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Effect of a Simulated Mine Rescue on Physiological Variables and Heat Strain of Mine Rescue Workers

Justin Konrad, MHK, Dominique Gagnon, PhD, Olivier Serresse, PhD, Bruce Oddson, PhD, Caleb Leduc, MHK, and Sandra C. Dorman, PhD

Objective: To describe physiological responses of mine rescuers during a simulated mine emergency. **Methods:** Body-worn monitors ($n = 74$) and core temperature (T_c) capsules ($n = 54$) assessed heart rate (HR), respiration rate (RR), energy expenditure (EE), oxygen consumption ($\dot{V}O_2$), T_c and skin temperature (T_{skin}), by team position and task. A multivariate analysis was performed with team positions, tasks, and measures as factors. **Results:** HR-$_{HRmean}$ and HR_{peak} were 78.6% and 94.5%, respectively, of predicted maximum heart rate. Arduous labor tasks elicited higher HR, RR, and $\dot{V}O_{2\,mean}$ than casualty care. Captains exhibited lower HR_{mean}, HR_{peak}, RR, RR_{peak}, $\dot{V}O_{2\,mean}$, T_c, and T_{skin} compared with other positions. $T_{c\ mean}$ exceeded 38.6 °C ($n = 14$ recorded T_c >39 °C). **Conclusions:** Captains' physical loading and heat stress were lowest. Nonetheless, all tasks and positions induced high physical load and heat strain.

Keywords: heat stress, mine rescue, mining, occupational health and safety, physical exertion

The mining industry has high occupational rates of serious injury and fatality: the Ontario Mining Industry reported 945 injuries in 2014 alone.[1] Frequent accidents involving fires underground, falls of ground, mobile equipment collisions, exposure to harmful environments, and falls from heights, often require rescue.[1] Ontario alone averages 44 mine-related rescues annually,[2,3] although mine rescue related injuries are not recorded separately in the statistics (personal communication: Ontario Mine Rescue). Globally, mine rescue workers have died; and in 1998 the International Mine Rescue Body (IMRB) was specifically created in the aftermath of one such tragedy; which claimed the lives of six Polish mine rescuers during a mission, from heat-related illness.[4] Canada has not had a similar tragedy to date, however, in 2015, Ontario conducted a comprehensive, underground mining health, safety and prevention review and identified: physiological factors associated with required fitness needs of volunteer, emergency responders; and acclimation to mine rescue conditions; as key health and safety issues, to have the greatest impact on improving health and safety outcomes.[5]

Currently, mine rescue work in Canada does not require a fitness standard. The Supreme Court of Canada (and described by Jamnik et al)[6] states that a fitness standard for a workforce be: criterion-based and validly linked to the critical, life-threatening, physical demands of the job. Specifically, the standard be based on "safe" (properly executing the life-threatening, physically demanding emergency task) and "efficient" (completing tasks in a time frame suited to the emergency circumstance) requirements. The assignment of Safe and Efficient policies is the responsibility of the occupation-specific participant-matter experts. These standards must take into account the individualities of the participants (age, sex, experience).[6] Therefore, to implement a fitness standard, describing the physical demands and the tasks performed during a mine rescue is a primary priority.[6]

Mine rescue work is performed by a team of volunteer mine employees who are trained in mine-related emergencies.[3,7] During an emergency involving a casualty, rescuers are required to carry supplies; weighing approximately 142 kg.[3,6] Furthermore, all tasks require personal protective equipment (PPE) (approximately 22 kg).[3,7] Mine rescue teams consist of six members: Captain, Vice-Captain, No. 2, No. 3, No. 4 persons, and a Briefing Officer: who remains on surface for the duration of the emergency.[3,7] The Captain is responsible for leading the team, communicating with the Briefing Officer, providing instructions to and ensuring the wellbeing of the team underground. The Captain does not perform other tasks unless under extreme circumstances.[3] The Vice-Captain is responsible for providing some instruction, but will assist in all rescue-related tasks.[3] Number 2, No. 3, and No. 4 persons have similar roles: work according to Captain's instructions and sharing tasks, (eg, eliminating hazards, treating a casualty, and firefighting).[3] This division of labor creates inherent differences in physical loads between the Captain and other members of the team. Differences between team positions have never been examined in the literature to date.

Research studying mine rescue work has only examined specific rescue-related tasks; showing these tasks to be extremely physically demanding.[3,8–11] Rescuers have never been studied during an actual mine rescue event. Stewart et al[8] reported a mean increase to 91% of the age-predicted maxima heart rate (APMHR) of mine rescue volunteers across three validated tasks during a controlled, simulated mine rescue environment: fire suppression, incremental carries, and shoveling. The American Conference of Governmental Industrial Hygienists (ACGIH) sets a recovery HR threshold of 110 bpm after 1-minute of rest following activity, as a way to assess heart strain.[12] This study determined rescuers could only achieve HR between 139 and 149 bpm after 90 seconds following fire suppression; and nearly 120 seconds after shoveling and incremental carries.[8] Heart rate in this range is considered high and well above ACGIH threshold level values of 110 bpm.[12] This is significant given that, in an actual emergency, there may not be time to adequately recover, and underlines the high risk for rescue participants during a mission.

These elevated physical loads can be exacerbated in underground mine conditions as they are characterized by temperatures

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Clinical significance: Mine Rescue was identified as a priority issue by the Ministry of Labour's Mining Health, Safety and Prevention Review (2015). Recommendations include instituting a fitness standard and mitigating heat stress. This study is the first step in enacting these recommendations and was supported by the International Mine Rescue Body.

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exceeding 40 °C, and 60% humidity.[12,13] The primary mechanism of heat loss (perspiration)[14–16] is inhibited by high humidity and extensive protective equipment.[10–11] These impaired cooling mechanisms, combined with high physical activity, will result in higher than normal core temperature (T_c), significantly increasing the risk of heat-related illnesses.[10–11]

Studies to date have been conducted in controlled, artificial settings, following precise work-rest schedules, in which individuals knew tasks beforehand and had ample time allocated for rest; often participants were not professional mine rescuers.[8–11,13] In a real rescue, mine rescuers often work supra-maximally for short bouts, often exceeding workloads of 1000 W.[8,9] Hardcastle et al[9] stated that real-life emergencies would endure greater physiological responses (than the study scenario) due to inadequate rest and hydration for the duration of the rescue.

However, other than collecting physiology data during an actual mine rescue, the closest approximation would be a simulated mining emergency. The IMRB oversees a global competition biennially to present realistic mine rescue simulations to evaluate and share skills required to perform rescue operations in a mining environment. In 2016, Ontario hosted this competition in an underground mine, under stressful, highly realistic conditions, providing a unique opportunity to study mine rescue workers during a realistic mine rescue event.

Therefore the purpose of this study was threefold: (i) to describe the mean HR, peak HR (HR_{peak}), respiration rate (RR), peak RR, energy expenditure (EE), and mean oxygen consumption ($\dot{V}O_{2\,mean}$) of the primary tasks performed in a mine rescue; (ii) to describe differences (if any) between the captain and other appointed positions on mine rescue teams; and (iii) to describe the T_c and skin temperature (T_{skin}) of mine rescuers during a simulated mine rescue emergency.

METHODS

Participants

At the 10th biennial International Mine Rescue Competition (IMRC), 27 teams comprised of six members each, competed. Teams were comprised of a: Captain, Vice-Captain, No. 2 person, No. 3 person, No. 4 person, and a briefing officer. We only recruited participants going underground and therefore did not recruit the briefing officer, leaving us with a total of 135 eligible participants. Seventy-six mine rescue personnel agreed to participate in this study (56.3% response rate). Of the 76 participants, 57 provided additional consent to ingest a thermometric T_c pill (42.2% response rate). All participants provided written, informed consent prior to the start of data collection. This study was approved from the Institutional University Research Ethics Board (REB #6009820).

