Thermal-work strain in law enforcement personnel during chemical, biological, radiological, and nuclear (CBRN) training

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Background: Thermal safety standards for the use of chemical, biological, radiological, and nuclear (CBRN) ensembles have been established for various US occupations, but not for law enforcement personnel.
Objectives: We examined thermal strain levels of 30 male US law enforcement personnel who participated in CBRN field training in Arizona, Florida, and Massachusetts.
Methods: Physiological responses were examined using unobtrusive heart rate (HR) monitors and a simple thermoregulatory model to predict core temperature (T_c) using HR and environment.
Results: Thermal strain levels varied by environments, activity levels, and type of CBRN ensemble. Arizona and Florida volunteers working in hot-dry and hot-humid environment indicated high heat strain (predicted max T_c>38.5°C). The cool environment of Massachusetts reduced thermal strain although thermal strains were occasionally moderate.
Conclusions: The non-invasive method of using physiological monitoring and thermoregulatory modeling could improve law enforcement mission to reduce the risk of heat illness or injury.

Keywords: Chemical, biological, radiological, nuclear (CBRN) ensembles, Core temperature, Heart rate, Law enforcement, Thermoregulatory model

Introduction

Law enforcement personnel increasingly utilize personal protective equipment (PPE) when exposed to potentially hazardous chemical, biological, radiological, and nuclear (CBRN) materials. Methamphetamine labs, bioterrorism threats, and anthrax are examples of situations that require the PPE designed for CBRN materials (or PPE-CBRN).[1–4] While this gear provides clear health and safety benefits for law enforcement personnel, wearing encapsulating PPE-CBRN also impedes the loss of excess body heat. Heart rate (HR), core temperature (T_c), and skin temperature (T_{sk}) all increase with the use of encapsulating PPE-CBRN. Wearing PPE-CBRN in combination with the physical labor requirements of law enforcement results in an increase in thermal strain, which in turn may be associated with performance decrements in physical and cognitive tasks.[5,6]

Thermal safety standards for PPE-CBRN gear have been established for certain occupational groups including: the military, firefighters, and hazardous material workers. However, no thermal safety standards exist for law enforcement personnel.[7,8] While, some of the job requirements of law enforcement officers are similar to other occupational groups for which standards exist, they are also involved in unique tasks that require PPE-CBRN, such as crime scene investigations. Furthermore, the overall fitness of law enforcement personnel is more variable than within the military, which has stricter physical fitness standards.[9] The lack of safety standards for heat stress management make US law enforcement personnel particularly vulnerable to heat illness and injuries when encapsulated in PPE-CBRN.

The purpose of this study was to quantify thermal-work strain of US law enforcement personnel wearing PPE-CBRN during CBRN training conducted in different climatic conditions.

This is the first attempt to collect physiological data to understand thermal strain/comfort levels of US law enforcement officers involved in actual PPE-CBRN training conducted in hot-dry, hot-humid, and cool environmental conditions. This study also introduces the combined usage of physiological monitoring systems and a thermoregulatory model to assess thermal strain levels of US law enforcement individuals. Findings in this study will be helpful for mission planning for law enforcement personnel involving CBRN operations.

