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REAL-TIME PHYSIOLOGICAL MONITORING WHILE ENCAPSULATED IN PERSONAL PROTECTIVE EQUIPMENT

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ABSTRACT

Heat strain was monitored in real-time in soldiers performing chemical, biological, radiological, and nuclear (CBRN) training. Wearable physiological status monitoring (PSM) systems (EQ-02; Hidalgo, Ltd, Swavesey, Cambridge, UK) were evaluated by nine soldiers from a Civil Support Team – Weapons of Mass Destruction (CST-WMD) team (age, 27.3±4.9 (SD) y; wt, 84.5±15.1 kg; ht, 178.1±10.1 cm). Seven of these soldiers wore the PSM system during CBRN training and provided subjective feedback regarding the systems utility; two soldiers observed the training exercise and commented on the utility of the PSM system. During CBRN training, participants marched ~1600 m in 45 min while wearing Level A CBRN personal protective equipment (PPE). A 0-to-10 Physiological Strain Index, i.e., a 0-to-10 index of thermal-work strain, was calculated from estimated core temperature and measured heart rate. Individual PSI levels varied, with three individuals at a PSI > 8 (high thermal-work strain) and four individuals at a PSI < 8 (moderate strain). Real-time PSI levels corresponded to the subjective feelings of thermal strain reported by the test volunteers. In addition, the CST-WMD soldiers reported that real-time PSI information could be used to improve work performance and decrease the likelihood of experiencing heat illness during CBRN missions.

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Keywords: heat illness; heat injuries; Level A; medical monitoring; military training; ambulatory monitoring; personal protective equipment; thermal strain

INTRODUCTION

Encapsulation in chemical biological, radiological, and nuclear personal protective equipment (CBRN PPE) compromises the human body's ability to thermo-regulate (1, 2), and commonly results in overheating that degrades work performance (2). By nature of its design, PPE imposes physiological strain on the body in two ways. The physical weight of the PPE itself increases work load and metabolic heat production; while the largely impermeable CBRN uniform impedes the dissipation of excess body heat, primarily by limiting heat loss through sweat evaporation. Petruzzelo et al. (3) in a laboratory study showed that even during brief bouts of exercise (~15 min) thermal strain increased in firefighters wearing PPE, as measured by a physiological strain index (PSI) (4).

The current military practice for thermal management during CBRN missions is typically limited to observing behavior changes of personnel. For example, if a soldier on a CBRN mission notices behavioral changes in a co-worker, e.g., ataxia, disorientation, speech impediments, the healthy individual will radio for assistance to remove, replace, or verify the health state of the impaired individual. This practice typically results in the removal and replacement of the compromised individual. This qualitative and imprecise method can be difficult to implement given that both the observer and apparent victim are wearing CBRN PPE. The PPE obviously makes it difficult to detect telltale changes in facial features, sweat rates, or speech patterns. A relevant analogy is trying to understand how hot an automobile engine is without a gauge. Furthermore, techniques for cooling soldiers during rest breaks, when CBRN PPE is partially or entirely removed, are ad hoc in nature with little or no measure of effectiveness of the cooling techniques. Use of physiological monitoring devices could provide quantitative awareness of work intensity and thermal state and, potentially, the effectiveness of cooling techniques. This improved health state awareness could enable CBRN personnel to make better-informed decisions regarding work rates, safe down-range stay times, work/rest scheduling, and rest and recovery practices such as the use of ice blankets.

In 2004, the Institute of Medicine noted the need for physiological monitoring of military personnel to help prevent heat illness and heat injuries, or to enhance or hasten treatment of these conditions should they occur (5). The capabilities and applications for physiological status monitoring (PSM) technologies have grown since 2004 (6). In addition, use by the military, industry, and space applications have been identified (7, 8). Previous research has shown the utility of real-time heat strain monitoring for CBRN personnel participating in an enclosed space exercise (1). During this training exercise, the Civil Support Team – Weapons of Mass Destruction (CST-WMD) medic station received near real-time updates of physiological status of all downrange personnel. The distance from the test volunteers wearing PPE and working in the enclosed space to the medic station was less than 50 m. Nevertheless, the physiological data provided was seen as useful by the CST-WMD medical officer for monitoring these soldiers. The present study expanded upon this earlier work by using a PSM system that was improved in three key ways. First, the range for real-time data telemetry was extended from 50 m to 800 m. Second, use of PSI (4) was estimated using heart rate (HR) and on-the-fly core temperature prediction made using a validated predictive algorithm running on the PSM system (9). Lastly, the PSI value, i.e., the 0-to-10 thermal/work strain level, was displayed on an Android-based cell phone attached to each individual in an easy to observe location (Figure 1). This device was termed the “Buddy Display,” as it allowed the wearer and other co-workers to observe his/her thermal strain in real-time.