All participants were trained, mine rescue personnel who were currently participating in, and had regularly performed mine rescue training activities in the past. With the exception of one team (a team of experts put together from multiple countries), all team members had previously trained together as a team and had been selected by their home country as their ‘‘best’’ to represent them at the International Mine Rescue Competition (IMRC).

Experimental Design

The competition was organized by Ontario Mine Rescue personnel, who created a series of scenarios to reflect common, real-life emergencies. Judges (experts in Mine Rescue) score the performance of each team, according to the rules and regulations governing Mine Rescue Competitions, as described on the IMRB website. The competition took place in an operational, underground mine in Sudbury's 114 ore body and is the most realistic mine rescue scenario possible, barring an actual event. Actors played the part of victims, and smoke was actively produced for the fire simulation. The participants did not know what the competition consisted of, until the briefing occurred, just prior to mine entry; mimicking an actual emergency. The day before the competition, baseline data were collected for individual participants characteristics (height, weight, age, team role, and chest-circumference for the body-worn monitor). Prior to the mine-rescue event, participants were equipped with the body-worn monitoring devices and (for $n = 57$ participants) also directed to ingest a T_c pill 2 hours prior,[14] both of which recorded and collected data continuously for the approximately 2-hour underground portion of the mine rescue simulation event. Up to four teams competed at a given time, as the starting of teams was staggered to process all teams over the 3 days (one team completing a task at any given time). Cameras were placed throughout the mine to video-record the primary key aspects of the competition for all teams. These tasks were time stamped, to allow for a coordinated examination of the physiological data with individual tasks.

During the underground competition, competitors were challenged by four key tasks. They descended underground via a jeep with a heavy basket containing various tools (weighing approximately 100 kg). Then leading into the four tasks are as follows:

(1) The first task involved an unconscious casualty and a casualty in shock; rescuers treated the casualties and prepared them to be transported to surface.
(2) The second task involved a simulated fire, in which rescuers constructed a barricade composed of various materials (eg, bricks, fire retardant wrapping, and beams).
(3) The third task involved a conscious casualty impaled on a steel post (alive and requiring first aid and rescue). This required rescuers to utilize extrication tools and perform precise first aid treatment to the wound.
(4) The fourth task, rescuers loaded the casualty into a basket with a trolley to perform removal of the impaled victim via an exit route with a steep incline. This basket, with tools and the casualty, weighed in excess of 180 kg. Tasks 1 and 3 were similar in nature (casualty care) as are tasks 2 and 4 (arduous labor).

See Appendix A (Supplemental Digital Content 1, http://links.lww.com/JOM/A495) for photographs illustrating and summarizing these four tasks.

Measures

Mining Environmental Conditions

Captains recorded ambient conditions with a portable weather meter (Kestrel 3500) Pocket Weather (Nielson-Kellerman, US) meter immediately upon arrival at each task site and these are the averages. See Table 1.

Heart and Respiration Rates

A heart and respiration rate monitor (Equivital Life Monitor™, Hidalgo, UK), with integrated technology, continuously measured and recorded HR, RR, T_{skin}, body position, and accelerometry. A Sensor Electronic Module (SEM) integrated within the

TABLE 1. Ambient Conditions of the Mine in the IMRC

Task	Dry-Bulb Temperature (°C) (T_{db})	Wet-Bulb Temperature (°C) (T_{wb})	Relative Humidity (RH) (°C) (%)
1	25.7	22.0	72.4
2	34.7	24.7	43.8
3	18.0	17.0	90.6
4	18.0	17.0	90.6

IMRC, International Mine Rescue Competition.

belt, recorded T_{skin} via infrared thermometry, as well as saved all other recordings for later analyses. This device weighs 38 g, measures 78 mm × 53 mm × 10 mm, is water resistant, intrinsically safe, and is utilized via a fitted-chest strap, containing a two-lead electrocardiogram located underneath the pectorals (ECG) (256 Hz). The ECG collects cardiovascular data, including HR and rhythm (HRV); however, HRV data analysis is not included in this manuscript. All measures were continuously recorded from before entering the mine up until the belt was removed following the underground competition. This was further analyzed to determine peak and minimum HR and RR values. This device was fitted on participants approximately 10 minutes prior to competition briefing. Energy expenditure and estimated $\dot{V}O_{2\,max}$ were estimated from HR (First Beat Technologies Software, Jyväskylä, Finland). Energy expenditure described the physical load of each task performed by team positions and estimated $\dot{V}O_{2\,max}$ provided insight on the cardiorespiratory fitness of the participants. RR was measured and recorded via thoracic expansion (around the lower part of the thorax) during breathing.

Core Temperature

T_c was measured via an ingestible thermometric pill (Vitalsense™, Respironics, Bend, Oregon), which measured T_c every 15 seconds and relayed recordings to the SEM for data storing. This medical-grade capsule has dimensions of 23 mm long × 8.6 mm diameter and weighs 1.6 g and is composed of biocompatible polycarbonate. Current literature involving ingestible T_c pills employs ingestion of 2 hours prior, as described by Hardcastle et al.[9]

Statistical Analysis

The participants' characteristics (Table 2) and physiological measures displayed in the tables and figures depict the mean ± SE. Participants were organized by positions (Captain, Vice-Captain, No. 2 person, No. 3 person, and No. 4 person) and tasks (Casualty care: tasks 1 and 3; and Arduous Labor: tasks 2 and 4), unless otherwise specified. Age, weight, body mass index (BMI), and estimated $\dot{V}O_{2\,max}$ were not normally distributed, as determined by Shapiro-Wilks test ($P < 0.05$), thus the Mann–Whitney U test was used to compare the role of the Captain and all other positions (Vice-Captain, No. 2, No. 3, No. 4 persons). Height was normally distributed, as determined by the Shapiro-Wilks ($P > 0.05$) and thus an independent t test was utilized. There were no statistical differences found between Captain and other positions (Vice-Captain, No. 2, No. 3, and No. 4persons), for any baseline measure (age, height, weight, BMI, HR_{max}, $\dot{V}O_{2\,max}$), see Table 1.

Data from the Equivital Life Monitor for two participants were lost due to equipment malfunction, resulting in a final sample size of 74 participants. However, these two participants produced good quality data from the ingestible T_c pill, and therefore were included for the T_c data analysis. Data from three participants for the ingestible T_c pill were lost due to equipment malfunction, resulting in a final sample size of 54 participants for the ingestible thermometric T_c pill.

Linear mixed models were performed on all physiological variables across positions (Captain vs other positions and tasks Casualty Care vs Arduous Tasks) with Scheffe post hoc tests where needed. Significance was accepted at $P < 0.05$. All results were analyzed using STATA version 15 (Statacorp LLC, College Station, TX).

RESULTS

Heart Data

Position

The HR_{mean} for all participants during the four tasks was 143 ± 1 bpm, representing 78.6% of APMHR (Fig. 1A). Captains reported the lowest HR_{mean} (135 ± 3 bpm) compared with Vice-Captain (149 ± 3 bpm, $P = 0.020$) and No. 2 persons (147 ± 3 bpm, $P = 0.044$). The HR_{peak} for all participants was 172 ± 1 bpm, which translates to an APMHR of approximately 94.5% (Fig. 1B). Captains (161 ± 3 bpm) reported the lowest HR_{peak} when compared with Vice-Captain (177 ± 3 bpm, $P = 0.002$); No. 2 persons (173 ± 3 bpm, $P = 0.019$); No. 3 persons (172 ± 2 bpm, $P = 0.023$); and No. 4 persons (176 ± 2 bpm, $P = 0.002$).

