Patterns of Heat Strain Among a Sample of US Underground Miners

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Objective: This study characterizes physiological measures of heat exposure among US underground miners. **Methods:** Core body temperature measured by using ingestible sensors during subjects' normal work shifts was categorized into four temperature zones: less than 37.5 °C, 37.5 °C to less than 38 °C, 38 °C to less than 38.5 °C, and more than or equal to 38.5 °C. **Results:** On average, subjects changed temperature zones 13.8 times per shift. Temperatures increased above the recommended limit of 38 °C nearly 5 times per shift for an average of 26 minutes each episode. **Conclusions:** Unlike previous heat stress research that reported only maximum and mean temperature measurements, this analysis demonstrates a dynamic pattern of physiologic heat strain, with core body temperatures changing frequently and exceeding the 38 °C limit multiple times per shift. Further research is needed on the impact of multiple short-term, intermittent heat exposures on miners.

Keywords: core body temperature, heat stress, mining

Heat stress is a growing issue in US mining. Heat stress, which refers to the total heat load placed on the body, can lead to heat strain, which is the physiologic effect of heat exposure. Because of increasing mineral consumption worldwide and the use of new technologies, underground mines are expanding to greater depths; globally, coal and metal mines have reached depths of 1500 and 4500 m, respectively.[1] As mines expand to deeper, hotter levels, the risk of heat strain and subsequent heat-related illness among miners will likely increase. Differences in heat exhaustion incidence by depth of mine have been reported.[2] Furthermore, heat waves are expected to increase in frequency, length, and intensity,[3] posing a substantial risk to surface miners.

Several organizations have developed standards to protect workers from the adverse effects of excessive heat exposure. A World Health Organization technical report noted that core body temperature should not exceed 38 °C "in prolonged daily exposure to heavy work and/or heat."[4] The American Conference of Governmental Industrial Hygienists (ACGIH) has formulated a threshold limit value for thermal stress designed to prevent the core body temperature of most workers from reaching 38 °C.[5] The International Organization for Standardization (ISO) has developed standards for measuring and monitoring heat exposure with the goal of preventing core body temperature from exceeding 38 °C.[6] Most standards are based on the assumption that workers are healthy, acclimatized, and well hydrated, and many require estimation of metabolic workload, environmental conditions, and clothing factors in order to monitor risk of heat strain.[7]

Such assumptions, however, may not necessarily generalize to the mineworker population. Mining is a dynamic activity, and guidance from national and international organizations does not account for the fact that miners work in varied environmental conditions, performing shifting job tasks with varying metabolic workloads. Studies have evaluated various heat indices to determine which index is most appropriate for mining, but a standard mining heat index has not been identified.[8–10] To determine the relevance and usefulness of guidelines to the US mining industry, understanding the pattern of physiologic heat strain among US miners would be helpful. However, the characteristics of physiologic heat strain among US miners have not been well studied.

In a study of underground metal miners who were observed during their regular work activities, a majority of the study participants demonstrated physiologic evidence of heat strain, with 51% of the highest 10-consecutive-minute core body temperature averages exceeding 38 °C.[11] This study by Lutz et al[11] demonstrated that a population of US miners exceeded the recommended core body temperature threshold set by international and national organizations such as ACGIH. However, many questions remain regarding duration and intensity of heat exposure among workers, including (1) whether short-term exposures to core body temperatures above 38 °C differ from long-term exposures; (2) whether the risk of heat-related illness is similar in intermittent versus continuous heat exposure; and (3) the duration of acceptable exposure time for different heat loads.[7] A better understanding of duration and intensity of heat strain among US miners would help to focus heat stress research on those aspects of heat strain that could provide useful information for the mining industry in mitigating this hazard.

For this purpose, a small study was performed to develop the methodology and assess the feasibility of underground research aimed at evaluating the physiologic and performance effects of heat exposure among US miners. This descriptive analysis characterizes the physiologic effects of heat strain among a small sample of US miners.

METHODS

All miners working underground at Mine A were eligible to participate, regardless of work location. Six underground metal mineworkers were recruited to participate in the study. Each subject was monitored during three non-consecutive shifts over a 7-day rotation, for a total of 18 person-shifts. A typical shift duration was approximately 10 hours. The study was conducted in an underground metal mine with working levels at depths of up to 5200 ft. underground. Prior to physiologic data collection, each participant completed a questionnaire to provide information on demographics, baseline medical conditions, medications, and risk factors that contribute to heat strain; symptoms of heat strain over the past 6 months; history of heat-related illness; and work history. In order to obtain general information on mining experience and possible

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Clinical Significance: Our findings describe frequently changing core body temperatures that exceed 38 °C on multiple occasions per shift. The long-term consequences of these intermittent temperature elevations on worker health and safety are unknown. This research identifies the need for further studies to better understand the health effects of these exposures.

