HEAT STRESS IN CANADIAN DEEP MECHANIZED MINES: LABORATORY SIMULATION OF TYPICAL MINING TASKS PERFORMED IN VARYING ENVIRONMENTS

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INTRODUCTION

Heat stress in the mining industry has been a cause for concern for most of this century. Many of the issues affecting work in hot environments which were first addressed in South African mining operations in the 1920's remain unresolved. In Canada, the growing need to combat personnel heat exposure in mines, as a function of depth, is becoming an increasingly important issue. The sources of heat in underground mines are numerous. Factors such as the rock and ground water temperature are considered as the main determinants of temperature at a given depth in an underground mine (5). Increased mine air temperature also occurs due to autocompression, powered equipment, electrical units, rock movement and blasting (2, 4).

Currently, the Canadian mining has adopted the American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Values (TLVs) as a heat stress screening criteria (see http://www.acgih.org/home.htm). TLVs refer to level of heat stress that all workers may be repeatedly exposed day after day without adverse effect. In the case of heat stress environments, TLVs for heat stress are provided in terms of WBGT values. The values are based on the assumption that nearly all acclimatized, fully clothed workers with hydration should be able to function effectively under the given working conditions without exceeding a core temperature of 38.0°C. Within its application, what is at issue is whether any environmental "standard" provides adequate protection to the worker and adequately accounts for the specific working conditions. The WBGT index is particularly poor in accounting for individual variation in heat stress response, which is known to be influenced by many factors such as physical fitness, age, body composition, health status, etc. Of particular importance is the fact that exposure guidelines are based upon a core temperature limit criteria of 38.0ºC; however, even when accounting for the non-environmental factors, core temperature response is still highly variable between individuals.

Current Canadian labour codes in all provinces employ the guidelines recommended by the American Conference of Governmental Industrial Hygienists (ACGIH) that are Threshold Limit Values (TLVs) based upon Wet Bulb Globe Temperature (WBGT) measurements. The TLVs are set so that core body temperature of the workers supposedly does not exceed 38.0ºC (~1.0ºC above resting values). At issue in the application of the ACGIH TLVs is that mining was not an industry that was originally considered in its derivation and consequently factors specific to deep mining operations, may not be adequately accounted for in the prediction of the work limits. Additionally, the criteria were based upon externally determined, regimented tasks and rates which may not apply to mining where the workers often determine the mechanical nature of the task and work rate (1). Thus, the following study was conducted to evaluate the thermoregulatory responses and work performance limits during simulated mining tasks performed under different levels of heat stress.

METHODS

Ten healthy and physically active male participants (age 20 ± 1 years: height, 1.77 ±0.06 m; mass, 69.5 ±10.9 kg; body fat, 15.5 ±3.7%) volunteered to participate in the study. All subjects were informed of the details of the protocol, signed a volunteer consent form and participated in a familiarization session before their participation. The experimental protocol was approved by the Human Research Ethic Committee at the University of Ottawa.

All participants were required to participant in 6 separate laboratory testing days (1 screening visit and 5 experimental testing sessions). On testing day 1, body adiposity and VO_{2max} were measured. Maximal oxygen consumption was measured during a progressive treadmill running protocol. The hydrostatic weighing technique was used to determine body density. Calculation of the percentage of body fat was based on the Siri equation (6) Also, during this session, the subjects were familiarized with all procedures to be performed during the investigation period.

During the 5 experimental testing sessions, the subjects were required to perform a simulated work/rest cycle during a 2-h exposure in a temperature controlled chamber maintained at an air temperature (T_{am}) and relative humidity (RH) and equivalent wet-bulb temperature (WBT) as follows:

Condition	T_{am} (ºC)	RH
WBT 24 ºC		
$\mathbf{A_{WBT24}}$	30	60
$\mathbf{B_{WBT24}}$	35	40
WBT 28 ºC		
$\mathbf{A_{WBT28}}$	35	60
WBT 32 ºC		
$\mathbf{A_{WBT32}}$	35	80
$\mathbf{B_{WBT32}}$	39	60

During the 2-h exposure subjects performed simulated mining tasks involving work patterns determined during a previous study directed at evaluating various common tasks that miners undertake during normal day-to-day mining operations. The work consisted of: i) video-recording miners performing selected tasks during a typical 8 to 10-hr work period, and ii) conducting a time/motion analysis of tasks based on these recordings. Based on the previous analyses, a 2-h work protocol was developed which involved the following 4 categories: 1) standing rest, 2) lower body movements only (walking), 3) upper body movements only (pulley system), and; 4) combined lower and upper body movements.