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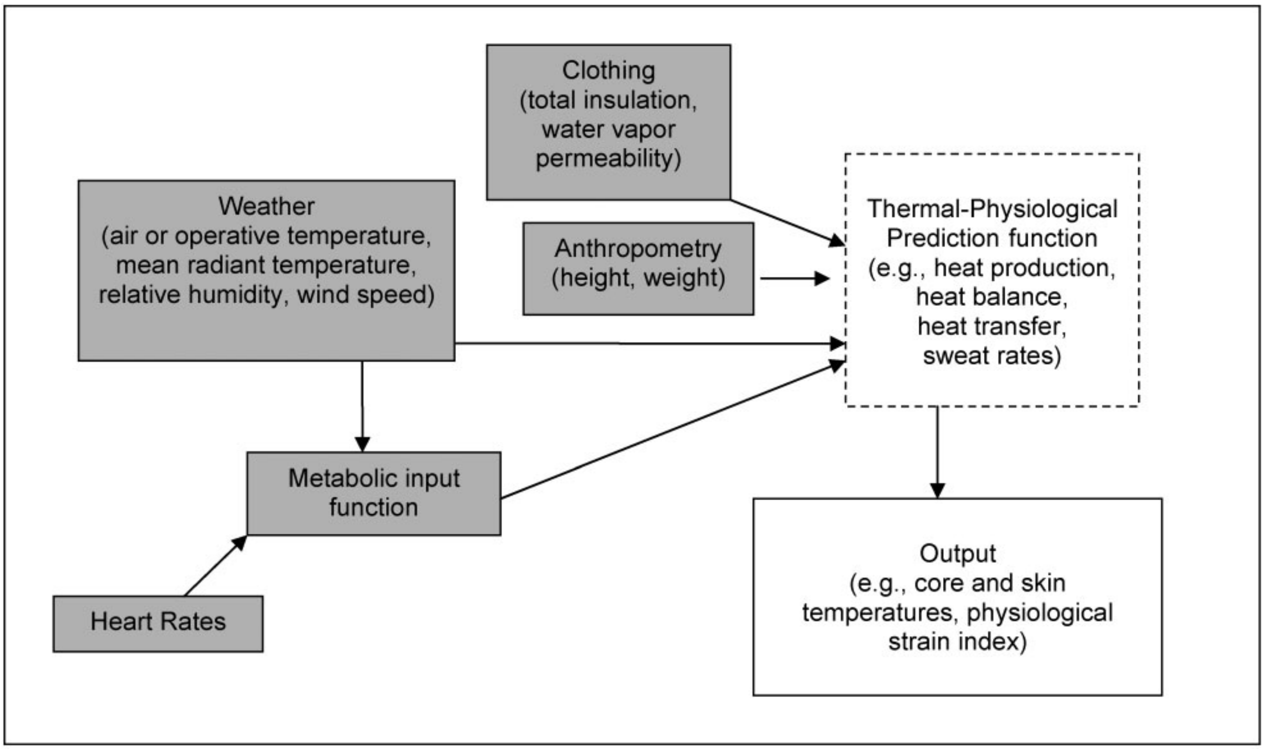

Figure 1 The diagram of the initial capability decision aid (ICDA) thermoregulatory model.

Methods

There are specific levels of T_c that have been set as safety standards and that can be tolerated during exposure to thermal stress in many occupations.[10–12] However, the use of thermometer pills for measuring T_c is cost prohibitive for most law enforcement agencies. Unobtrusive HR monitors and a simple thermoregulatory model were used to evaluate thermal-work strain in this study. A thermoregulatory model, based on mathematical representations of known principles of physiology and thermodynamics, predicts human thermoregulatory responses including T_c to various combinations of human characteristics, clothing biophysical characteristics, exercise levels/work intensity, and environmental conditions. A non-invasive approach to predict T_c can be used to estimate thermal strain levels of law enforcement personnel working in PPE-CBRN conditions. If successful, the use of a thermoregulatory model could be used in mission management.

Thermoregulatory model

The initial capability decision aid (ICDA), has been used to predict thermal strain.[13] The ICDA is a mathematical model where the human body is represented as a cylinder consisting of two compartments (core and skin) surrounded by a clothing layer. Compared to other thermoregulatory models, this model is relatively simple to use and requires only a few non-invasive input variables. Model inputs include the participant's anthropometric values (height, weight, and body mass index [BMI]), HR, environmental conditions (air temperature [T_a], relative humidity [RH], mean radiant temperature [MRT], and wind speed [WS]), and biophysical properties of the clothing/equipment worn (total insulation [clo], water vapor permeability [im]). Highlights of the ICDA model are described here and Fig. 1 provides a schematic of the model. Detailed descriptions of this model are provided elsewhere.[13,14]

The model inputs characterize individuals and are used to determine energy flows between and within compartments, body temperatures, and physiological responses. The overall heat balance for a person in the ICDA model is expressed as:

$$S = M - Q_{res} - Q_k - Q_{bf}\,[\mathrm{W\,m^{-2}}] \quad (1)$$

where S is the rate of heat storage; M is the rate of metabolic heat production; Q_{res} is respiratory heat loss; Q_k is the rate of conductive heat loss through the tissue to the skin; and Q_{bf} the rate of convective heat loss through blood flow between core and skin.

