehydration (USG = 1.020). No differences were observed for mood or perceived exertion over time; however, measures of fatigue state were greater post-shift compared with pre- and mid-shift values for both sites.

Conclusions: Our findings indicate that the majority of mine workers in North Western Australia are able to regulate work rate in hot environments to maintain core temperatures below ISO safety guidelines; however, 22% of workers reached or exceeded the safety guidelines, warranting further investigation. Furthermore, hydration practices, especially when off-work, appear inadequate and could endanger health and safety.

Keywords: core temperature; heat; hydration; safety; thermal work limits

INTRODUCTION

Working in hot and humid environments presents unique challenges to both performance and occupational health and safety. Physical exertion under hot environmental conditions (ambient temperatures >30°C) is associated with a significant increase in the perception of effort (Tucker, 2009) and a decrease in physical work capacity (Tucker et al., 2004; Abbiss and Laursen, 2005; Peiffer et al., 2010). For example, Gonzalez-Alonso et al. (1999) observed a significantly shorter time to fatigue during constant-paced exercise in the heat (40°C), compared with that in a cooler condition (18°C). In addition, if left unchecked, rises in core temperature during exposure to heat can increase the risk of heat-related illnesses (Brake and Bates, 2002; Casa and Roberts, 2003; Smalley et al., 2003). In an industrial setting, an increase in thermal-induced fatigue and decrease in mental arousal (Nybo and Nielsen, 2001) could increase the probability of injury to the...
workers. Individuals working in the mining industry in North Western Australia are increasingly susceptible to heat-related injury and illness as ambient temperatures in this region can be in excess of 30°C wet bulb globe temperature (WBGT, which is a measure for the effects of temperature, humidity, wind, and solar radiation on the organism) for extended periods. Therefore, understanding the influence of hot environmental temperatures on worker physiology is essential in order to implement effective strategies to enhance worker safety.

Surrogate parameters, such as the WBGT, are often used as indirect heat stress indices and the primary indicator of thermoregulatory stress in occupational settings. Nevertheless, the efficacies of many of the existing heat stress indices have been questioned due to poor development or limitations in practicality and/or application (Brake and Bates, 2002). For this reason, Brake and Bates (2002) developed the thermal work limit (TWL), a calculation of the maximal metabolic work rate possible for an acclimatized, euhydrated worker under various heat stresses (e.g. ambient temperature and WBGT) in order to maintain a safe deep body core temperature <38.2°C. The use of TWL has been validated in a laboratory setting (Brake and Bates, 2001) and in underground miners (Miller and Bates, 2007) and has been suggested to be superior to the widely used WBGT, which can result in an overly conservative approach to worker safety (Brake and Bates, 2002). The validation of TWL in above ground workers is lacking. Bates and Schneider (2008) examined TWL in United Arab Emirates (UAE) workers; however, this study used tympanic temperature as the criterion for core temperature. Tympanic temperature can misrepresent core temperature as a mean bias of 1.0°C has been observed when using tympanic temperature compared with rectal temperature in human participants (Casa et al., 2007). For this reason, validations of TWL in above ground workers under thermal stress are needed.

With a greater world reliance on Australian mined iron ore and the lack of adequate information available in relation to individuals working in these environments, the purposes of the present study were to (i) examine the core temperature, hydration status, and perception of fatigue, mood, and exertion in individuals working above ground at both mining/processing and processing/shipping sites under thermally hostile environments, (ii) assess the efficacy of TWL in this group, and (iii) examine differences in individuals’ responses to working in hot conditions.

METHODS

Participants

Seventy-seven men volunteered to participate in this study. Of the 77 participants, 31 individuals [age: 34.4 ± 10.3 years; height: 178.6 ± 7.9 cm; weight: 91.8 ± 13.9 kg; body mass index (BMI): 29.4 ± 3.3 kg·cm⁻²] were working as iron ore mining/processing staff at an open-cut mine located in North Western Australia (Site₁), while the remaining 46 individuals (age: 35.2 ± 11.5 years; height: 176.2 ± 9.6 cm; weight: 82.3 ± 17.8 kg; BMI: 29.2 ± 6.1 kg·cm⁻²) were working at a North Western Australia processing/shipping port (Site₂). Participants were selected based on their risk of exposure to high environmental temperatures; thus all participants worked in manual labour positions that required prolonged daily exposure (~10 h) to outdoor conditions. In addition, at the time of data collection (January–March), all participants had been employed in their current position at this site for >3 months; thus these individuals were considered heat acclimatized (Gill and Sleivert, 2001). Participants were provided with the risks and benefits of participation in this study and a signed informed consent was obtained prior to data collection. This study was approved by the Human Research Ethics Committees at Edith Cowan University and Murdoch University prior to start of data collection.