Based on the work/rest cycles measured in the field, the activities were performed in the following cycle: Task 3 (1 min), Task 4 (2 min), Task 2 (1 min), Task 4 (23 min), Task 2 (1min), Task 1 (3 min), Task 4 (28 min), Task 1 (23 min), Task 4 (32 min), and Task 2 (6 min) for a total of 120 minutes. The work periods were divided into 6 main work periods as follows: period 1 = 386 W; period 2 = 360 W, period 3 = 345 W, period 4 = 227 W, period 5 = 365 W, period 6 = 285 W.

The presentation of the experimental trials was balanced between participants so that the effect of order was avoided. Testing days were separated by a minimum of 72 h. All trials were performed at the same time of day. Participants were asked to arrive at the laboratory after eating a small breakfast (i.e. dry toast and juice), but consuming no tea or coffee that morning, and also avoiding any major thermal stimuli on their way to the laboratory. Participants were also asked to not drink alcohol or exercise for 24 h prior to experimentation. On arrival to the laboratory subjects were instrumented and clothed in a standardized mining ensemble consisting of cotton shorts, cotton socks, coveralls, hard hat, safety belt and steel-toe boots.

Esophageal temperature (T_{es}) was measured using a thermocouple temperature probe (Mon-a-therm General Purpose, Mallinckrodt Medical, MO, USA) inserted through a nostril, into the esophagus, estimated to be positioned at the level of the heart (3). Rectal temperature (T_{re}) was measured using a paediatric thermocouple probe (Mon-a-therm General Purpose Temperature Probe, Mallinckrodt Medical, St-Louis, MO, USA) inserted to a minimum of 12 cm past the sphincter. Skin temperature was measured at 9 points over the body surface using 0.3 mm diameter T-type (copper/constantan) thermocouples integrated into heat-flow sensors (Concept Engineering, Old Saybrook, CT, USA).

A one-way analyses of variance (ANOVA) was used to analyze the differences in T_{re}, T_{es}, T_{au}, and T_{sk} at end of exposure between ambient conditions. Differences were considered significant when $p \leq 0.05$. When significance was found, a pair-wise comparison was performed using a paired sample t-test.

RESULTS

The mean rectal, esophageal and skin temperature responses are presented in Table 1. None of the subjects could complete the 2-hour simulated mining work task at a WBT of 32 ºC. The mean exposure times were 89 and 84 min for A_{WBT32} and B_{WBT32} respectively.