The values of Q_k and Q_{bf} were determined from standardized equations, using T_c, T_{sk}, and heat transfer coefficients for tissue and blood flow, respectively.[15,16] All measures of heat transfer were estimated and not measured directly. External work, which is difficult to quantify and measure in real-time, and is rarely continuous for extended periods of time, is excluded from this model.

The ICDA model generates real-time estimates of metabolic heat production (M, watts) from the ratio of measured HR and baseline HR, body surface area, and environmental operative temperature (T_o).[17] All of the M is assumed to be generated in the core compartment. The M equation from the inputs was calculated as follows:

$$M = [0.68 + 4.69\ (HR_{ratio} - 1)\ - 0.052\ (HR_{ratio} - 1)\ (T_o - 20)]\ 58.1 A_D \quad (2)$$

where HR_{ratio}=observed HR given at the time/resting HR of the individual, and T_o=operative temperature in degree Celsius. The A_D is the body surface area (m^2). The T_o was calculated as the average of the MRT and air temperature weighted by the respective heat transfer coefficients. Cardiac output, indicated by HR, supplies blood and oxygen for metabolism and blood flow to the skin for thermoregulation. For a given metabolic activity, the HR will increase with rising environmental temperature due to the thermoregulatory need for increased skin blood flow.

Core and skin compartment temperatures are estimated from heat gains and losses primarily through respiration (Q_{res}), conduction through the tissue to the skin (Q_k), and convection from blood flow (Q_{bf}). The Q_{res} was determined as:

$$Q_{res} = M/A_D(0{\cdot}0014(34 - T_a) + 0{\cdot}0023(44 - P_a))\ [\mathrm{W\,m^{-2}}] \quad (3)$$

where P_a is the ambient water vapor pressure (Torr) and T_a is the ambient temperature (°C).[15]

The model predicts physiological responses including T_c, T_{sk}, sweat rates, and physiological strain index (PSI). Physiological strain index is an 11-point ordinal scale (0=no strain; 10=very high strain) that assesses thermal-work strain levels of individuals based on HR and T_c.[18] The PSI was calculated as follows:

$$PSI = 5(T_{c_t} - T_{c_0})(39.5 - T_{c_0})^{-1} + 5(HR_t - HR_0)(180 - HR_0)^{-1} \quad (4)$$

where T_{c_t} and HR_t are core temperatures and HR at a time t, and T_{c_0} and HR_0 were baseline values at resting states. The PSI scale ranges from 0 to 10, corresponding to an ordinal scale of no/little ($PSI \leq 2$) to very high ($PSI \geq 9$) thermal-work strain.[18]

The ICDA model has been previously validated with T_c in both controlled laboratory (n=18; T_a: 22–35°C; 45–55% of VO_{2max} continuous or intermittent treadmill walk for 30–75 minutes) and field (n=10; T_a: ~19°C; marched 5 km with 37 kg load carriage for ~45 minutes) studies including protective garments.[13,14,19] Model predictions of T_c were typically within an acceptable range using common mathematical validation methods such as (a) a root mean square deviation (or the average difference between measured and predicted values across the time) <0.5°C and (b) the Bland–Altman plots (x axis for representing average values of measured and predicted T_c and y axis for differences between measure and predicted values). The model tends to over-predict T_c with root mean square deviation exceeding 0.5°C in the field study data and *ad libitum* exercises in a hot chamber environment. Possible reasons for the over-prediction of T_c include a time lag in heat balance calculations that can occur when short abrupt changes are present (e.g., opening the jacket, frequent intermittent activity changes such as walking to running, and vice versa), improper baseline HR selection, or unspecified individual factors (e.g., alcohol usage, medication use, sleep deprivation). Despite the simplistic nature of the model, it is still useful for understanding overall thermal strains of law enforcement personnel engaged in PPE-CBRN operations.