Figure 1. Buddy Display showing a Physiological Strain Index (PSI) of 10 equivalent to extreme thermal-work strain.

METHODS

Volunteers

Study volunteers included seven CST-WMD soldiers experienced in CBRN operations, and two additional volunteers (one being a trained physician's assistant) who did not participate in the actual training exercise, but did observe and provide subjective feedback regarding the PSM system and its use in the training event. Volunteers were briefed on the purpose, risks, and potential benefits of the study and each gave their written informed consent prior to study participation. The study was approved by the Scientific and Human Use Review Committees (SRC and HURC) at the U.S. Army Research Institute of Environmental Medicine (USARIEM) (Natick, MA). Participants averaged 27.3 ± 4.9 (SD) years of age; weighed 84.5 ± 15.1 kg and were 178.1 ± 10.1 cm in height. The participants had an average of 6.7 ± 2.8 years of service and all volunteers participated in regular physical training.

Training Exercise

The observed training exercise consisted of a ~45 minute self-paced ~1600 m march in Level A CBRN PPE (Level A is the highest level of protection provided for CBRN missions) (Figure 2). The march simulated an approach to a target location of a CBRN contaminated area. The Level A CBRN PPE consisted of a positive pressure, full face-mask self-contained breathing apparatus (SCBA), a fully-encapsulating chemical-protective suit, coveralls, inner and outer chemical-resistant gloves, chemical-resistant boots, and a hard hat.

The measured meteorological conditions: mean ambient air temperature: 21.9°C (min: 21.3°C and max: 22.9°C), mean relative humidity: 36.2% (min: 33% and max: 38%), and direct sunlight with no cloud cover.

Figure 2. Soldiers participating in a self-paced march in Level A chemical, biological, radiological, and nuclear personal protective equipment (CBRN - PPE).

Real Time Physiological Measurements

Volunteers were outfitted with the Equivital™ EQ-02 Sensor Electronics Module (SEM) and belt (Equivital Hidalgo, Swavesey Cambridge, UK) (Figure 3). This PSM system is a 510k Food and Drug Administration (FDA) certified medical monitoring device. The SEM weighs 38 gm, is IP67 certified, and has a Class 1 Bluetooth interface. The SEM has a battery life of up to 48 hrs and 8 GB of memory which allows for ~50 days of data-logging. The data recorded by the system includes: heart rate, respiratory rate, electrocardiogram (ECG) waveforms, and respiratory waveforms. The SEM has embedded algorithms that estimate heart rate and respiration rate. Body motion and body position are determined from accelerometers in the SEM, which is worn on the body's mid-section. Skin temperature is determined from a temperature sensor in the back of the belt/SEM system. Core temperature is obtained using an ingestible thermometer pill (MiniMitter, Inc., Bend, OR) which transmits temperature information to the Equivital™ EQ-02 SEM. Participants wore the Buddy Display taped to their upper arm on the outside of their CBRN PPE (Figure 4). Information from the SEM was sent via Bluetooth to the Android-based cell phone

(Google, Mountain View, CA). The Buddy Display was color-coded so PSI values less than 7 were shown in green (safe), PSI values of 8 and 9 were shown in yellow (watch the individual), and a PSI of 10 was shown in red (take action to relieve heat strain). An auditory alarm was also associated with a PSI of 10.

Figure 3. Equivital™ EQ-02 Sensor Electronics Module (SEM) and belt (Equivital Hidalgo, Swavesey Cambridge, UK).

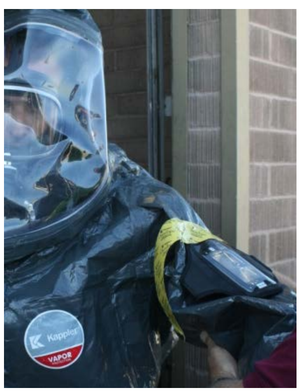

Figure 4. Example of the Buddy Display attached to the upper arm of the Level A chemical, biological, radiological, and nuclear personal protective equipment (CBRN - PPE).