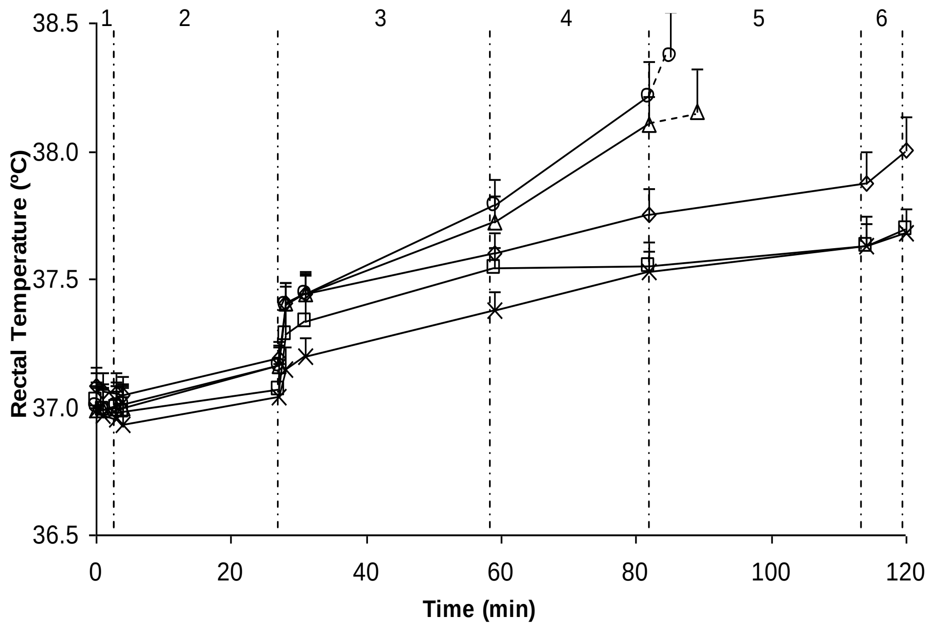

Figure 1. Mean rectal temperature during a 2-hr simulated mining work period under the following ambient conditions: a) wet-bulb temperature (WBT) of 24ºC: ambient air temperature (T_{am}) of 30°C and 60% relative humidity (RH) (□); b) WBT of 24ºC: T_{am} of 35°C and 40% RH (×); c) WBT 28ºC: T_{am} of 35°C and 60% RH (◇); d) WBT of 32ºC: T_{am} of 35°C and 80% RH (△); and, e) WBT of 32ºC: T_{am} of 39°C and 60% RH (○).

There were no significant difference in the end of exposure T_{re} and T_{es} between the two ambient conditions for the WBT 24 ºC (i.e., A_{WBT24} *vs* B_{WBT24}) (p=0.564, p=0.660) and 32 ºC (i.e., A_{WBT32} *vs* B_{WBT32}) (p=0.205, p=0.100) conditions respectively (Figure 1). We show that the T_{re} and T_{es} were significantly greater for both ambient conditions at a WBT of 32 ºC as compared to all conditions for both WBT 24ºC (p=0.004, p<0.001) and T_{es} was significantly greater for 28 ºC(p=0.016) but T_{re}, was not (p=0.172). T_{es} was significantly lower for both conditions at the WBT 24ºC as compared to WBT 28ºC (p=0.001), but T_{re} was not (p=0.285).

Table 1. Mean rectal, esophageal and skin temperatures at end of exposure during a simulated mining work protocol.

Condition	T_{re} (°C)	T_{es} (°C)	T_{sk} (°C)	Exposure time (min)
WBT 24 ºC				
$A_{WBT24\ (30ºC\ 60\%\ RH)}$	37.70	37.39	34.05	120
$B_{WBT24\ (35ºC\ 40\%\ RH)}$	37.68	37.43	35.08	120
WBT 28 ºC				
$A_{WBT28\ (35ºC\ 60\%RH)}$	38.01	37.81	35.53	120
WBT 32 ºC				
$A_{WBT32\ (35ºC\ 80\%\ RH)}$	38.16	38.13	35.94	89
$B_{WBT32\ (39ºC\ 60\%RH)}$	38.37	38.48	36.36	84

CONCLUSIONS

Our previous work has demonstrated that there in addition to the diversity of the tasks miners perform in Canada's deep mechanized mines, there is a high degree of variability of the environmental conditions under miners must perform. While the ambient temperatures can vary significantly from one location to another within the mines, they are also highly variable within a given location depending on the operational conditions (i.e., type of work performed, use of water spray, use of machinery and transport vehicles, etc.). It is therefore important for mine supervisors to monitor the ambient conditions in order to ensure the safety of the miners. We show that miners performing common mining tasks over a 2-h work period are at risk of developing heat-related injuries when performing in ambient conditions equivalent to a WBT of 28°C as rectal temperature achieved 38.0°C which is considered the upper limit for exposure as currently applied in Canadian mining operations (based on the ACGIH TLVs). Typically, work shifts are 10 to 12 hours in duration. Thus, it is important that miners be provided appropriate management tools that can assist them to reduce the risk of heat stress under these conditions. It is evident however that work performed in more extreme conditions (i.e., WBT 32°C), such as in mine shafts or work zones the removal of heated air and replacement with cooler air (ventilation and (or) refrigeration) is unavailable implementation of heat stress controls to protect mining personnel is critical.

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