The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

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acclimatization status within the work history portion of the questionnaire, participants provided information on the number of years they had worked in mining in total, at the current mine, and in their current job position. Pre- and post-shift urine samples were collected to assess hydration status by measuring urine specific gravity using a refractometer (Atago Pocket Pal-10S, Atago USA, Inc., Bellevue, WA). Throughout each shift, participants completed brief questionnaires to assess symptoms of heat strain.

During each monitored shift, subjects were equipped with instruments to collect physiological and environmental temperature data while performing their normal work duties. Core body temperature was collected using ingestible sensors and real-time monitoring data recorders (CorTemp®, HQInc., Palmetto, FL). Ingestible sensors were administered to subjects approximately 1 hour before going underground. Heart rate measurements were collected by using programmable chest straps (T31 Transmitter, POLAR Electro Inc., Bethpage, NY). Dry bulb temperature, naturally aspirated wet bulb globe temperature, and relative humidity were collected using handheld heat stress trackers (Kestrel 5400, Nielsen-Kellerman Company, Boothwyn, PA). The instrument used to collect environmental data was tested in an environmental chamber against a primary standard heat stress monitor (QUESTemp™ 46 Heat Stress Monitor, 3M Company, St. Paul, MN) prior to field sampling to confirm measurement validity in environmental conditions similar to the mine site. Subjects who worked in multiple areas of the mine were asked to carry a Kestrel meter on their person throughout the entirety of their work shift. In these cases, the Kestrel meter was adhered to the subjects' hard hats. All physiologic measurements were collected at 20-second intervals, and environmental conditions were collected at 20 to 30-second intervals for the duration of the subject's shift.

The core body temperature recorders had to be maintained in close proximity to the subject's abdomen. Most recorders were affixed to subjects' belts. However, sometimes the recorder dislodged and failed to record. Of 18 total shifts, 0.8% of heart rate and 13.5% of core body temperature data were missing.

Occasionally, heart rate or core body temperature data readings were outside the likely physiologic range. For example, brief fluctuations in core body temperature values below 35 °C (95 °F) and above 40.5 °C (105 °F) and heart rate values below 40 and above 220 beats per minute (BPM) were observed, and accordingly, excluded. The fluctuations were likely caused by recorder misreads or by subjects drinking hot or cold fluids. Approximately 2.4% of core body temperature and 0.3% of heart rate observations were excluded based on these criteria. Missing data were imputed by extrapolating the last valid recorded heart rate or core body temperature. After data were imputed, 3-minute rolling averages were calculated for heart rate, core body temperature, and wet bulb globe temperature. Wet bulb globe temperature data were synchronized with the heart rate and core body temperature data prior to analysis. Because start and stop times were not identical between physiological and environmental measurements, data could not be merged according to seconds. However, there was little difference in values at these intervals. Therefore, data were merged on the first value of every minute within the 3-minute rolling averages. All observations before the start of each shift were excluded.

After combining wet bulb globe temperature and physiologic data, the rolling averaged data were grouped into core body temperature zones. The first zone (normal temperature) comprised core body temperatures less than 37.5 °C. The second zone (warm temperature) comprised core body temperatures of 37.5 °C to less than 38 °C. The third zone (elevated temperature) comprised core body temperatures of 38 °C to less than 38.5 °C. The fourth zone (hot temperature) comprised temperatures more than or equal to 38.5 °C. The normal temperature zone was defined based on a systematic literature review performed by Sund-Levander et al[12] that found normal rectal (ie, core) body temperatures in men ranged from 36.7 to 37.5 °C. The elevated and hot temperature zones were chosen based on the ACGIH recommendations for core body temperature thresholds.

Because we hypothesized that core body temperatures would vary during the course of a shift because of changing workloads, work tasks, or environmental conditions, we characterized the movement of core body temperatures into and out of each temperature zone by shift. Core body temperature values were grouped based on consecutive temperatures within the same temperature zone. Upon changing to a different zone, a new group was formed. For example, if the first 50 consecutive observations were categorized into the second zone (warm temperature), followed by 20 consecutive observations categorized into the third zone (elevated temperature), followed by 30 consecutive observations again categorized in the second zone, then these 100 observations would be analyzed in three separate groups (ie, zone 2, zone 3, and zone 2 repeated). Core body temperature data categorized into the same temperature zone but separated by a data grouping within a different temperature zone were considered different groups. Therefore, during one shift, a participant could have multiple groups of data within each temperature zone. For example, if a subject's core temperature moved from zone one to two to three to two to three to four, six different temperature groups would be categorized.