Procedures

Participants were required to work a normal 12-h shift (6.00 am to 6.00 pm) and instructed not to complete additional tasks not normally required within their job duties. All data for each site were collected over a period of five consecutive days (between the months of January and March) under hot and humid (mean conditions for both sites: ambient temperature: 33.8 ± 2.6°C, relative humidity: 38.1 ± 14.8%, WBGT: 30.7 ± 2.6°C; Table 1) environmental conditions. Two hours before the start of the 12-h shift, participants were instructed to ingest a radiotelemetric core temperature pill (HQinc, Palmetto, FL, USA) for the measurement of internal body temperature. Immediately before the 12-h shift, hydration status was measured from a urine sample (see below), core temperature was recorded, body mass was measured, and levels of fatigue (1–10; 1 = not fatigued at all; 10 = very fatigued) and mood state (1–10; 1 = terrible mood; 10 = great mood) were measured using a 10-point scale. Mid-shift (12.00 pm), participants reported to a designated area where core temperature, self-reported fluid intake, ratings of perceived exertion (1–10 scale; 1 = none at all;
10 = great deal; Borg, 1982), mood and fatigue state, and body mass were measured. Immediately after the completion of the 12-h work shift, the complete battery of measurements was again obtained. With all scale measurements, participants were instructed to mark, using a pen, the number that matched closest their actual feelings at that time.

**Thermal work limits**

Hourly (6.00 am to 6.00 pm) data for ambient temperature, humidity, and wind speed were obtained from the Australian Bureau of Meteorology for each testing day. Using the technique previously described by Brake and Bates (2002), mean TWL was calculated for each work day using the mean ambient temperature, humidity, and wind speed. In addition, TWL was calculated for a condition of zero wind, as many participants worked within workshops that allowed negligible wind flow within their work areas (Table 1).

**Hydration status**

Pre- and post-work urine-specific gravity (USG) were measured using a handheld refractometer (Nippon Optical Works, Japan) with a USG recording >1.020 defined as dehydrated (Casa et al., 2000). In addition, changes in body mass (pre-shift–post-shift) and self-reported fluid intake (l) were used to indicate the participants’ ability to match sweat loss with fluid consumption. Participants were instructed to drink water only from their company issued 4.0-l personal hydration device (small insulated water container) estimating total volume consumed from the water remaining at the end of shift, plus any additional beverages (i.e. coffee, soft drinks) ingested. Body mass was measured using a portable electronic scale (Taylor model 7506) with an accuracy of ±0.1 kg. Furthermore, body mass was always measured wearing the same clothing pre- and post-shift and following voiding the bladder.

**Statistical analysis**

Differences in core temperature, hydration status, perceived fatigue, mood, and effort during the 12-h work shift (pre-shift, mid-shift, and post-shift) between sites were analysed using a two-way analysis of variance (site × time) with repeated measures. Significant main effects or interactions were analysed using Tukey’s honest significant difference post hoc analysis. Mean core temperature data from each site, at each measured time point, were analysed against the International Safety Organisation (ISO) guidelines for core temperature thermal safety (38°C; ISO7933; International Standards Organization, 2004) using a single-value t-test with Bonferroni corrections for multiple comparisons. In addition, a similar analysis was completed for mean USG values against the pre-defined USG (1.020) consistent with dehydration (Casa et al., 2000). All statistical analyses were completed using Statistica data analysis software (version 7; StatSoft, Tulsa, OK, USA) with the level of significance set to $P \leq 0.05$. Data are presented as mean ± standard deviations.

**RESULTS**

Mean environmental conditions for Site$_1$ and Site$_2$ during the monitoring periods are summarized in Table 1. Mean ambient temperature was greater at Site$_1$ (35.3±1.9°C) compared with Site$_2$ (31.5±2.1°C; $P < 0.01$); conversely, mean relative humidity was lower at Site$_1$ (30.9±11.5%) compared with Site$_2$ (47.1±13.4%; $P = 0.02$). No differences were observed for WBGT, TWL with wind, or TWL without wind between sites.