Task

Overall, HR_{mean} values were high for all tasks ranging from 71.4% to 86.8% APMHR for all participants, which reflect vigorous intensity (Fig. 1C). Task 4 (158 ± 2 bpm) reported higher values than task 1 (130 ± 2 bpm, $P = 0.000$); task 2 (146 ± 3 bpm, $P = 0.002$); and task 3 (143 ± 3, $P = 0.002$). Also, task 3 reported higher values than task 1 ($P = 0.011$) and task 2 was also higher than task 1 ($P = 0.011$). Overall, HR_{peak} values were high for all tasks ranging from 91.8% to 98.9% of the calculated APMHR for all participants (Fig. 1D). Only task 4 (180 ± 2 bpm) reported higher HR_{peak} when compared with task 2 (169 ± 2 bpm, $P = 0.000$).

Respiration Rate

Position

RR_{mean} for all participants was 34 ± 0 rpm (Fig. 2A). Captains (31 ± 1 rpm) reported lower RR_{mean} when considering mean of all tasks when compared with the Vice-Captain (35 ± 1 rpm, $P = 0.019$), No. 2 person (35 ± 1 rpm, $P = 0.024$), and No. 3 person (35 ± 1 rpm, $P = 0.012$). RR_{peak} for all participants was 44 ± 0 rpm (Fig. 2B). Captains (41 ± 1 rpm) reported lower RR_{peak} when compared with No. 3 person (45 ± 1 rpm, $P = 0.035$) and No. 4 person (45 ± 1 rpm, $P = 0.037$).

TABLE 2. Participant Characteristics ($n = 76$) Across All Tasks

	Total ($n = 76$)	Captain ($n = 15$)	Vice ($n = 15$)	No. 2 ($n = 16$)	No. 3 ($n = 15$)	No. 4 ($n = 15$)
Age, y	36.5 ± 0.70	37.5 ± 1.73	35.2 ± 1.55	35.4 ± 1.01	36.0 ± 1.16	38.5 ± 2.17
Height, m	1.8 ± 0.01	1.8 ± 0.02	1.8 ± 0.02	1.8 ± 0.02	1.7 ± 0.02	1.8 ± 0.02
Weight, kg	87.5 ± 1.65	90.4 ± 4.29	94.4 ± 3.87	82.8 ± 3.13	83.0 ± 3.74	87.0 ± 2.92
BMI, kg m^{-2}	27.8 ± 0.39	28.7 ± 1.20	29.2 ± 0.88	26.0 ± 0.6	26.8 ± 0.88	28.2 ± 0.53
HR_{max}* predicted, bpm	182 ± 1	182 ± 1	183 ± 1	183 ± 1	183 ± 1	181 ± 2
Estimated $\dot{V}O_{2\,max}$,† ml min^{-1} kg^{-1} ($n = 70$)	45.4 ± 1	43.6 ± 1.66	44.1 ± 1.21	47.7 ± 0.47	46.4 ± 0.80	44.9 ± 0.83

*$HR_{max\ predicted}$ was derived from the equation 208 – age × 0.7.[34]

†Highest value from all conditions during the IMRC; derived from Firstbeat Analysis Software via HRV data. BMI, body mass index; HR, heart rate; bpm: beats per minute; HRV, heart rate variability; IMRC, International Mine Rescue Competition; $\dot{V}O_{2\,max}$, the maximum volume of oxygen the person can utilize, measured in millilitres, per minute, per kilogram body weight.

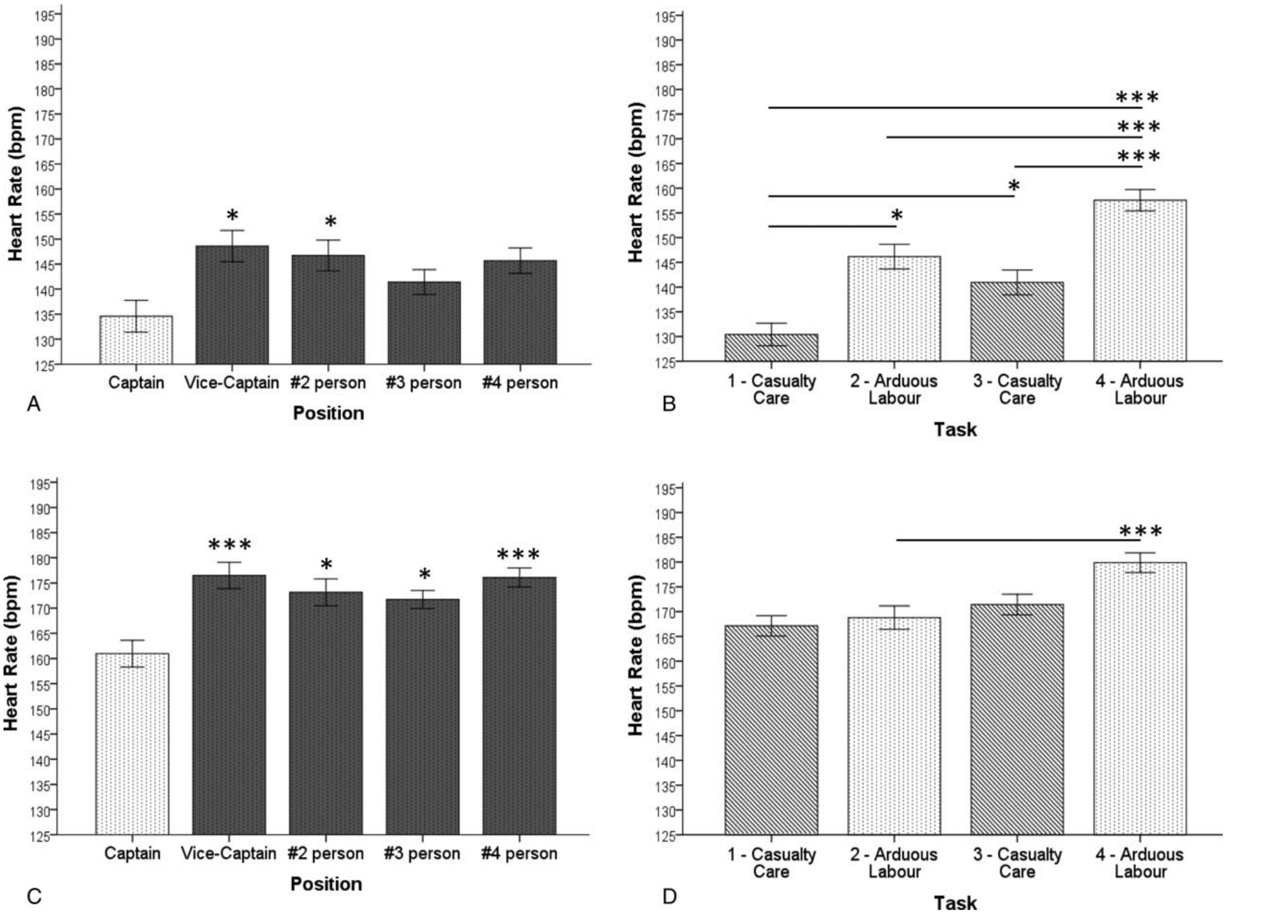

FIGURE 1. (A) Mean heart rate for all positions across all tasks; (B) mean heart rate for each task across all participants; (C) peak heart rates for each position across all tasks; (D) peak heart rates for each task across all participants; significance was accepted at $P < 0.05$ ($^{*}P < 0.05$, $^{**}P < 0.01$, and $^{***}P < 0.005$).