Mean, maximum, and range were calculated for the number of times participants moved from one core body temperature zone to another across the three monitored shifts, in addition to the number of times participants crossed the 38 °C threshold (ie, average number of times per shift that participants exceeded the ACGIH guideline temperature threshold). Mean, maximum, and range of minutes spent in each zone per shift were also calculated. Mean and maximum heart rate and wet bulb globe temperature corresponding to each core body temperature zone were calculated across three shifts. To assess inter- and intra-individual variability, each measure was analyzed both by individual participant and across all participants.

RESULTS

Subjects were men aged 25 to 60 years. Mean number of years reported working in mining was 16.1 (range 0.5 to 32). Mean number of years worked at the current mine and current job position were 9.8 and 6.3, respectively. Participant job positions and tasks varied and included the following: general laborers (ie, maintenance and upkeep of mine area, such as laying pipe and fixing rails); supervisor for general laborers; support laborers responsible for the loading and hauling of supplies/materials needed for mining; general miner (ie, drilling, blasting, bolting, and collecting rock/ore at the rock face); running equipment to collect the rock/ore at the rock face; and running equipment to direct the flow of sand to backfill previously mined areas to prevent collapse. During observed shiftwork, subjects reported one symptom consistent with heat strain during 67% of shifts, two symptoms during 33% of shifts, and three or more symptoms during 22% of shifts. Subjects commonly reported having ever had heat-related illness in the past, with reports of varying combinations of heat stroke, heat exhaustion, heat cramps, heat syncope, and heat rash. Additionally, symptoms consistent with heat strain were commonly reported to have occurred while at work in the past 6 months, with reports of nausea, dizziness, headaches, irritability, profuse sweating, excessive weakness, confusion, excessive fatigue, or excessive thirst that was not easily quenched. Of pre- and post-shift urine samples collected on 15 of the 18 shifts, 62.5% of pre-shift samples had a urine specific gravity above 1.020 (defined as dehydration), whereas 50% of post-shift samples had a specific gravity above 1.020, with an additional 25% above 1.030.

Mean wet bulb globe temperatures in the areas where participants worked ranged from 13.5 to 28.9 °C. Participants changed

TABLE 1. Mean, Median, and Range of Number of Times and Minutes in Zone Per Shift Among All Participants

Core Body Temperature Zone	No. of Times in Zone Per Shift			No. of Minutes in Zone Per Shift		
	Mean	Median	Range	Mean	Median	Range
Zone 1 (<37.5 °C)	4.7	4	0–11	232.8	210.5	0–563
Zone 2 (37.5 to <38.0 °C)	6.7	7	0–14	198.8	175	0–553
Zone 3 (38.0 to <38.5 °C)	2.9	3	0–11	61.4	31	0–329
Zone 4 (≥38.5 °C)	0.5	0	0–4	4.2	0	0–50

core body temperature zones a mean of 13.8 times per shift, with a median of 14.5 and a range of 0 to 30. Wide inter- and intra-individual variability in mean, median, and range of occurrences and minutes per shift that participants spent in each of the four core body temperature zones was noted (Table 1). For example, the number of times participants moved into zone 3 (ie, core temperature 38 °C to less than 38.5 °C) per shift ranged from 0 to 11 times (Table 1). Participants moved into zone 2 (ie, core temperature 37.5 °C to less than 38 °C) most often, with a mean of 6.7 times per shift, but spent the most cumulative time in zone 1 (ie, core temperature less than 37.5 °C), with a mean of 232.8 minutes per shift. Mean zone changes per shift varied from 7.3 to 18.0 between participants, whereas the maximum number of zone changes per shift ranged from 18 to 30 changes between participants (Fig. 1). Wide variations between and within participants were observed in the proportion of time spent in the different temperature zones (Fig. 2).

On average, participants' core body temperatures increased above the ACGIH recommended limit (38 °C) 4.9 times per shift, with a median of 5.0 and a range of 0 to 13. During each individual temperature elevation, participants' core temperatures remained at or above 38 °C for a mean and median of 26 and 9 minutes, respectively, before decreasing below that threshold. Considerable variability in minutes of each temperature elevation occurrence existed, with a range of 1 to 255 minutes. Adding all time intervals spent at elevated temperatures, participants spent an average of approximately 1 hour per shift at or above 38 °C. However, some participants spent no time at an elevated temperature during some shifts, whereas one participant had an elevated temperature for a total of approximately 5.5 hours during one shift. Substantial variability in number of times per shift that participants exceeded a core body temperature of 38 °C existed both between participants and within participants' various shifts, with one participant averaging approximately two temperature elevations per shift and three participants having a mean of approximately six temperature elevations per shift (Fig. 3). The maximum number of times each participant exceeded the 38 °C threshold varied between six and 13 times during a shift (Fig. 3). Among all six subjects overall, 50.4%, 37.5%, 11.2%, and 0.9% of time was spent in zones one (less than 37.5 °C), two (37.5 °C to less than 38 °C), three (38 °C to less than 38.5 °C), and four (more than or equal to 38.5 °C), respectively.

