EFFECTS OF BUNKER GEAR TEMPERATURE AND DIFFERENT WORK RATES ON MICRO-E AND HEAT STRESS

by

JARED H. HORNSBY

PHILLIP A. BISHOP, COMMITTEE CHAIR
JOHN A. DANTZLER
JONATHAN E. WINGO
MARK T. RICHARDSON
YASMIN H.NEGGERS

A DISSERTATION

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy
in the Department of Kinesiology
in the Graduate School of
The University of Alabama

TUSCALOOSA, ALABAMA

2015

Copyright Jared H. Hornsby 2015
ALL RIGHTS RESERVED

ABSTRACT

Wearing protective clothing (PC) such as firefighter bunker gear leads to increased heat strain. Bunker gear has multiple layers which creates a heat sink during the first several minutes after donning, potentially providing some amount of cooling of the micro-environment (micro-E) around the skin. Furthermore, predicting heat strain at various work rates while wearing PC is important for determining work tolerance limits. The purpose of these studies was to determine the effect of a COLD (< 0 °C) bunker gear on rectal temperature (T_{re}) and micro-E at a steady-state exercise intensity and to begin creating a regression model to predict micro-E temperature and relative humidity under bunker gear based on work rate. Studies I and II utilized a repeated-measures randomized experimental design, which consists of 4 trials (LO, MOD, HI (HOT), and HI (COLD)). Human volunteers wore bunker gear for 30 min while oxygen uptake ($\dot{V}O_2$), heart rate, perceptive measures (ratings of perceived exertion, thermal sensation, sweating sensation, and clothing comfort), T_{re}, skin temperature, and micro-E (temperature and relative humidity at the anterior and posterior portion of the jacket and pants) were measured. A repeated measures MANOVA with a Bonferroni post hoc analysis was used to evaluate: the physiological measures; while the Friedman's Test was performed with a Wilcoxon Signed Rank Test on all perceptual measures. The COLD bunker gear did not significantly alleviate heat strain when compared to HOT bunker gear. Additionally we low, moderate and high intensities of work in ~ 29 °C macro-E WBGT did not differentially affect micro-E WBGT under bunker gear, and these data were used to derive models of micro-E from macro-E.

Further data is needed to cross-validate the derived micro-E WBGT model predicted from macro-E WBGT and work rate.

Key Words: protective clothing, micro-E, personal cooling

DEDICATION

This dissertation is dedicated to my professors, colleagues, family, friends, and the numerous others who have helped me along the way.

LIST OF ABBREVIATIONS AND SYMBOLS

χ^2	Chi Square
°C	Degrees Celsius
°C/h	Degrees Celsius per hour
Δ	Delta
~	Equivalence
=	Equal to
>	Greater than
<	Less than
%	Percent
ANOVA	Analysis of variance
beats/min	Beats per minute
C	Celsius
CO_2	Carbon dioxide
COLD	< 0 °C dry bulb
CON	Control
cm	Centimeter
FF	Firefighter
g/h	Grams per hour
h	Hour

HR	Heart rate
LO	Low intensity trial (~ 100 kcal/h)
MOD	Moderate intensity trail (~ 330 kcal/h)
HI	High intensity trial (~ 450 kcal/h)
HOT	32 °C dry bulb
Kcal/h	Kilocalorie per hours
kg	Kilogram
L/min	Liters per minute
Macro-E	Ambient environment
Micro-E	Microenvironment
min	Minute
n	Number
NFPA	National Fire Protection Association
p	P-value
PARQ	Physical activity readiness questionnaire
PC	Protective clothing
PCM	Phase change material
rH	Relative humidity
RM	Repeated-measures
RPE	Ratings of perceived exertion
SCBA	Self-contained breathing apparatus
SPSS	Statistical Package for the Social Sciences
T_{re}	Rectal temperature

T_{sk}	Mean skin temperature
USG	Urine specific gravity
$\dot{V}O_2$	Oxygen uptake
WBGT	Wet bulb globe temperature
yr	Year

ACKNOWLEDGEMENTS

First off, I want to thank my parents as they have set the standard of excellence in my life. In addition, I want to thank my wife Hannah and her parents for the encouragement and support they have provided throughout this process. As this chapter of my career ends, I am ever reminded that it is not by my efforts that I succeed, but because of those around me.