Current field study

Study volunteers included 30 US law enforcement personnel from Arizona, Florida, and Massachusetts participating in tactical training that required the use of PPE-CBRN. The study was reviewed and approved by the Scientific Research Committee (SRC) and Human Use Review Committee (HURC) at the US Army Research Institute of Environmental Medicine (USARIEM). All study volunteers were briefed concerning study procedures and risks and provided informed consent before their participation. The PPE-CBRN worn by volunteers included a t-shirt, shorts, socks, and the outer-garment. In addition, a helmet, mask, gloves, boots, a self-contained breathing apparatus (SCBA), firearm, body armor, and other accessories (e.g., radio, ammunition) were either worn or carried. All groups utilized the same size SCBA cylinder (45 minutes). The exact equipment worn and/or carried varied slightly depending upon the job assignments and individual preferences. Training/exercise tactics varied by location, with volunteers assigned to different roles/tasks. The investigators had no influence on the conduct of the training exercises. Investigators did record the type and time engaged in the various activities during the law enforcement training and activity logs were reviewed in a post-training focus group and any gaps in the sequence of activities were filled. The training exercises generally involved standing, riding in a vehicle, walking, running, kneeling, firing a rifle, climbing up and down stairs, and carrying/dragging a human body. Volunteers were permitted to consume fluids as desired before and after exercises. No fluids were consumed during the exercise because the mask and SCBA equipment configuration prevented fluid consumption. Subjective thermal discomfort experienced by the study participants was assessed at the completion of the training exercise by asking volunteers the maximum level of thermal discomfort they experienced during the training exercise using a 10-point scale. The scale ranged from 1=minimum thermal discomfort to

Table 1 Summary of local weather data, anthropometry, load carriage, and main activities by training locations and clothing types

Training sites	Arizona		Florida		Massachusetts
Clothing types	Class 2	Class 3	Class 2	Class 3	UC
n	7	6	4	3	10
Air temperature (°C)	34.7±0	34.7±0	29.3±0.1	29.3±0.1	4.2±0.2
Mean radiant temperature (°C)	34.7±0	34.7±0	79.0±0	79.0±0	14.5±2.3
Relative humidity (%)	10.0±0	10.0±0	58.0±0	58.0±0	96.6±3.5
Wind speed (m s^{-1})	0.1±0	0.1±0	4.9±0	4.9±0	4.5±0.1
Age	42±4	38±10	42±5	45±9	42±7
Height (cm)	178±6	180±7	176±5	185±11	178±6
Weight (kg)	79±7	87±13	84±11	98±14	89±9
Body mass index (kg/m^2)	25±1	27±2	27±2	29±4	28±2
Load carriage (kg)	23±4	23±6	20±2	11±2	20±0
Activity durations (minutes)	~20	~20	~20	~20	45 (exercise) – 45 (rest) – 45 (exercise)
Training activities	bio-hazard investigation; looking for/rescuing a hostage; capturing suspects in a two-story house		a slow walk of ~1 km to a fire tower; investigating hazardous material sites; rescuing an injured person in a fire tower		searching for suspected hazardous materials; capturing suspects in a two-story house; rescuing an injured police officer

Weather, anthropometry, and load carriage values: mean±standard deviation.
UC: uncategorized protective ensembles.

10=maximum thermal discomfort defined as the brink of heat exhaustion and feeling like they might faint. HR data were collected with a chest strap sensor (Equivital™ EQ-01; Hidalgo Ltd., Cambridge, UK). Local meteorological data were obtained every 15 minutes from the closest automated weather station via MesoWest network.[20] Biophysical characteristics (i.e., clo and im) of the PPE-CBRN ensembles worn in the studies were determined by thermal sweating manikin testing.[21,22]

Table 1 shows the summary of subjects' characteristics and operational and environmental conditions by training locations and clothing types. Detailed characteristics by study locations are described below.