Among half of the participants, mean heart rate increased with increasing core body temperature zone, but the other participants' mean heart rates were relatively stable between temperature zones (Fig. 4). Maximum heart rate did not appear to vary substantially between temperature zones, even decreasing between the lowest and highest temperature zones in some of the participants (Fig. 4). Similar to temperature, mean and maximum heart rate demonstrated inter-individual variability between participants (Fig. 5). Additionally, mean and maximum wet bulb globe temperature did not consistently increase with increasing core body temperature and in fact decreased among some participants with increasing core body temperature (Fig. 5).

DISCUSSION

Research on occupational heat stress has not adequately demonstrated patterns of exposure, often leading to assumptions that heat strain occurs in a progressive, linear manner (ie, temperatures remain elevated for prolonged periods once they begin to increase). We demonstrated a dynamic pattern of physiologic heat

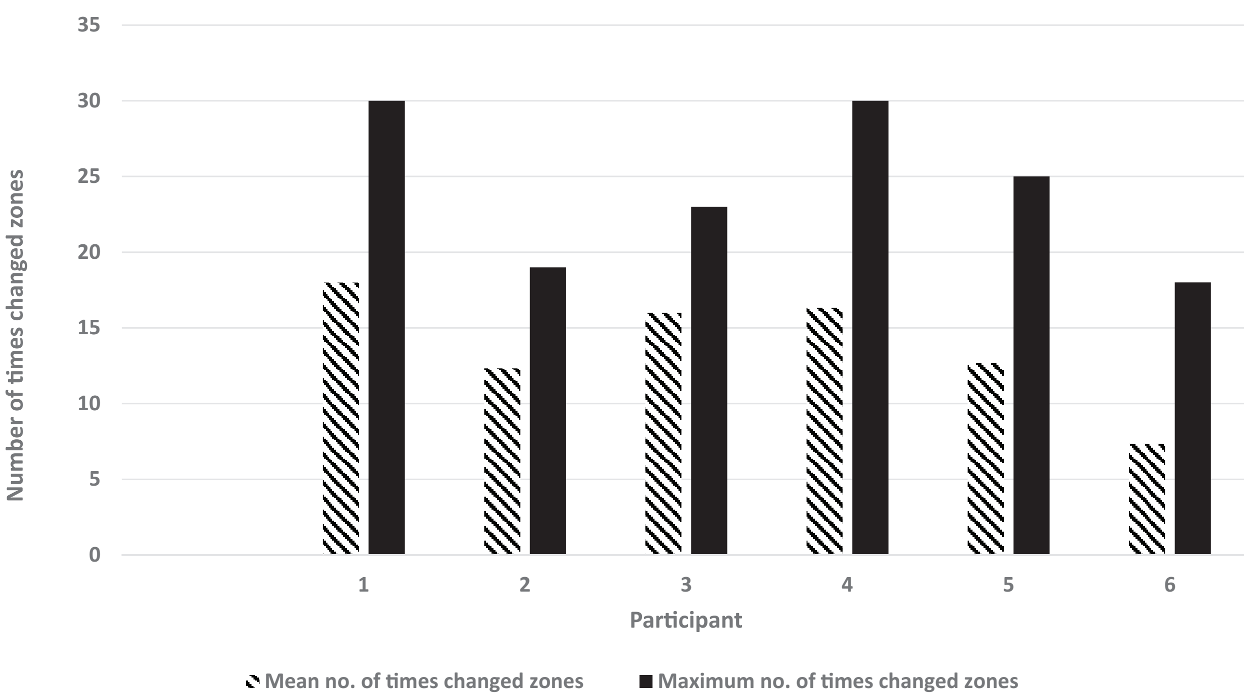

FIGURE 1. Mean and maximum number of times per shift that participants changed temperature zones, by individual participant.