In addition, I want to thank my mentors both current (Dr. Phillip Bishop) and previous (Drs. Eric O'Neal and Matthew Green) for providing the examples of professionalism in my life. I am forever indebted to my committee: Dr. Phillip Bishop for guiding me through this process: Dr. John Dantzler for providing me with statistical guidance; Dr. Mark Richardson for providing a fresh prospective to my writing; Dr. Jonathan Wingo for his expertise on the subject matter and attention to detail through the editing process; Dr. Yasmin Neggers for aiding the review process and providing kind words of encouragement.

Lastly, I want to thank Alex Martinez, Jason Ng, Sara Baggett, Kermit Crew, David Diggs, Anthony Fava, and Ryan Fowler for the conversations we had as I proceeded through the dissertation process. These friends provided their time, effort, and energy; without their willingness to help, my success could not have been possible.

CONTENTS

ABSTRACT ii

DEDICATION iv

LIST OF ABBREVIATIONS AND SYMBOLS v

ACKNOWLEDGEMENTS viii

LIST OF FIGURES x

CHAPTER I: INTRODUCTION 1

CHAPTER II: EFFECTS OF COLD FIREFIGHTER BUNKER GEAR ON HEAT STRAIN IN A HOT ENVIRONMENT 3

CHAPTER III: IMPACT OF WORK RATE ON MICRO-E UNDER FIREFIGHTER BUNKER GEAR AT 29 ˚C WBGT 20

CHAPTER IV: COOLING TECHNIQUES FOR FIREFIGHTERS: A BRIEF REVIEW…….. 39

APPENDIX…. 56

LIST OF FIGURES

1.1 Δ Temperature (°C WBGT) 11

1.2 Δ T_{re} (°C) 11

1.3 Δ HR (beat/min) 12

1.4 Mean perceptual measures (a-d) 13

2.1 Micro-E WBGT (°C) 29

2.2 Polynomial regressions (second order) Micro-E WBGT (°C) - entire work bout 29

2.3 Polynomial regressions (second order) Micro-E WBGT (°C) - beginning at 15 minutes 29

2.4 Δ T_{re} (°C) (0,10,20, and 30 min) 30

2.5 HR (beat/min) 31

2.6 Mean perceptual measures (a-d) 32

AUTHOR'S NOTE

All studies are written in journal format for *Journal of Occupational and Environmental Hygiene.*

For the body of the dissertation, the following key will be used in reference to my own research.

It is my plan to publish all currently unpublished works in the following order:

Study 1: *Effects of Cold Firefighter Bunker Gear on Heat Strain in a Hot Environment*—(Hornsby et al. 20xxb)

Study 2: *Impact of Work Rate on Micro-E Under Firefighter Bunker Gear at 29˚C WBGT*—(Hornsby et al. 20xxc)

Study 3: *Cooling Techniques for Firefighters: A Brief Review*—(Hornsby et al. 20xx

CHAPTER I

INTRODUCTION

Humans working in a hot ambient environment (macro-E) maximize evaporative cooling and mitigate heat stress by adjusting their clothing to expose a large surface *area of skin to the macro-E. When wearing protective clothing (bunker gear), such as firefighter bunker gear, workers are unable to remove clothing to promote heat dissipation via sweat evaporation. Therefore, heat storage is increased—even in moderate temperatures—due to the semi-permeable and insulative characteristics of the bunker gear, which encapsulates the body. More specifically, bunker gear allows little air to exchange between the micro-environment (micro-E)—the small layer of air closely surrounding the body [(1)]—and the macro-E, resulting in the micro-E being heated by metabolism and humidified by sweat. [(2)] The micro-E changes rapidly once the clothing is donned and physical activity has begun and reaches a near-plateau within 20-30 min while in a hot macro-E wet bulb globe temperature (WBGT). [(3)] As the macro-E temperature increases, the ability for heat transfer between micro-E and skin is reduced, which leads to an increased deep body temperature.