Subjective Assessments of the Utility of the Buddy Display

The effectiveness of the real-time PSM and Buddy Display system was measured using questionnaires and small focus groups consisting of 4-5 individuals. The purpose of these assessments was to determine whether potential users found the PSM system provided useful, actionable information that could be used to minimize the likelihood of overheating during CBRN missions. Focus groups were video-taped and later transcribed and the responses to questions were summarized and tabulated into similar category responses to allow for a summary and frequency data to be presented.

Data Analysis

Data were analyzed using SPSS 20 (SPSS an IBM Company, Chicago, IL). Analyses include means and S.D., min, max, and frequency (n and %) of responses.

RESULTS

The estimated minute-by-minute PSI was calculated for each individual (Figure 5). As seen in Figure 5, individual responses differed. While the march was self-paced, all individuals finished within 1 min of each other, and the distance between the individual that finished first and the individual that finished last was <100 m. The potential heat illness danger line was set at a value of 8 based on PSI ratings and their associated meaning previously defined by Moran et al. (4) and the fact that physical activity while wearing encapsulating CBRN PPE increases the likelihood of heat illness when a PSI of 8 or higher is achieved [10].

Subjective assessments of the utility of the Buddy Display device and the information it provided was generally positive. Three individuals had PSI values exceeding a value of 8 (Figure 5) and briefly had a PSI of 10. Their Buddy Display showed a corresponding PSI value of 10 and the alerting alarm on the Buddy Display was triggered. The four individuals that did not cross the PSI safety line did not have their Buddy Display alarms go off. Hence, there were no false positive or false negatives with regard to the Buddy Display alarms and/or display colors changing from green to yellow and/or red. Table I summarizes the subjective assessments provided by the participants during the focus group. As noted in Table I under Topics 1, 2 and 5, participants felt the information from the Buddy Display was accurate and useful and the PSI and heart rate information that was provided on the display was appropriate.

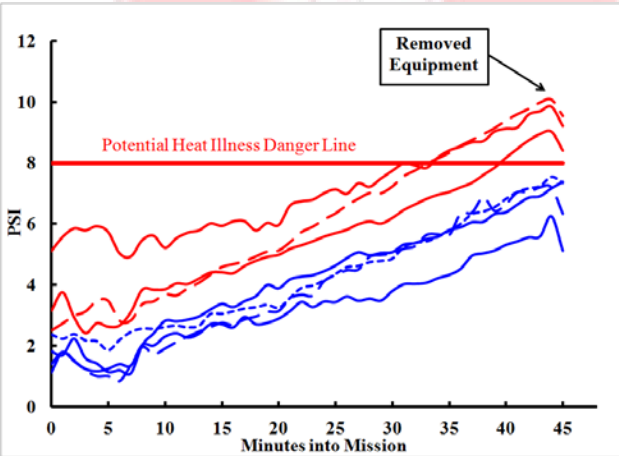

Figure 5. Estimated minute by minute physiological strain index values for each individual.

Table I. Subjective assessment of Buddy Display device and the information it provided

Topic	Buddy Display Question or Comment Summary		
	Yes or Agree With Response Question	***n***	**%**
1	Buddy Display would be useful in manging heat illnesses or injuries	9	100
2	Physiological Strain Index (PSI) was thought to be accurate	9	100
3	Physiological Strain Index (PSI) should be re-named	9	100
4	Understood the Physiological Strain Index (PSI)	5	55
5	All current information displayed on the Buddy Display should remain	9	100
6	Taping or attaching Buddy Display to outside of the Level A suit is appropriate	8	89
7	Form-factor of cell phone should be changed	5	55
8	Attachment to forearm is a better location for the Buddy Display	5	55
9	Illumination of display was appropriate (neither too bright nor too dim)	6	67
10	Buddy Display should be ruggedized and made water proof for harsh environments	6	67
11	The amount of air left in the self contained breathing apparatus (SCBA) should also be displayed on the Buddy Display in pounds per square inch (PSI)	9	100
12	Heart rate display should be larger	4	44