Arizona study: Thirteen male law enforcement participants wore either National Fire Protection Association (NFPA) Class 2 Lion Multi-threat garment (n=7; MT94, Lion Apparel, Dayton, OH, USA, clo=1.48, im=0.02) or Class 3 Lion Extended Response Suit (n=6; ERS, Lion Apparel, Dayton, OH, USA, clo=1.33, im=0.15). The NFPA Class 2 garment is generally ~1.0 kg heavier, has greater insulation, and provides more biological/chemical protection than the Class 3 garment.[23] Starting from notification of a simulated CBRN incident, it took approximately 40 minutes to get fully equipped with the PPE-CBRN and prepared for their training exercise which was typically ~20 minutes in duration. The training exercises included identifying methamphetamine-associated activities, rescuing a hostage(s), and capturing suspects in a two-story house. Most of the training was conducted inside a non-air conditioned building (estimated values: T_a: 34.7±0°C; MRT: 34.7±0°C; RH: 10±0%; WS: 0.1±0 m s^{-1} for ~20 minutes training period). Building environmental conditions were estimated based on the average external environmental conditions between the training period and 12 hours before the training.[20]

Florida study: Seven male law enforcement participants wore either NFPA Class 2 Lion Multi-threat garment (n=4) or Class 3 Lion Extended Response Suit (n=3) participated in approximately 20 minutes of outside training (T_a: 29.3±0.1°C; MRT: 79.0±0°C; RH: 58.0±0%; WS: 4.9±0 m s^{-1}). The training consisted of a slow walk of approximately 1 km to a fire tower. The fire tower contained a simulated hazardous material site with an injured person requiring evacuation.

Massachusetts study: Ten male law enforcement participants wore un-categorized NFPA CBRN protective ensembles (insulation: clo=1.58; water vapor permeability: im=0.25, Rampart suit, Gentex, Simpson, PA, USA) and participated in two field training sessions (total duration=1.5 hours) in cool spring-time weather conditions (T_a: 4.2±0.2°C; MRT: 14.5±2.3°C; RH: 96.6±3.5%; WS: 4.5±0.1 m s^{-1}). Training consisted of searching for suspected biological/chemical hazards and capturing suspects engaged in an illegal drug operation in a two-story house. Participants also practiced rescuing and evacuating an injured police officer from the crime scene. During the ~45 minutes intermission between the two training exercises, volunteers were able to remove their PPE-CBRN ensembles, rest, and consume fluids.

Physiological responses, including measured HR, predicted T_c, and PSI were measured. A $T_c \geq 38.5$°C was utilized as a threshold for heat strain based on thermal safety guidelines provided by National Institute of Occupational Health and Safety and the Occupational Safety and Health Administration.[12,24]

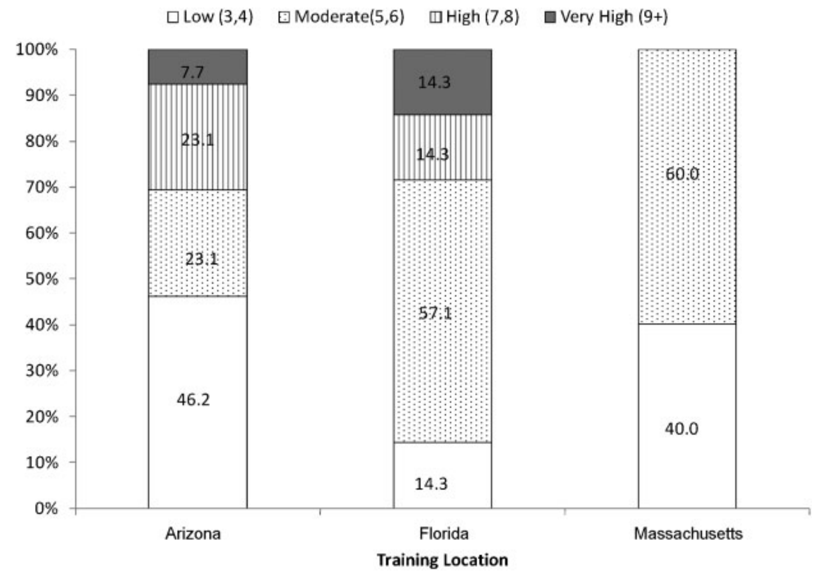

Figure 2 The percent distribution of participants' maximum predicted physiological strain index (PSI) by training venue.