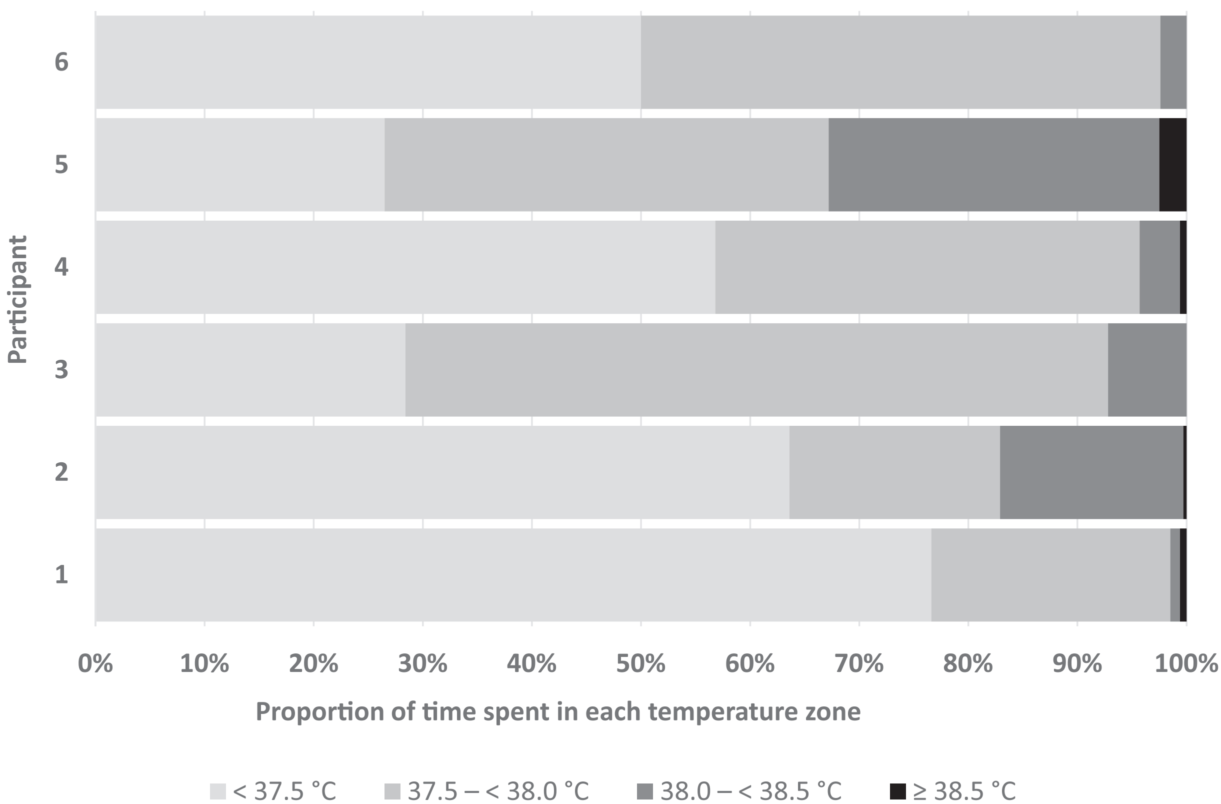

FIGURE 2. Proportion of time over three shifts that participants spent in each temperature zone, by individual participant.

strain among a small sample of underground miners, with subjects' core body temperatures exceeding 38 °C a mean of 4.9 times per shift. Considerable inter- and intra-individual variability was seen in the number of times and minutes per shift that core body temperatures exceeded 38 °C, with a range of 0 to 11 times and 0 to 329 minutes per shift. Although subjects spent an average of approximately 1 hour total per shift at core temperatures at or above 38 °C, they averaged 26 minutes each time they reached or exceeded that threshold. In general, very little time was spent at a temperature at or above 38.5 °C, although one subject's core temperature exceeded that threshold for 50 minutes during one shift.

These results demonstrate that further research on duration and intensity of heat exposure among miners needs to be conducted in order to evaluate the impact of multiple short-term, intermittent