Task

Overall, RR_{mean} values were high for all tasks ranging from 31 ± 1 to 38 ± 1 rpm (Fig. 2C). Task 4 (38 ± 1 rpm) reported higher RR_{mean} than all other tasks, Task 1 (31 ± 1 rpm, $P = 0.000$); Task 2 (33 ± 1 rpm, $P = 0.000$); and Task 3 (33 ± 1 rpm, $P = 0.000$). Also, Task 3 reported higher RR_{mean} when compared with Task 1 ($P = 0.000$). Overall, RR_{peak} for all tasks was 44 ± 0 rpm (Fig. 2D). Task 4 (47 ± 1 rpm) reported higher RR_{peak} when compared with Task 1 (42 ± 1 rpm, $P = 0.037$) and task 2 (42 ± 1 rpm, $P = 0.000$). Task 3 (45 ± 1 rpm) also reported higher RR_{peak} from task 1 ($P = 0.023$) and task 2 ($P = 0.000$).

Total Energy Expenditure and Oxygen Consumption

Position

There were no significant differences reported for EE between positions. The lowest reported mean EE was Captains ($11.0 \pm 0.60\,kcal\,min^{-1}$ or 769 ± 42 W) (1 Watt $= 0.0143\,kcal\,min^{-1}$). The reported mean EE for positions was Vice-Captains ($13.2 \pm 0.63\,kcal\,min^{-1}$ or 923 ± 42 W); No. 2 persons ($12.8 \pm 0.76\,kcal\,min^{-1}$ or 895 ± 56 W), No. 3 persons ($11.6 \pm 0.52\,kcal\,min^{-1}$ or 811 ± 35 W); and No. 4 persons ($12.3 \pm 0.46\,kcal\,min^{-1}$ or 860 ± 35 W). The $\dot{V}O_{2\,mean}$ value for all positions was $27.2 \pm 0.45\,mL\,kg^{-1}\,min^{-1}$, which translates to approximately 60% $\dot{V}O_{2\,max}$ effort (Fig. 3A). Captains ($24.1 \pm 1.18\,mL\,kg^{-1}\,min^{-1}$) reported lower $\dot{V}O_{2\,mean}$ when compared with No. 2 person ($29.5 \pm 1.03\,mL\,kg^{-1}\,min^{-1}$, $P = 0.005$), No. 3 person ($27.6 \pm 0.88\,mL\,kg^{-1}\,min^{-1}$, $P = 0.039$), and No. 4 person ($27.8 \pm 0.87\,mL\,kg^{-1}\,min^{-1}$, $P = 0.037$).

Task

There were no statistically significant differences reported for EE between tasks. The lowest reported mean EE was $9.5 \pm 0.43\,kcal\,min^{-1}$ or 661 ± 28 W for task 1. The highest reported mean EE was $15.2 \pm 0.50\,kcal\,min^{-1}$, or 1063 ± 35 W for task 4. The mean EE for task 2 was $12.9 \pm 0.51\,kcal\,min^{-1}$ or 902 ± 35 W, and for task 3 was $11.4 \pm 0.50\,kcal\,min^{-1}$ or 797 ± 35 W. $\dot{V}O_{2\,mean}$ values were high for all tasks ranging from 22.3 ± 0.81 to $32.4 \pm 0.66\,mL\,kg^{-1}\,min^{-1}$, which translate to 49.1% to 71.4% of the estimated $\dot{V}O_{2\,max}$ (Fig. 3D). Task 4 ($32.4 \pm 0.66\,mL\,kg^{-1}\,min^{-1}$) was higher than task 1 ($22.3 \pm 0.81\,mL\,kg^{-1}\,min^{-1}$, $P = 0.001$) and task 3 ($26.1 \pm 0.84\,mL\,kg^{-1}\,min^{-1}$, $P = 0.015$). Also, task 2 ($28.7 \pm 0.81\,mL\,kg^{-1}\,min^{-1}$) reported higher $\dot{V}O_{2\,mean}$ than task 1 ($P = 0.024$).

Temperature

Position

$T_{c\ mean}$ for all participants was $38.3 \pm 0.04\,°C$ when considering mean of all tasks (Fig. 4A). The only difference for $T_{c\ mean}$ reported was for Captains ($38.0 \pm 0.09\,°C$) when compared with No. 4 persons ($38.5 \pm 0.10\,°C$, $P = 0.005$). $T_{c\ peak}$ for all participants

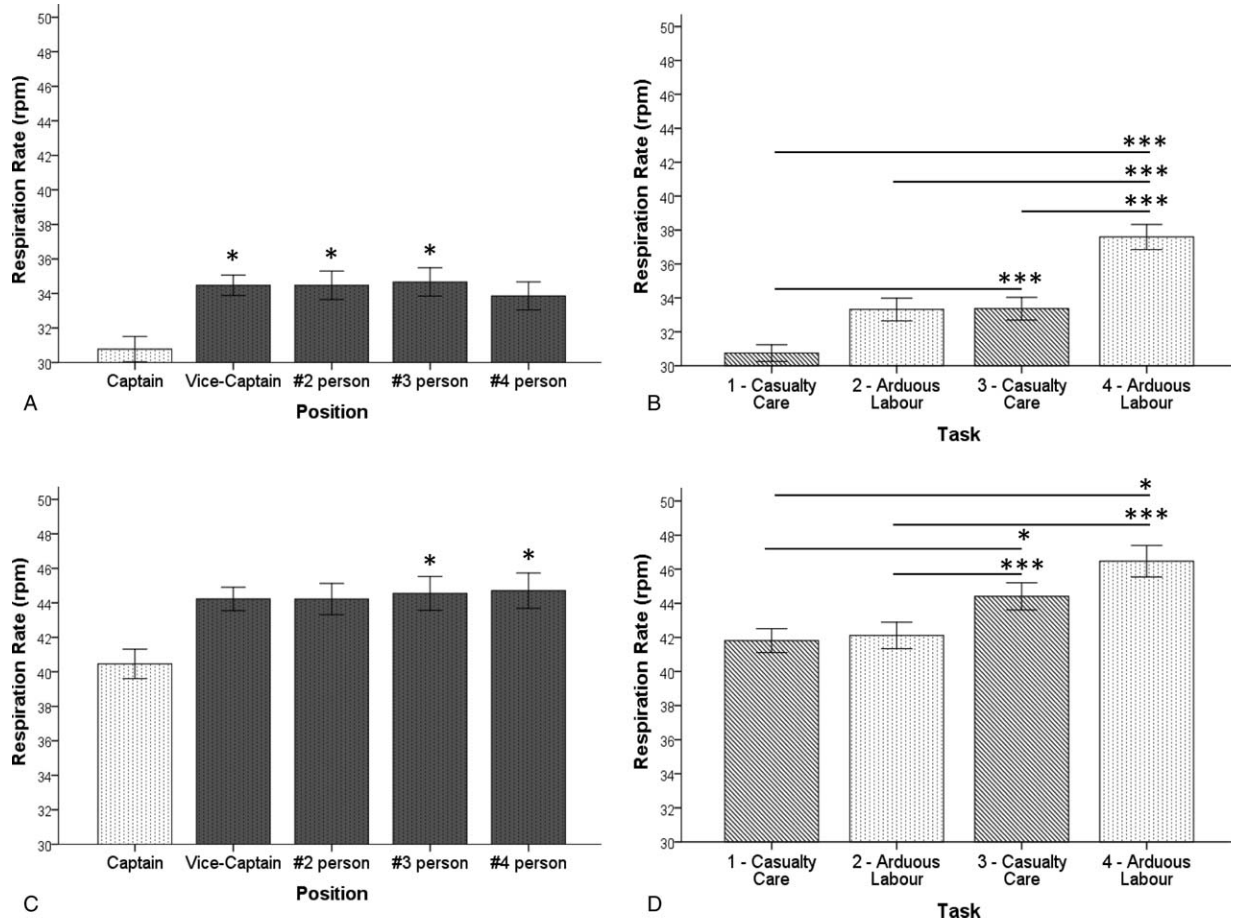

FIGURE 2. (A) Mean respiration rate for each position across all tasks; (B) mean respiration rate for each task across all participants; (C) peak respiration rate for each position across all tasks; (D) peak respiration rate for each task across all participants; significance was accepted at $P < 0.05$ ($^{*}P < 0.05$, $^{**}P < 0.01$, and $^{***}P < 0.005$).