A significant main effect for time ($P < 0.01$) was observed for core temperature in both sites with higher core temperatures recorded mid-shift ($P < 0.01$) and post-shift ($P < 0.01$) compared with pre-shift values (Fig. 1). Furthermore, mid- and post-shift core temperatures at Site$_1$ (37.5±0.4 and 37.6±0.2°C; respectively) and Site$_2$ (37.5±0.4 and 37.6±0.3°C; respectively) were lower ($P < 0.05$) than the ISO suggested threshold for core temperature (38°C; ISO7933; International Standards Organization, 2004). Examination of the individual subjects’ data indicated that throughout the day a total of 6 participants were at or above the ISO

<table>
<thead>
<tr>
<th>Ambient temperature ($^\circ$C)</th>
<th>Relative humidity (%)</th>
<th>WBGT ($^\circ$C)</th>
<th>TWL$_w$</th>
<th>TWL$_wo$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site$_1$</td>
<td>35.1±1.8$^a$</td>
<td>29.9±10.7</td>
<td>30.5±1.7</td>
<td>140.5±9.5</td>
</tr>
<tr>
<td>Site$_2$</td>
<td>31.5±2.1</td>
<td>50.4±11.2$^b$</td>
<td>30.9±3.8</td>
<td>146.5±21.5</td>
</tr>
</tbody>
</table>

$4.8 \pm 1.5$ m·s$^{-1}$ = speed used to calculate TWL at Site$_1$; $5.9 \pm 0.7$ m·s$^{-1}$ = value used to calculate TWL at Site$_2$.

$^a$Site$_1$ significantly greater compared with Site$_2$.

$^b$Site$_2$ significantly greater compared with Site$_1$. 

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Table 1. Ambient temperature ($^\circ$C), humidity (%), WBGT ($^\circ$C), and thermal work limits with (TWL$_w$) and without (TWL$_wo$) air flow measured over 3 days at an above ground iron ore mining/processing site (Site$_1$) and an iron ore processing/shipping port (Site$_2$) in North Western Australia.
Fig. 1. Mean (±SD) core temperature (bottom) for Site₁ (closed squares) and Site₂ (open squares) and individuals core temperature values for Site₁ (top) and Site₂ (middle) measured pre-, mid-, and post-shift. *Significant main effect for time > than pre-shift values.
A significant main effect for site \( (P < 0.01) \) was observed in USG measures with a higher mean USG measured in Site 1 \( (1.029 \pm 0.006) \) compared with Site 2 \( (1.021 \pm 0.007) \) \( (\text{Fig. 2}) \). Furthermore, mean pre-shift \( (P < 0.01) \) and post-shift \( (P < 0.01) \) USG measures recorded from Site 1 and post-shift \( (P < 0.01) \) measures recorded from Site 2 were greater than the pre-determined USG threshold for dehydration.

**Fig. 2.** Mean (±SD) USG (bottom) for Site 1 (closed squares) and Site 2 (open squares) and individual USG values for Site 1 (top) and Site 2 (middle) measured pre- and post-shift. †Significant main effect for site.
Examination of the individual subjects’ data indicated that throughout the day USG was >1.020 in a total of 28 participants at Site 1 and 29 participants at Site 2 (Fig. 2). Changes in body mass and self-reported fluid intake for each site are highlighted in Table 2. No differences were observed for body mass between sites ($P = 0.95$) or over time ($P = 0.98$) (Table 2). Self-reported fluid intake showed a main effect for time ($P = 0.03$) with $0.4 ± 1.3$ l (data pooled for Site 1 and Site 2) greater fluid intake measured in the morning (i.e. pre- to mid-shift) compared with the afternoon (mid- to post-shift).

Ratings of perceived exertion, mood, and fatigue state are outlined in Table 3. No differences were observed for perceived exertion or mood state between sites ($P = 0.20$ and 0.92, respectively) or over time ($P = 0.98$) (Table 2). Self-reported fluid intake showed a main effect for time ($P = 0.03$) with $0.4 ± 1.3$ l (data pooled for Site 1 and Site 2) greater fluid intake measured in the morning (i.e. pre- to mid-shift) compared with the afternoon (mid- to post-shift).