Ways the Buddy Display could be improved included better educating the user community about PSI. Most participants understood that PSI was related to heat strain but did not understand that it was an index of both work intensity and heat strain and was derived from heart rate and body core temperature. In addition, there was confusion surrounding the use of the PSI (physiological strain index) acronym since PSI is normally an abbreviation for "pounds per square inch" and is used by CBRN personnel to monitor the air pressure in their SCBA tanks (11). All participants believed the PSI (physiological strain index) term should be renamed (Table I, Topic 3) and the acronym PSI be reserved for pounds per square inch of air left in the tank. All volunteers believed the amount of air left in the tank should also be displayed on the Buddy Display in PSI (Topic 11). The majority of volunteers felt the form factor of the Buddy Display should be changed from a rigid cell phone to something more flexible and form-fitting. A flexible forearm sleeve, similar to a quarterback's forearm play-calling device was recommended and agreed upon by 5 of the 9 volunteers (Table I, Topics 7 and 8). Most of the volunteers mentioned that the device must be ruggedized and made waterproof for the harsh operational environments they sometimes are called to work in. With regard to being waterproof, participants believed a clear plastic casing of some sort would suffice, even if the device itself could not be waterproofed.

DISCUSSION

Thermal strain responses to walking in CBRN PPE in a warm environment differ by individual. While the sample size was too small to identify the causes of these individual differences in this study, previous research with military personnel has shown the effects of anthropometrics, body fat, aerobic fitness, hydration state and other individual characteristics affect the thermal strain experienced for a given work load in a particular operational environment (12,13). Furthermore, there is a continued need for conducting human factors evaluations for these types of equipment to ensure maximal comfort, acceptability, and usability by the intended users (14).

As noted, individual thermal-work strain responses to a common activity varied. Mission management could involve shifting a soldier with a safe but moderately elevated PSI (e.g., a 5 or 6) to a more sedentary task such as being responsible for radio communications back to the command post. Meanwhile, a team member with a lower PSI (e.g., 2 or 3) could perform a more physically demanding task such as preparing a victim for extraction from a contaminated site. Information on work rate and its impact on SCBA air consumption would also be useful for mission management. Understanding the relationship between work rate and air consumption further could allow for safe and effective conduct of CBRN missions. This type of mission management would allow CBRN teams to extend their on-site work time, because teams are only effective as "their weakest link." The PSM system, in addition to providing current thermal strain information for a given individual, may ultimately be able to predict thermal strain up to 20 min into the future (15, 16).

The term PSI, while understandable for physiologists, introduced confusion to CST-WMD personnel who are used to monitoring the amount air in their SCBA tanks. These soldiers monitor the air left in their tanks in pounds per square inch which is also abbreviated as PSI. Therefore, it is recommended that PSI be changed to heat strain index (HSI) and that PSI, referring to air in the tanks also be shown on the Buddy Display.

The final recommendation had to do with the form factor of the Buddy Display. While these soldiers did not have an issue with the cell phone type display taped to the upper arm, it was hard for the individual to monitor himself. It was suggested that a lighter weight device similar to what quarterbacks use for play-calling be positioned on the forearm. The device should not be rigid but should be flexible to accommodate the curvature of the forearm. It was also recommended that placing a device of the same weight on the forearm as the cell phone used in this study would impede fine motor tasks, such as obtaining a sample of CBRN material. Therefore, reducing the weight of the Buddy Display is imperative if it is moved to the forearm.

This accessible real-time information can also serve as a useful tool for improving human performance of a variety of activities by providing biofeedback (17). This biofeedback can be provided to the intended user, his/her buddy, and/or medical personnel monitoring the mission. Another rationale for the use of PSM systems is to provide the data needed to improve CBRNE ensembles and their associated equipment. Physiological data could be used to encourage innovations that improve dry and wet heat dissipation by CBRN PPE, and argue for the use of microclimate cooling systems that mitigate thermal strain experienced by CBRN personnel.

CONCLUSION

In conclusion, this study demonstrated that real time monitoring would be useful to CST-WMD personnel operating in a CBRN environment. Individual differences in responses to the thermal strain experienced show the importance of monitoring, because generalized work standards do not apply to all individuals. Use of physiological monitoring systems could enable extended mission times by allowing mission to be managed based in part on the thermal-work strain being experienced by the individual.

DISCLAIMER

The opinions or assertions contained herein are the private views of the authors and are not to be construed as official or as reflecting the views of the Army or the Department of Defense. The authors have no financial or personal interest in the systems tested in this study. The investigators have adhered to the policies for protection of human subjects as prescribed in Army Regulation AR 70-25 and USAMRMC Regulation 70-25, and the research was conducted in adherence with the provisions of 32 CFR Part 219. Citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement or approval of the products or services of these organizations.

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