Results

Table 2 summarizes the descriptive results (maximum HR, maximum T_c, maximum PSI, and maximum self-reported thermal discomfort) by study locations. Individuals wearing Class 2 PPE-CBRN ensembles in Arizona and Florida had higher mean maximum predicted T_c and PSI levels even during the shorter 20 minutes of training. A $T_c>38.5°C$ during the exercises was predicted in 6 out of 13 Arizona law enforcement officers (46%), 4 out of 7 (57%) Florida law enforcement officers, while Massachusetts law enforcement personnel did not have T_c exceeding 38.5°C.

A summary of the maximum predicted PSI levels by training location is shown in Fig. 2. Four Arizona (30%) and two Florida (29%) law enforcement officers had high predicted PSI levels during the exercise. Despite the cool weather, six Massachusetts personnel (60%) had predicted moderate PSI levels during the training. Post-study ratings of maximum thermal discomfort experienced during the training showed that nine individuals (69.2%) from Arizona, five individuals (71.4%) from Florida, and three individuals (30.0%) from Massachusetts self-reported thermal sensations of six or greater. A value of six represents moderate thermal discomfort. One individual was treated for heat exhaustion during the training in Florida.[25] Study participants self-reported feeling hot in PPE-CBRN gear when engaged in vigorous activities such as carrying and evacuating an 86 kg person (~45 m distance), running, and/or climbing stairs (~1–3 minutes in duration). The cool environmental conditions in the Massachusetts training reduced thermal-work strain of the law enforcement personnel, allowing them to work for more than 45 consecutive minutes.

Figure 3 shows the measured HR and predicted T_c over time and by type of PPE-CBRN worn for officers at each training location. The combination of PPE-CBRN gear and work activities resulted in physiologically heavy work (i.e., HRs greater than 120 bpm[26] and predicted T_c exceeding 38.5°C) toward the end of the training exercise for officers working in high temperatures in Arizona and Florida. The cooler conditions in Massachusetts resulted in a smaller rise in HR or predicted T_c over time.

Discussion

Law enforcement personnel encapsulated in PPE-CBRN are vulnerable to heat strain. This study found high maximum PSI levels for workers training in Florida and Arizona and moderate PSI levels among personnel in Massachusetts. Self-reported thermal discomfort of Arizona and Florida law

Table 2 Descriptive summary of measured maximum heart rate (HR), maximum predicted core temperature (T_c), predicted maximum physiological index, and self-reported thermal discomfort by three US locations and clothing types

Training sites	Arizona		Florida		Massachusetts
Clothing types	Class 2	Class 3	Class 2	Class 3	UC
n	7	6	4	3	10
Mean and standard deviation (SD) of maximum heart rate (bpm)	138±11	115±11	142±12	145±13	139±26
Mean and SD of maximum core temperature(°C)	39.4±0.7	37.8±0.3	39.0±0.4	38.0±0.4	37.5±0.3
Mean and SD of maximum physiological strain index	6.9±1.4	3.4±0.8	6.9±1.3	4.8±0.7	4.7±1.4
Mean and SD of self-reported thermal discomfort	6.3±0.5	4.2±1.0	5.6±1.5	4.0±0.0	4.1±0.3

UC: uncategorized protective ensembles.