Ratings of perceived exertion, mood, and fatigue state are outlined in Table 3. No differences were observed for perceived exertion or mood state between sites ($P = 0.20$ and 0.92, respectively) or over time ($P = 0.66$ and 0.24, respectively). A significant ($P < 0.01$) main effect for time was observed for fatigue with greater levels of fatigue measured post-shift compared with pre-shift ($P < 0.01$) and mid-shift ($P < 0.01$) values.

**DISCUSSION**

The purpose of this study was to examine the influence of working in a thermally hostile environment on core body temperature, hydration status, perceived exertion, fatigue, and mood state in above ground iron ore mining staff in North Western Australia. The main findings from this study were as follows: (i) a significant increase in core temperature was observed over time; however, mean core temperature did not exceed ISO safety standards and (ii) overall, hydration status was considered poor with USG values measured above dehydration thresholds for both sites.

In the iron ore mining sector, the typical demands associated with manual labour increase the risk of injury (Bhattacherjee et al., 2007). Furthermore, in many Australian mines, it is not uncommon for mining staff to work in thermally hostile conditions (WBGT > 30°C). These workers must not only be aware of the inherent dangers of their occupation but also the dangers imposed by the environment. In our participants, working in hot ambient temperatures (Table 1) resulted in a significant increase in core temperature during the 12-h work shift (Fig. 1). Nevertheless, the increase was relatively small $(0.6 ± 0.5°C)$ with the greatest increase observed from pre- to mid-shift $(0.5 ± 0.5°C; 6h)$ with only a further increase of $0.1 ± 0.4°C$ observed mid- to post-shift $(6h)$. The highest core temperature averaged over all participants in the present study ($~37.6°C$) was below temperatures commonly associated with negative side effects (Nybo and Nielsen, 2001; Tucker et al., 2004; Yeo, 2004) and significantly below the ISO suggested threshold for core temperature $(38°C; $ISO7933; International Standards Organization, 2004$). These findings may be taken to suggest that the nature of work completed by the mine processing staff involved in this study does not result in dangerous high core temperatures, even when working in a hot environment. However, our observed changes in mean core temperature does not discount the need for caution as several individual
workers did present with core temperature measurements in excess of ISO safety standards (International Standards Organization, 2004) (Fig. 1). Indeed, a total of 17 of 77 (22%) participants in the present study reached or exceeded the ISO safety standards for core body temperature. Further, it is possible that certain circumstances, not monitored in this study (e.g. confined space work and natural circadian rhythms in core temperature), could increase the risk of developing dangerously high core temperatures. For instance, core temperature increases in a rhythmic manner (Drust et al., 2005) with peak core body temperatures observed late in the day. Such natural circadian changes in temperature coupled with unusually high work rates or working in confined non-ventilated spaces could result in significant number of workers exceeding ISO guidelines. Further studies providing continuous monitoring of core temperature changes during various mining activities are therefore warranted.

The moderate core temperatures observed in this study were not completely unexpected despite WBGT temperatures in excess of 30°C. Current ISO7243 guidelines have identified a WBGT of 30°C as a threshold leading to a significant reduction in work performance and as a temperature warranting greater break frequency during work periods (International Standards Organization, 1989). Nevertheless, in our participants, working in conditions >30°C WBGT (Table 1) did not result in dangerously high core temperatures. As workers are able to self-select their work rate, it is possible that prolonged exposure to the high environmental temperatures resulted in a down-regulation of work intensity (Tucker et al., 2004; Hanna et al., 2011). Supporting this, ratings of fatigue recorded in the afternoon/evening (i.e. post-shift) were significantly greater compared with morning values (i.e. pre- and mid-shift; Table 3). This higher perception of fatigue later in the day would have resulted in a decrease in work pace (Tucker et al., 2004), resulting in the attenuated increase in core temperature observed in the later part of the day (Fig. 1). Our findings indicate that using WBGT as an indicator of thermal stress in above ground mining staff may result in an overly cautious approach to worker safety. Alternatively, thermal indices that incorporate greater environmental and physiological data (i.e. wind speeds, clothing insulatory capacity, and sweat rates) can provide more accurate depictions of thermal stresses that workers may encounter. Indeed, mean TWL, when calculated with wind, was >140 W m\(^{-2}\) for both sites during the collection period, with few limitations to work rate or frequency suggested at these levels (Brake and Bates, 2002).