when considering the mean of all tasks was $38.5 \pm 0.04\,^{\circ}$C (Fig. 4B). Captains ($38.2 \pm 0.08\,^{\circ}$C) reported lower $T_{c\ peak}$ when compared with Vice-Captains ($38.6 \pm 0.10\,^{\circ}$C, $P = 0.040$) and No. 4 persons ($38.7 \pm 0.10\,^{\circ}$C, $P = 0.002$). $T_{c\ peak}$ for remaining positions was: No. 2 persons $38.5 \pm 0.08\,^{\circ}$C; and No. 3 persons $38.6 \pm 0.08\,^{\circ}$C. T_{skin} for all participants were $37.2 \pm 0.06\,^{\circ}$C when considering mean of all tasks (Fig. 4E). Captains ($36.8 \pm 0.13\,^{\circ}$C) reported lower T_{skin} compared with Vice-Captains ($37.2 \pm 0.13\,^{\circ}$C, $P = 0.013$), No. 2 persons ($37.6 \pm 0.10\,^{\circ}$C, $P = 0.001$), and No. 3 persons ($37.4 \pm 0.10\,^{\circ}$C, $P = 0.002$). $T_{skin\ peak}$ for all participants were $37.7 \pm 0.48\,^{\circ}$C when considering all tasks (Fig. 4G). Captains ($37.3 \pm 0.12\,^{\circ}$C) reported lower $T_{skin\ peak}$ compared with Vice-Captain ($37.8 \pm 0.11\,^{\circ}$C, $P = 0.001$), No. 2 person ($38.0 \pm 0.08\,^{\circ}$C, $P = 0.000$), No. 3 person ($37.9 \pm 0.08\,^{\circ}$C, $P = 0.000$), and No. 4 person ($37.7 \pm 0.12\,^{\circ}$C, $P = 0.005$).

Task

For $T_{c\ mean}$, task 4 ($38.6 \pm 0.07\,^{\circ}$C) was higher than tasks 1 ($37.8 \pm 0.06\,^{\circ}$C, $P = 0.000$) and task 2 ($38.3 \pm 0.07\,^{\circ}$C, $P = 0.000$). Task 3 ($38.6 \pm 0.07\,^{\circ}$C) was higher than tasks 1 ($P = 0.000$) and task 2 ($P = 0.000$). Additionally, task 2 was higher than task 1 ($P = 0.000$).

For $T_{c\ peak}$, task 4 ($38.7 \pm 0.07\,^{\circ}$C) was higher than tasks 1 ($38.1 \pm 0.05\,^{\circ}$C, $P = 0.000$) and task 2 ($38.4 \pm 0.08\,^{\circ}$C, $P = 0.000$). Task 3 ($38.7 \pm 0.08\,^{\circ}$C was higher than tasks 1 ($P = 0.000$) and task 2 ($P = 0.000$). Additionally, task 2 was also higher than task 1 ($P = 0.000$).

For T_{skin}, task 4 ($36.6 \pm 0.13\,^{\circ}$C) was higher than tasks 3 ($37.6 \pm 0.08\,^{\circ}$C, $P = 0.000$) and task 2 ($37.8 \pm 0.07\,^{\circ}$C, $P = 0.000$). Task 3 was higher than task 1 ($37.0 \pm 0.10\,^{\circ}$C, $P = 0.000$). Also, task 2 was higher than task 1 ($P = 0.000$).

$T_{skin\ peak}$, task 4 ($37.1 \pm 0.13\,^{\circ}$C) was higher than task 2 ($38.1 \pm 0.06\,^{\circ}$C, $P = 0.000$) and task 3 ($38.1 \pm 0.06\,^{\circ}$C, $P = 0.000$). Task 3 was higher than task 1 ($37.7 \pm 0.07\,^{\circ}$C, $P = 0.000$). Additionally, task 2 was higher than task 1 ($P = 0.000$).

DISCUSSION

To our knowledge, this is the first study to record physiological measures during an accurate enactment of a mine rescue simulation, in an operational, underground mine. It is also the first to assess the influence of team position and task on physiological loading of mine rescue participants during this simulated emergency. We employed objective methods to describe the following physiological measures: HR, RR, EE, $\dot{V}O_2$, T_{skin}, and T_c to gain insights on physiological responses and risk of heat-related events during a simulated mine rescue emergency. Captains displayed significantly lower physiological loads, except for EE, when compared with other positions. Both arduous labor and casualty care tasks required high physical demand, although arduous labor required higher demands with significantly higher HR, RR, and