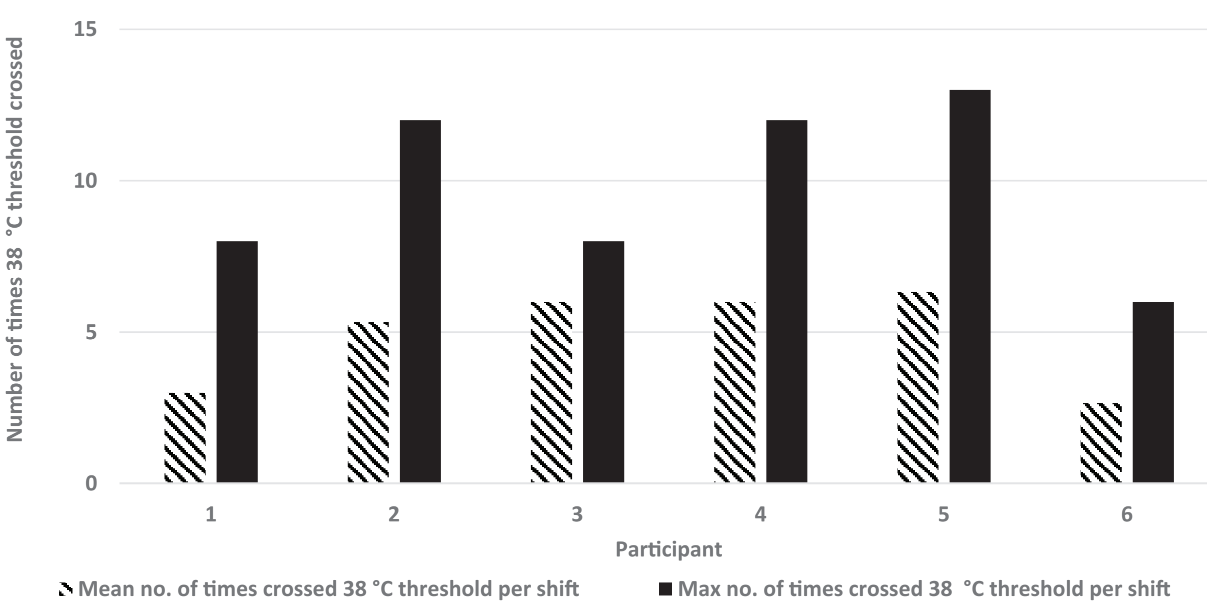

FIGURE 3. Mean and maximum number of times per shift that participants exceeded 38 °C threshold, by individual participant.

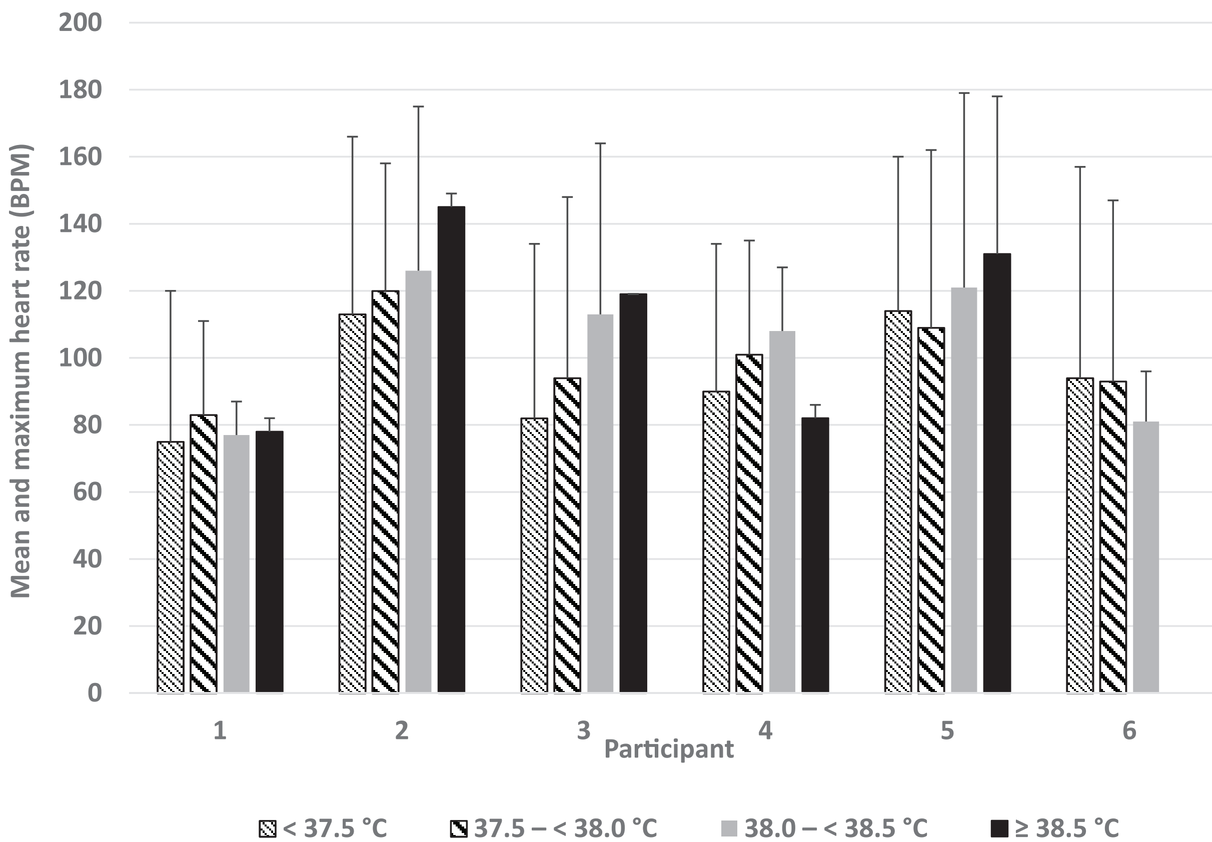

FIGURE 4. Mean and maximum 3-minute average heart rate (beats per minute) by temperature zone and participant.