It should be noted, however, that the calculation of TWL requires the addition of wind speed data, which may not be available on all mine sites or within specific locations in each site (i.e. covered areas, different depths within an open pit). Indeed, this study utilized global environmental conditions for each site to calculate TWL. When TWL was calculated with zero wind speed, as may be experienced in confined space works, the results indicated (110–116 W m\(^{-2}\)) that a far more cautious approach to work would be necessary. Therefore, we suggest that when all necessary data can be obtained, TWL provides the best indicator of thermal stress for worker safety; however, in absence of data, workers should revert to WBGT guidelines.

Working in hot environmental conditions can place a large strain on an individual’s body as the need to cool the core results in high sweat rates (Donaldson et al., 2003). Without proper hydration, prolonged sweating can lead to a decrease in the total volume of water stored within the body and can acutely decrease performance, alter mental states (Casa et al., 2000), and lead to syncopy (Binkley et al., 2002). For this reason, adequate hydration practices are paramount when working in hot environmental conditions and are a priority in most Western Australian mining operations. Despite a large educational program within the two monitored sites, our data indicate that most mining staff start and finish work in a state at or above dehydration thresholds (Fig. 2). Interestingly, fluid intake during work hours was adequate to maintain body mass, thus indicating that workers are able to judge their sweat rate and ingest fluid at an appropriate level. It should be noted, however, that the clothing worn by participants during post-exercise measurements may have held some water/sweat, therefore resulting in an underestimation of body weight loss. Despite this, the high USG at commencement of work indicates that participants in the present study adopted inadequate hydration practices outside of work, during workers’ ‘off-time’. These findings are not novel and have been observed in a study by Brake and Bates (2003). Interestingly, we also observed a significant difference in the level of hydration (USG) between the two sites monitored in this study. Although core temperature changes, weight loss, fluid intake, and WBGT during work were similar between the sites, it is possible that the higher ambient temperature observed in Site 1 may have contributed to the greater dehydration observed at Site 1. Clearly, further research is warranted in order to better understand ‘off-time’ practices of workers and factors influencing hydration status, especially with regards to work in varying environmental conditions.
The results of the present study provide useful information on the thermal stresses experienced by Western Australian open-cut mining staff; however, we do acknowledge that limitation in our data collection may have affected our findings. Without an actual measure of physical activity, it is not possible to quantify changes in self-selected work rate, which may have occurred during prolonged exposure to the high environmental temperatures. Nevertheless, as ratings of fatigue increased over time while rating of perceived exertion remained stable (Table 3), it is logical to suggest that work rate would have decreased. Indeed, a decrease in self-selected work rate under hot environmental conditions has previously been observed in high-intensity exercise-based research (Tucker, 2009; Peiffer and Abbiss, 2011). Additionally, our hydration measures incorporated a self-reported fluid intake, which can be prone to over- or underestimation (Westerterp and Goris, 2002). Furthermore, the participants’ knowledge that fluid consumption would be measured in this study may have resulted in over consumption (i.e. Hawthorne effect). Regardless, as all staff were accustomed to using the designated fluid delivery mechanisms and reported ‘normal’ drinking habit, we are relatively confident that the reported fluid intake was accurate.

CONCLUSION

An increased demand for Australian iron ore has resulted in an Australian mining boom, with increased numbers of individuals finding work within this sector. For this reason, mining companies, and workers alike, need to be aware of the inherent dangers of working in the heat. Our findings indicate that albeit working in a hot environment (WBGT > 30°C), open-cut mining staff in North Western Australia are able to self-regulate work intensity to maintain relatively safe internal body temperatures. Nevertheless, hydration strategies while sufficient during work hours are not adequately being addressed after hours, which could present safety issues. Although mining companies provide sound education to workers with regard to all aspects of safety, it is suggested that education on thermal stress, specifically ‘at home’ or off-duty hydration practices, should be increased to help minimize the possibility of heat-related illness and accidents.

FUNDING

This project was completed with funding from BHP Billiton Limited.

REFERENCES