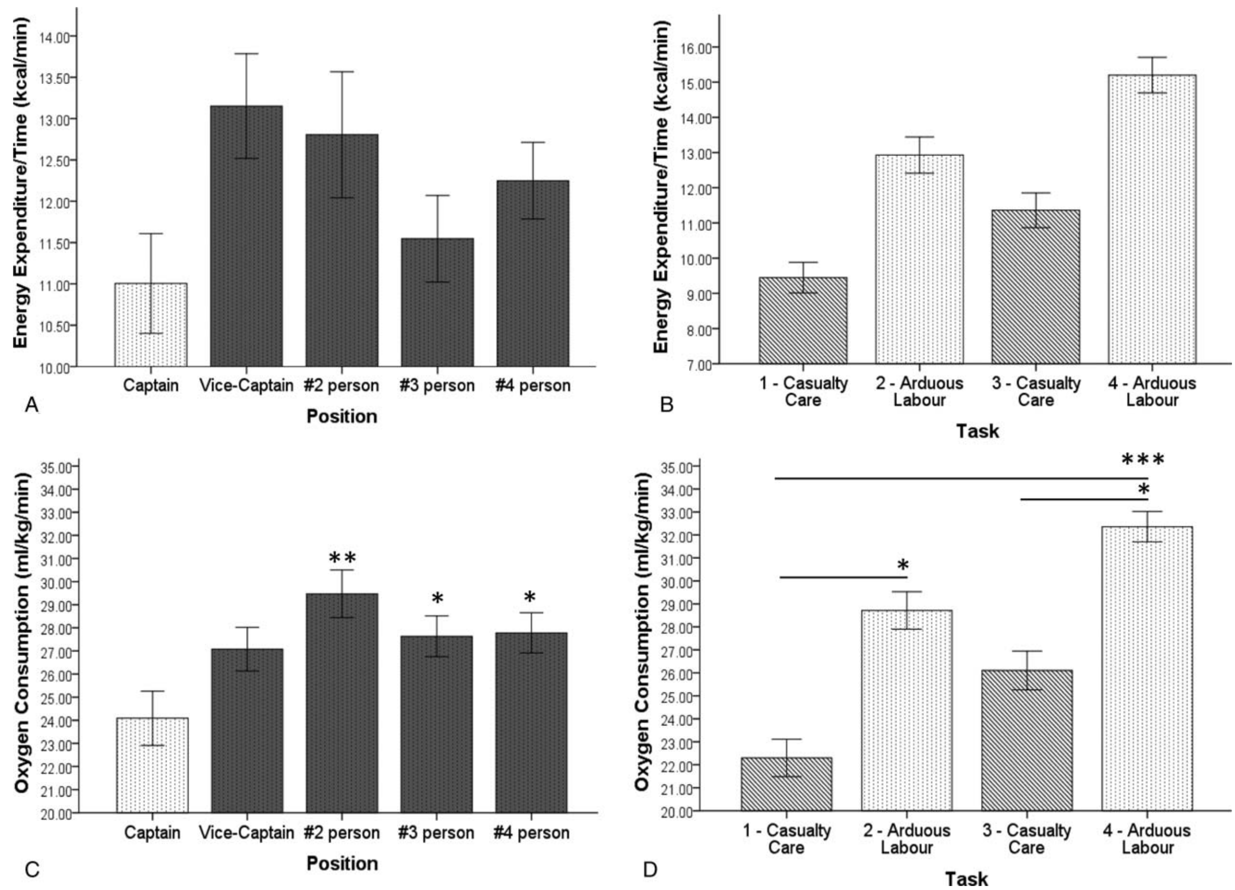

FIGURE 3. (A) Mean energy expenditure for each position across of all tasks; (B) mean energy expenditure for each task across all participants; (C) mean oxygen consumption for each position across all tasks; (D) mean oxygen consumption for each task across all participants; significance was accepted at $P < 0.05$ ($^{*}P < 0.05$, $^{**}P < 0.01$, and $^{***}P < 0.005$).

$\dot{V}O_2$ measures. Finally, all participants displayed elevated T_{skin} and T_c values. Our results highlight that all positions, including Captains, are performing very strenuous work during all mine rescue tasks performed in hot and humid conditions, putting them at risk for both heat stroke and a cardiovascular event.

Task-Specific Demands

Simulated mine rescue-related tasks examined in similar studies (eg, shovel, casualty-carry, walk, etc) have documented the intense workload required to perform these tasks in comparison with the implementation of allotted rest intervals.[8–10] Stewart et al[8] reported mean %APMHR of 91% for the duration of a 9-minute, simulated work-circuit comprised of: incremental casualty carry, coal shoveling, and hose drag. Similar findings from Hardcastle et al[9] highlighted mine rescuers performing mean workloads of 538 W for an average of 66 minutes that resulted in mean T_c of 38.14 °C in 10 individuals; this study was performed in an operational, shallow mine with much cooler conditions, without realistic mining conditions ($T_{drybulb} = 16.9\,°C$; $T_{wetbulb} = 14.9\,°C$); compared with the present study.

The simulated mine rescue competition in this study involved four primary tasks; which we sub-categorized into Casualty Care (Tasks 1 and 3) and Arduous Labor (Tasks 2 and 4). These tasks were developed by specialists in mine rescue (OMR), and reflect frequently occurring emergencies. Both laborious and casualty care tasks required a high physical demand, where arduous labor displayed higher HR, RR, and $\dot{V}O_2$ measures. The inability to rest before the beginning of Tasks 2, 3, and 4, led to a sustained or greater HR and RR. In addition, although casualty care involves kneeling and seemingly a chance to recover, participants remained in hot ambient conditions while wearing approximately 40 lbs of gear. These were not favorable conditions for adequate recovery and thus impacted physiological responses. Both HR_{peak} and RR_{peak} increased during task 3, showing higher values than task 2 (arduous labor). During task 3, the casualty was impaled by a steel bar through their abdomen and anecdotally, was very realistic and distressing for the competitors. This likely contributed to the increase in HR and RR, via activation of the sympathetic system due to the visual stressors.[17]

Our results demonstrated that 31 (41.9%) participants exceeded 100% of the APMHR (182 bpm), during tasks 2 and 4. Tasks 1 and 3 also demonstrated moderate-vigorous intensity with 70% to 85% of APMHR. These values are much higher than previous findings[8–10] Given that previous research examined mine tasks over a short duration, with scheduled rest breaks, this is not surprising.[10,13] In our study, participants performed work for approximately 2 hours, where "rest" consisted of either walking or kneeling for brief periods (less than 5 minutes). This pattern is representative of mine rescue work, unlike that observed in previous literature.[3] In comparison, Stewart et al,[8] utilized a job-task circuit composed of 9 minutes of work followed by 24 minutes of rest, in which they still reported APMHR of nearly 100%.[8] Future research should focus on methods to improve or maximize opportunities to rest (eg, hydration, rest protocol, or utilize back-up teams to reduce rescue mission time).