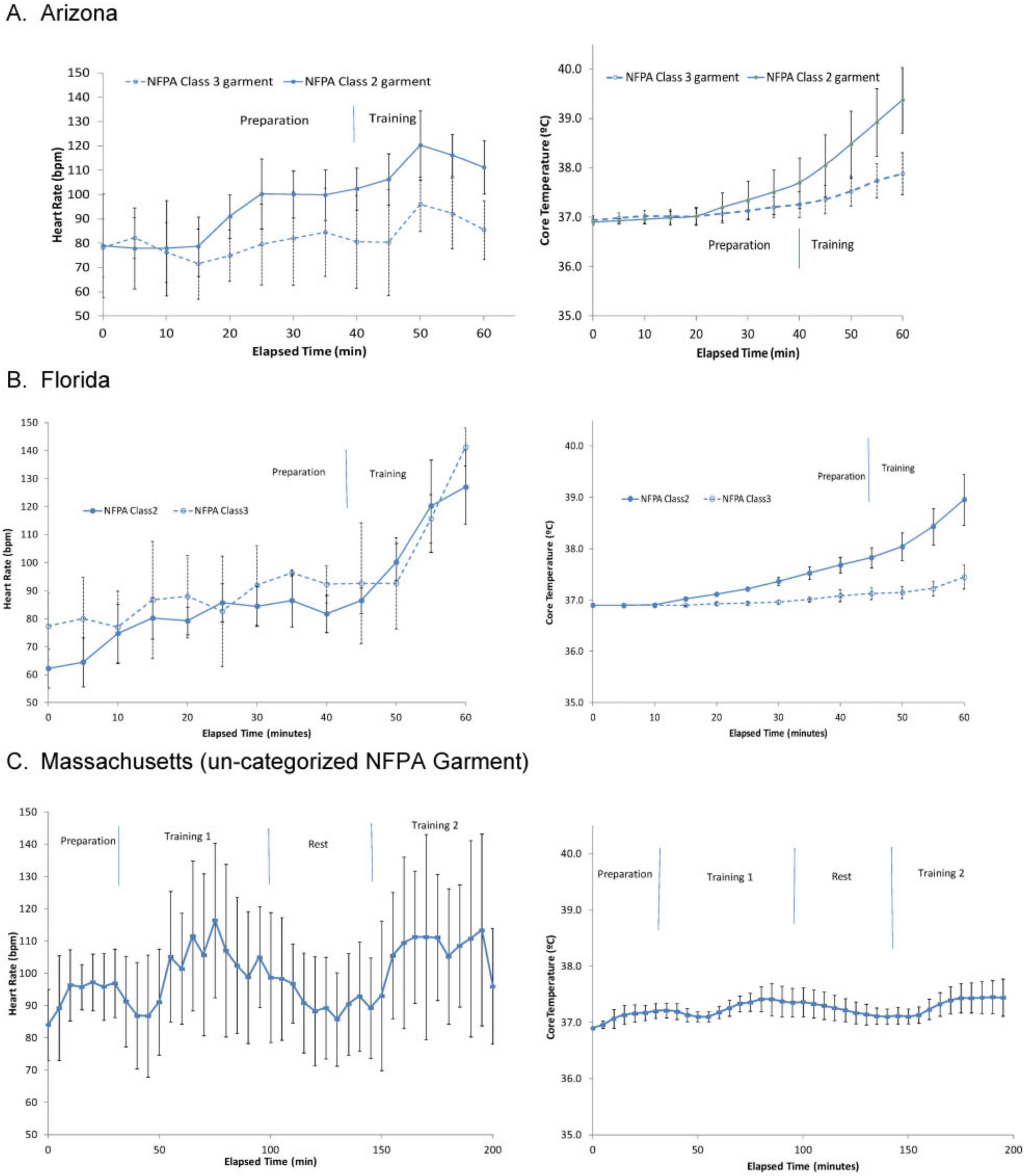

Figure 3 Group means of measured HR and predicted core temperature (T_c) of law enforcement personnel by PPE-CBRN and locations. Vertical bars indicate standard deviations of the data points.

enforcement personnel was greater than moderate discomfort, likely due to working in hot temperatures while encapsulated in PPE-CBRN, although some workers in the cooler Massachusetts environment did report moderate thermal discomfort when engaged in strenuous activities. Predicted T_c values showed that 46% of Arizona and 57% of Florida law enforcement personnel exceeded safety thresholds regarding thermal strain. A recent study indicated that measured T_c of UK law enforcement personnel wearing PPE-CBRN were greater than 39.0°C during their firearms house entry simulations in a moderate environment (18°C/65% RH).[27]

Increased risk of heat illness is a likely result of the combined effects of wearing PPE-CBRN, hot environmental conditions, physiologically demanding activities, and fluid restriction. Although individuals in PPE-CBRN were able to work for longer time periods in the Massachusetts environment, performing strenuous activities while encapsulated can still result in a thermal burden. Previous research has indicated that soldiers working in a cold environment