heat exposures. Studies are needed to evaluate whether long durations of elevated core temperatures versus intermittent, repeated temperature elevations affect workers' health and performance in the same manner, and whether brief exposure to temperatures well above the 38 °C threshold impacts workers' health. Although subjects in this study spent a mean of only 4.2 minutes per shift at core body temperatures at or above 38.5 °C, the impact of these short exposures to more extreme temperature elevations is unclear. It is also unclear whether temperature thresholds recommended by national and international organizations should be considered maximal levels that should never be exceeded, or if a range of values around these thresholds is acceptable.[7] Future investigations should also evaluate whether temperature thresholds exist above which worker performance begins to decline. Studies have demonstrated associations between heat exposure, unsafe worker behavior, and elevated injury rates.[13–20] A better understanding of the impact on performance of both short-term and long-term exposure to elevated temperatures is needed to ensure that miners can safely perform their tasks in varied mining conditions and physiologic states.

Previous research has presented limited descriptions of heat strain, focusing on mean and maximum core body temperatures and heart rates, which fails to capture a representative pattern of physiologic heat strain among miners. Studies assessing whether temperature elevations among workers exceed recommended limits have been mixed.[21–25] Regardless of whether temperatures exceed recommended limits, most of these studies provide only core body temperature means, maximums, or ranges, without useful information on duration or pattern of temperature elevations. One analysis presented maximum values of core body temperatures averaged over 10, 30, and 60 consecutive minutes, but additional information on frequency of temperature changes would have been useful.[11] Other analyses of heat stress among miners have been performed in environmental chambers and thus do not provide information on real-world heat stress conditions.[26] Our analysis provides a more complete characterization of a likely pattern of heat strain that occurs among miners. In contrast to limiting our description to mean and maximum core body temperatures as other studies have done, our analysis provides information on duration and intensity of time spent (ie, exposure time) at different temperature levels and provides a useful characterization of patterns of heat exposure among underground miners. Similar to other studies, our investigation demonstrated that a majority of pre-shift urine specific gravity values were consistent with dehydration, with an even higher proportion of post-shift values consistent with dehydration. The hot conditions and elevated metabolic work requirements seen in many mining environments make it difficult for workers to hydrate adequately when they begin their shifts in a dehydrated state.

This analysis also provides information on the variability in heat exposure between individual workers and shifts, supporting the need to develop monitoring strategies that address dynamic work environments such as mining. Considerable inter- and intra-individual variability was seen in the number of occurrences and minutes per shift that core body temperature occupied the various temperature zones. Therefore, miners' risk of heat-related illness and heat-related performance decrements likely fluctuate within and between shifts. Although mean and maximum heart rates increased with increasing temperature zone for some subjects, this pattern was not seen for all participants. Furthermore, mean and maximum wet