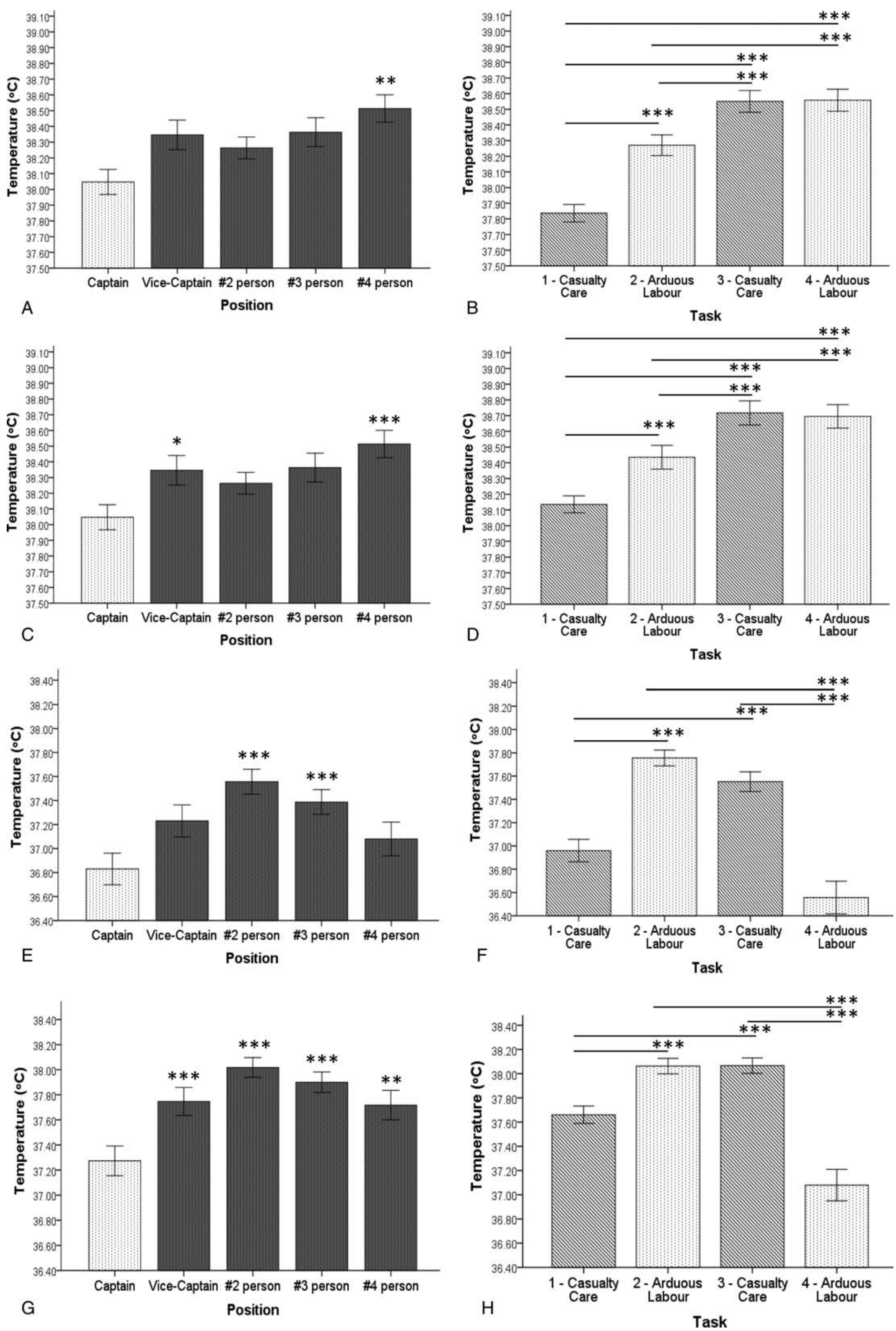

FIGURE 4. (A) Mean core temperature for each position across all tasks; (B) mean core temperature for each task across all participants; (C) peak core temperature for each position across all tasks; (D) peak core temperature for each task across all participants; (E) mean skin temperature for each position across all tasks; (F) mean skin temperature for each task across all participants; (G) peak skin temperature for each position across all tasks; (H) mean of all peak skin temperature for each task across all participants; significance was accepted at $P < 0.05$ ($^{*}P < 0.05$, $^{**}P < 0.01$, and $^{***}P < 0.005$).

Participants' mean and peak T_c were higher in task 3 compared with tasks 1 and 2, but not different from task 4. Whereas, mean and peak T_{skin} depicted a decrease from task 3 to task 4. This can be attributed to a decrease in ambient conditions (Table 2). Core temperature is less influenced by ambient conditions compared with T_{skin}, which is in direct contact with the environment.[17] The resulting gradient between T_{skin} and T_c would improve the ability to dissipate heat and balance heat gained versus heat lost, ultimately stagnating the rise in T_c.[17] Nonetheless, 30 of the 54 participants reported measures of mean T_c at 38.6 °C or above and the highest T_c recorded in the competition was 39.88 °C, which nearly meets the criteria (40 °C) for heat stroke as defined by the Taylor et al.[18]

A study by Varley,[19] in mine rescuers during regular training, showed that, following an increase in T_c active cooling did not begin until approximately 25 minutes following training. This is significant because tracking T_c is not currently practiced during mine rescue. Current post-emergency policies include 6 hours of rest between shifts, and 24 hours of rest for those exposed to extreme heat.[3] When emergencies exceed 24 hours, doctors must be made available 24 hours a day and each team member must be examined by the doctor at least once a day.[3] During competitions paramedics are made available and remain at the end of the scenario to examine any individual experiencing any heat illness symptoms (eg, weakness, nausea, cramps, etc) (T. Hanley, Ontario Mine Rescue: personal communication, December 15, 2017). However, closer attention immediately following a rescue event should be given to all mine rescue personnel, including testing for ongoing heat strain. This monitoring should continue for at least an hour following team-exit from the mine after an emergency. Paramedics or doctors should be present at the exit, and examine all workers for visible symptoms of heat illness (eg, excessive sweating, lack of sweating, red skin, complacency, etc) and to make certain they are rehabilitating properly (eg, drinking plenty of water, resting, etc). Future research should focus on practices to actively cool rescuers throughout an emergency and immediately upon exit from the mine, which would be beneficial and potentially life saving.

Team Position Demands

For HR_{mean}, Captains were different from Vice-Captain and No. 2 person ($P < 0.05$), but not different from No. 3 person and No. 4 person. Other physiological measures that followed this pattern included RR_{mean}, RR_{peak}, and oxygen consumption, in which the Captain differed from a few positions, but not all. We hypothesize this is because the Captains as a group were often not as physically fit as the other team members which would result in eliciting higher physiological measures when performing lower intensity work.[20] On the other hand, for HR_{peak}, Captains displayed lower values than all other positions; this may be attributed to the difference in responsibilities of roles during a competition. However, in real-life emergencies, Captains will help for the best outcome and therefore could elicit higher physiological responses.

Although Captains displayed lower physiological measures, except for EE, compared with other positions, Captains' HR_{mean} for the duration of the competition was 74.2% of APMHR, which still reflects vigorous physical activity. Considering HR, $\dot{V}O_2$, and EE are linearly correlated and there is no difference in EE, we suggest this may be due to the calculation used by Firstbeat Software (Firstbeat Technologies, Jyväskylä, Finland) to calculate values, which was not provided. Captains are required to wear the same PPE (approximately 22 kg) and walk the same distance, so it is expected that the Captain should have sufficient cardiovascular and muscular endurance to keep up with other members. Concern regarding a fitness standard is that it may prevent these members from active duty: causing a significant loss in experience and expertise.[3] Captains are not lifting or carrying heavy equipment and casualties, so in theory, should not be required to meet the same muscular strength standard as other members. However, in a circumstance when another member is injured, the Captain must fill their role, and would be required to perform heavy lifting. Therefore, a multifaceted fitness standard that encompasses all aspects of fitness (eg, muscular strength and endurance, cardiovascular endurance) should be implemented and should be the same for all positions.

When referring to T_{skin} and T_c, Captains were different from most other positions. In agreement with Hardcastle et al,[9] the metabolic work performed (mean of 856.6 W for all positions) during the rescue event was sufficient to produce mean T_c values of 38.31 °C for all positions, and 38.10 °C for Captains. This is important as T_c of 38.0 °C is associated with an impaired ability to make decisions, and impaired reaction time.[15,21] Captains are responsible for making decisions on behalf of the team, as well as any casualties encountered in the mine, making heat strain a major concern.[3] Based on the results from Racinais et al,[21] the Captain was making impaired decisions in the IMRC ($T_c > 38.0$ °C). As for other positions, the highest reported T_c was 39.88 °C, which is nearly considered heat stroke, and if not treated immediately can be fatal.[19] Furthermore, at a T_c of 38.6 °C and above, physical heat strain has begun and, if not mitigated, will progress to acute heat illness and eventually the life-threatening condition of heat stroke.[15]

Heat stroke is a recognized serious risk for mine rescue, and has previously caused the death of several mine rescuers.[19] However, cardiovascular disease (CVD) is also an important cause of death among miners[22–24] and should be given equal consideration when developing prevention strategies for mine rescue work. Over the last decade, our understanding of CVD among structural firefighters has significantly improved and provides insight into potential preventive strategies for mine rescue. Mine Rescue workers perform under similar circumstances as structural firefighters and the physiology of cardiovascular arousal and other changes that occur in association with acute firefighting activities have been well characterized.[25–29] Also, like mining, despite the strenuous nature of emergency duty, firefighters' prevalence of low fitness, obesity, and other CVD risk factors are high.[30,31] Statistical analyses have shown that on-duty CVD events do not occur at random in the fire service. They are more frequent at certain times of day, certain periods of the year, and are overwhelmingly more frequent during strenuous duties compared with non-emergency situations.[27] Moreover, as expected, on-duty CVD events occur almost exclusively among susceptible firefighters with underlying CVD.[27] These findings suggest that preventive measures with proven benefits be applied aggressively to workers.

Based on the descriptive data from this study and the literature around firefighting, we would make three recommendations for Mine Rescue programs globally. These recommendations are outlined below.