(−33–0°C) can experience thermal strain that exceeds safety levels (e.g., T_c>38.0°C) when encapsulated in PPE-CBRN during continuous hard work (340–680 W).[28] In addition, Goetz *et al.* estimated peak metabolic heat production of these law enforcement personnel during PPE-CBRN exercise varied between 200 and 800 W.[25] These intermittent high work rates were driven not only from strenuous activities (e.g., walking upstairs, running, carrying casualties, and breaching buildings) but also from the weight of the PPE-CBRN.[25] Since law enforcement personnel indicated they sometimes carry even heavier loads than those reported (i.e., ~13–34 kg), it is likely that workers may experience high levels of heat strain independent of environmental conditions.

The biophysical characteristics of PPE-CBRN utilized in the three study locations were different, yet the effect of protective clothing on thermal strains of participants in this study was inconclusive because of variation in anthropometrics, equipment, and activities performed by location. Although thermal effects of different protective garments on physiological responses were inconclusive, heat strains experienced by law enforcement personnel wearing PPE-CBRN could reach beyond a T_c threshold based on other occupational thermal safety guidelines during the training exercises. While PPE-CBRN with high insulation provides more protections from hazardous materials, it also limits the length of work. Currently, there is no consistent approach for purchasing and using PPE-CBRN for law enforcement officers, resulting in inconsistent thermal risk management across US agencies. We recommend that more attention be given to setting standards for the (1) type of PPE-CBRN ensembles, (2) proper resting periods and work rates (i.e., related to environment and PPE-CBRN worn), (3) hydration recommendations, and (4) use of cooling devices during a CBRN exercise and/or pre-cooling before the exercise. There is a need for more data-driven research in these areas and results can be used to ensure the health and safety of law enforcement personnel.

The SCBA used in this study prevents law enforcement personnel from consuming fluids. It has been well established that lack of hydration increases thermal strain and may result in impaired job performance.[29,30] There are alternative SCBA systems (e.g., Patriot life support system, Wilcox Industries Corp., Newington, NH, USA) available that allow the consumption of fluids using the equipment. We recommend that law enforcement agencies consider the benefits of these systems. Furthermore, some law enforcement personnel reported their job may require them to be in their PPE-CBRN for more than 2 hours searching for biohazard materials. Working continuously in PPE-CBRN without breaks and without proper hydration could exacerbate the physiological states observed in the present study. Thus, adoption of masks that allow for hydration while encapsulated in CBRN and the use of physiological monitoring systems are important for law enforcement personnel engaged in PPE-CBRN training or actual missions. Furthermore, although removal of PPE-CBRN might not be tactically possible, reduction of work levels to decrease metabolic heat production while still encapsulated could be considered.

The US law enforcement specific standards for thermal strain still need to be established. Direct measures of T_c, T_{sk}, and other thermal strain/physiological parameters are necessary for establishing these standards. However, measuring T_c in particular, by thermometer pill, esophageal, or rectal probes for prolonged working hours could be aversive, expensive, and time-consuming to those entrusted with overseeing monitoring. This study used a physiological monitoring system and thermoregulatory model, and the thermal strain of law enforcement personnel involving in PPE-CBRN work was quantified. Actual means of T_c and T_{sk} for establishing thermal standards could be collected in a similar manner to what is presented in this study using thermometer pills and skin temperature sensors. Operationally, the use of real-time physiological monitoring and real-time predictive models/algorithms could identify thermal strains on time during the work at any operational and environmental situations associated with PPE-CBRN activities, mitigate the risk of heat illness, assist greater medical awareness, and further provide associated safe mission management in a dynamic working environment.

Disclaimer statements

Contributors MY was responsible for data collection, data analysis, thermal modeling, writing, and administrative tasks. AK was responsible for data collection and technical support. WT was responsible for study design, recruitment of participants, data collection, and editing. MY is the guarantor.

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Ethics approval The investigators have adhered to the policies for protection of human subjects as prescribed in Army Regulation 70–25, and the research was conducted in adherence with the provision of 32 CFR Part 219.

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