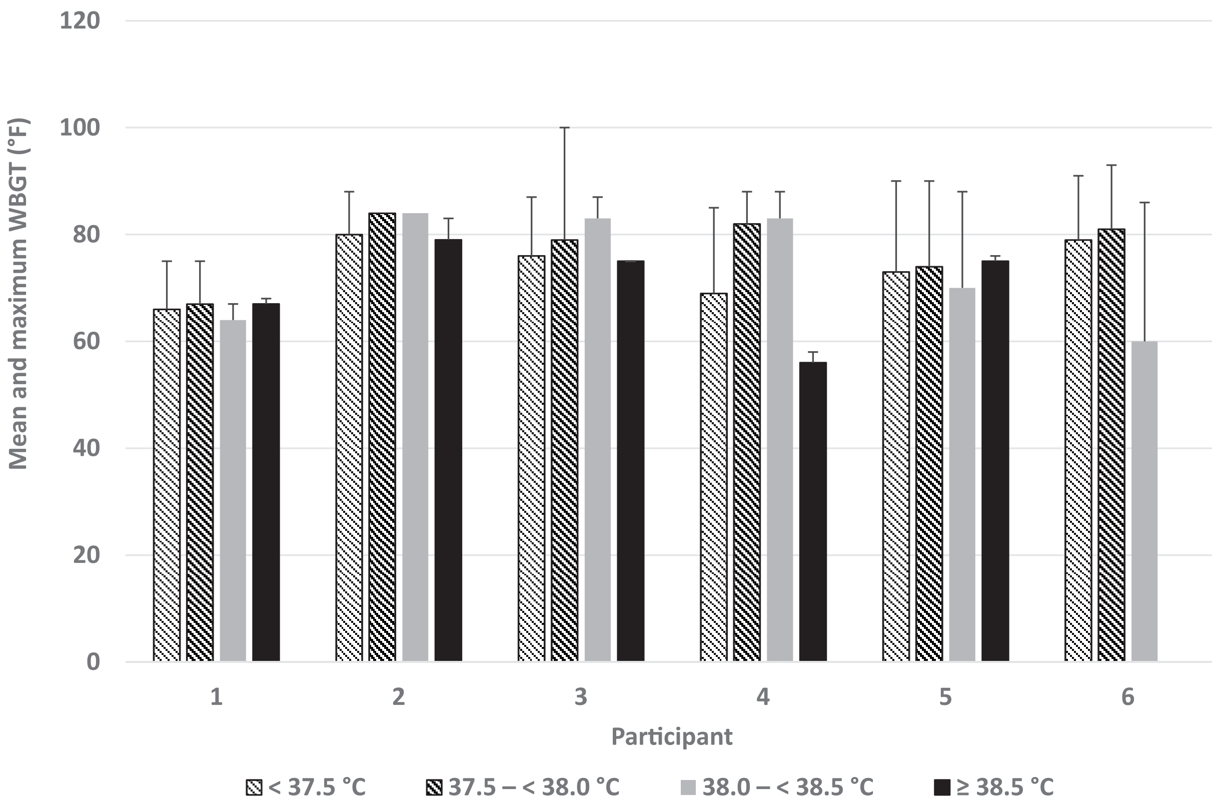

FIGURE 5. Mean and maximum 3-minute average wet bulb globe temperature (WBGT) (°F) from worksites of each participant, by core body temperature zone and participant.

bulb globe temperatures remained relatively stable across temperature zones among some participants while substantially fluctuating among others, even decreasing at times with increasing core body temperature. These results indicate that the relationship between heart rate, environmental conditions, and core body temperature is likely affected by additional factors such as the metabolic workload of specific job tasks. Task workloads in this study comprised a range of exertion levels, from equipment set up and tear down requiring little effort to high energy activities such as breaking rocks manually, climbing ladders, and lifting and carrying heavy objects. The requirement of metabolic workload estimation in ACGIH and ISO heat stress guidelines is difficult to implement given the dynamic nature of mining work, and our findings further support the need for more feasible methods to assess and monitor heat stress among this workforce.

Although this study provides useful information on the variability and pattern of heat strain among a small group of underground miners, some study aspects limit its generalizability. The small sample size limits both overall generalizability as well as statistical testing between groups. Missing core body temperature data occurred in approximately 13.5% of observations and required the use of data imputation for analysis. However, values directly before and after missing data were generally very close, if not equivalent, and thus data imputation likely did not change the overall results. The temperature capsule readings were affected not only by core body temperature but also by factors such as drinking cold fluids, and some isolated readings were deleted because they were briefly beyond the physiologic range. The subjects in this study did not always work in the hottest areas of the mine, and thus patterns of heat strain might be very different from those of miners working in hot areas. Nevertheless, our subjects still demonstrated evidence of heat strain, indicating that miners in mine areas beyond obvious ''hot areas'' are likely at risk of heat strain. Work history was assessed to determine possible acclimatization status, but recent loss of acclimatization from vacation or other time off was not evaluated. Finally, Kestrels measuring wet bulb globe temperatures were placed in work areas by the participants rather than by investigators, and therefore might not have captured the most accurate worksite environmental conditions.

Despite these limitations, this study provides a novel way of assessing heat strain by evaluating blocks of consecutive core temperatures, offering a more complete picture of the overall burden and pattern of heat exposure among miners. Future study plans include performing similar assessments in a larger sample of miners to obtain more generalizable findings, incorporating assessments of work intensity, and including measures of worker performance to evaluate heat-related decrements in performance. To develop a better understanding of heat strain among US miners and its effects on worker performance, these study plans involve evaluating workers at their worksites and within an environmental chamber. Results from this study will be used to develop improved monitoring and mitigation strategies. A better understanding of the pattern of heat strain among miners will also enable investigators to identify gaps in knowledge to drive future research—an important endeavor given the expected rise in heat stress burden among both underground and surface miners.

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