Recommendations for Mine Rescue

Mandatory Fitness Standard

First, as recommended in the Mining Health, Safety and Prevention Review (2015),[5] we concur that a fitness standard should be developed for mine rescue workers. However, given the specific fitness requirements outlined in Jamnik et al[6] for Canada, we would recommend a novel approach. Specifically, we recommend the development of a mandatory fitness program whereby "monitoring participation" in the program be a key aspect of achieving the fitness standard. Personalized fitness goals be set at the outset of the program start, including targets for: aerobic fitness (VO_{2max}), percentage body fat, core body strength, and grip strength, with periodic testing to measure progress toward and maintenance of goals. Given the high heart rates reported in this study, a primary concern for workers (in addition to the risk of heat stroke) is that they would suffer a cardiac event during or after the rescue.

Therefore to mitigate both risks, regular training, including an aerobic component, would protect workers from these outcomes.[28–31] We recommend that body composition, with the goal to reduce total percentage fat, be included for workers, as higher body fat is associated with enhanced body heat retention.[32] Core and grip strength are recommended as components of the fitness program to help protect workers from common physical injuries including slip/trip and back injuries. Enhanced core and grip strength have been shown to be protective for these types of injuries.[33,34] Lastly we recommend that workers include regular training (three to five times per week) targeting their respiratory muscles to offset the negative impacts[35–37] of wearing the self-contained breathing apparatus.

Furthermore, mine rescue workers should continue to have entry-level medical evaluations, but also institute periodic medical and fitness evaluations, and require return-to-work evaluations after any significant illness. A combination of a fitness evaluations (eg, $\dot{V}O_{2\,max}$ testing, grip strength, etc) and job simulation tasks (ie, rescue simulations) for a hybrid physical standard would be the best approach.[6] Fitness evaluation would provide insight regarding the worker's general fitness and can be used to evaluate achievement of personal goals; this in combination with the successful completion of simulated rescue missions would, in our opinion, better safeguard workers. It is possible to consider different fitness standards based on team role; Captains might benefit from a lower standard for muscular strength, as they are not, under normal circumstances, involved in lifting tasks; however, based on the results from this study, we think they should be held to the same aerobic standard.

Finally, on the basis of the overwhelming evidence supporting markedly higher relative risks of on-duty death and disability among structural firefighters with established coronary heart disease,[38–40] mine rescue workers, with clinically significant coronary heart disease should be restricted from participating in the mine rescue program.

Body-Worn Physiological Monitoring

Our second recommendation is that Mine Rescue incorporates body-worn monitors, ideally capable of relaying physiological measures in real-time to the Briefing Officer during all rescue and simulation training events. The Briefing Officer should, in the future, use these indices to decide, in consultation with the Captain, whether to extract a team during a rescue for safety reasons. We do not think the current standard of regular health check-ins with the Captain, based on verbal confirmation from workers regarding their personal fitness to continue and visual cues is sufficient. We argue that given the high risk of a heat stress event and the poor conditions (eg, smoke, PPE obstruction) for visually identifying a problem, a better method needs to be put in place to proactively protect these workers. Although various personal monitoring devices exist, we would note that the Equivital from Hidalgo was well tolerated by all participants in this study, and it is the only wearable (to our knowledge) that is intrinsically safe for mine use while incorporating all the physiological measures we would recommend be monitored in real time (heart rate, respiratory rate, heart-rate variability, skin temperature, and body position). We recognize that this wearable does not measure true core temperature (only estimates it based on skin temperature); but we do not think the ingestible core temperature method is feasible, nor recommended, for regular use as a component of mine rescue work. Skin temperature in relation to heart rate is the best proxy measure for field use in first responders, including Mine Rescue workers, at this time.[41–43]

Heat Exposure Health Screening Standard

Lastly we recommend that upon exit from an emergency rescue and from simulated training exercises all mine rescue workers be automatically screened and treated for heat strain. It is clear based on the data from this study that many of the participants were suffering from some degree of heat strain when they exited the mine. Future studies should incorporate a survey question to capture this data and should continue to monitor the core temperature of participants after the simulation is over. We recommend that Mine Rescue organizations globally develop a standard screen practice, potentially including a rectal temperature measure upon exit from the emergency rescue or training simulation. These data should be maintained, collected, and studied to help develop better recovery practices for these workers; we would recommend that Ontario Mine Rescue, or similar bodies oversee this data. We would also recommend that workers be treated upon exit from the emergency as if they have heat exhaustion, as a component of the prevention process. As a measure to prevent the further progression to heat stroke, this would include immediate hydration and rapid efforts to cool the worker, ideally this would include water immersion of the torso.[44,45] In addition, a recovery standard should be developed that includes mandatory 24 hour time-off from work after all rescues and training simulations. Currently, the Mine Rescue Handbook states: no one should be permitted to take a second shift until they have had at least 6 hours rest. Personnel exposed to extreme heat, and worked under the time limits of the OMR Heat Exposure Standard, must have 24 hours rest.[3] This Recovery Standard should expand on the guidelines for the worker to follow, including: what symptoms to watch for, beverage and food consumption practices, physical activity engagement, and sleep. Future studies should verify the success of these programs in preventing heat stress and in enhancing worker recovery.

Other Considerations/Recommendations

Notably, we have not made any recommendations for practice regarding acclimatization, as a means to protect the workers from heat strain. The literature supports the use of acclimatization as one way to protect workers from a heat event.[46] However despite the potential for workers to become acclimatized at work, due the rapid loss of this protection (within 3–5 days)[46] in practice, it is difficult to maintain. Anecdotally, mine rescue workers told us that they were not acclimatized to the heat for the competition and unless both workers and workplaces wanted to create shift schedules to specifically address this effect or develop a program for daily exposure (eg, via simulated high temperature exposure) we do not see this as a practical approach for Canadian Mine Rescue workers at this time.

Other factors should be considered in future research to further protect these workers from injury and heat strain including: pre-fatigue, that is, worker activities just prior to emergency call; and an inability to sufficiently hydrate prior to and during an actual emergency.

Limitations

Although this competition provided a unique opportunity to study mine rescuers performing mine rescue tasks in an underground mine while participating in scenarios prepared by mine rescue experts and based on previous mining disasters, there are some limitations to this research. First, the scenarios created were part of a competition, not a true emergency, thus their true physiological data remain unknown. In addition because it was a competition participants had knowledge of "when" they were competing; and therefore had time to prepare physically. For example, they could ensure sufficient hydration and ample rest the night prior. Alternatively, this may also have had negative consequences on their performance, for example, this may have affected their ability to sleep due to nervousness. Second, a baseline collection of physiological responses was not possible due to scheduling of the event and the arrival times of teams. We could not influence or modify the schedule of the IMRC to fit our needs, as there were other aspects of the competition before and following the underground scenario. We were given a strict allocated time to get anthropometric measures the day prior to the event, and were unable to gather baseline physiological data. Third, we were unable to conduct a post competition survey to assess perceptions of heat illness and perceived exertion, again due to time constraints and language barriers. We never attempted to measure symptoms of heat illness after the competition; however, extrapolating from the results of T_c and HR, it is likely participants experienced them. Therefore, future research should utilize district and provincial competitions to allow ample time to collect baseline data (eg, HR, RR, T_c, etc) and post competition data (eg, heat illness symptoms and perceived exertion).

CONCLUSION

In conclusion mine rescue work is highly demanding with high risk of a heat stress or a cardiovascular event. Workers need to commit to a regular fitness program to offset these risks and government and industry needs to support this commitment. In addition, workers should be monitored throughout a rescue and training simulation for heat strain to safeguard their health. Lastly workers should be tested and treated for heat strain after every rescue and training simulation; this should include a planned recovery program for the worker. These changes will have practical implications on industry, but should also improve the overall health of the organization, which could have other benefits.

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