The physiological challenges bunker gear places on workers such as firefighters makes effectively modeling heat stress while wearing bunker gear important in order to predict work tolerance times. A bunker gear adjustment factor can be expressed as a higher WBGT—after 20-30 min of exposure—and is the simplest and most practical approach to modeling heat stress. However, work by Reneau and Bishop [(4)] found the protective clothing adjustment factor was unstable and dependent on the ability of the protective clothing to exchange heat and water vapor

between the micro-E and macro-E. For example, when firefighters are extinguishing a fire, the protective clothing adjustment factor could become negative due to the insulative effect of firefighter bunker gear, resulting in micro-E conditions being cooler than the macro-E. [4]

Micro-E temperature and relative humidity can be measured directly via wearable data recorders (e.g. iButton, Maxim Integrated Products, Sunnyvale, CA) inside the bunker gear. Measuring the micro-E directly reflects the actual micro-E conditions that firefighters experience inside bunker gear. Direct micro-E measurement is more precise than the protective clothing adjustment factor, which for accuracy requires constant adjustment based on the macro-E WBGT for a given PC. [5]

Micro-E cooling mitigates heat stress in PC. [6-9] Unpublished data collected from our laboratory suggests that bunker gear itself may be a source of cooling for a short time since the temperature of the environment in which the PC is donned also affects the rise in micro-E temperature and relative humidity. This relatively short period of cooling could be important for firefighters because each exposure to a fire is limited to about 30 min due to the necessity to replenish the respiratory supply equipment. Given the importance of modeling the micro-E and the potential for reducing heat storage by precooling bunker gear prior to donning, the purpose of these studies were two-fold: (a) determine the effect of COLD (< 0 °C dry bulb) bunker gear on rectal temperature (T_{re}) and micro-E when compared to HOT (32 °C dry bulb) bunker gear worn while working at the same rate (kcal/h) and WBGT, and (b) determine the impact of work rate on micro-E under bunker gear at one macro-E to contribute to development of a predictive model.

CHAPTER II

EFFECTS OF COLD FIREFIGHTER BUNKER GEAR ON HEAT STRAIN IN A HOT ENVIRONMENT

ABSTRACT

This study investigated the effects of cold (< 0 °C dry bulb; COLD) versus hot (32 °C dry bulb; HOT) firefighter bunker gear on rectal temperature (T_{re}) and micro- environment (micro-E) wet bulb globe temperature (WBGT) while working in a 29 °C WBGT ambient environment. Ten men performed two counterbalanced trials (COLD vs. HOT) while wearing bunker gear. The weighted work rate for each trial was $\dot{V}O_2$ of 1.6 ± 0.15 L/min (480 kcal/h) consisting of 12 min (80% of total work-cycle time) of walking at 1.34 m/s km/h^{-1} (3 mph) combined with 3 min of arm curls (20% of total work-cycle time). This cycle was performed twice for a total of 30 min for each trial. Micro-E (WBGT between inner and outer clothing) and other measures were recorded every 5 min. The repeated-measure MANOVA indicated treatments were not different for micro-E WBGT (COLD 29.1 ± 0.5 °C; HOT 29.8 ± 0.3 °C; p = 0.16). T_{re} was COLD 37.4 ± 0.1 °C vs. HOT 37.2 ± 0.2 °C; p = 0.15. Mean skin temperature ($\overline{T}_{sk}$) was COLD 34.7 ± 0.3 °C vs. HOT 35.0 ± 0.2 °C; p = 0.27. Heart rate (COLD vs. HOT) was 132 ± 6 beats/min; 132 ± 5.3 beats/min; p = 0.9, respectfully. Sweat production rate (COLD 1754.4 ± 785.5 g/h; HOT 1261.6 ± 696.6 g/h; p = 0.06). Sweat evaporation rate (COLD 630.8 ± 290.9 g/h; HOT 551.9 ± 259.5

g/h; p = 0.44). Friedman two-way ANOVA, revealed no differences between treatments for rating of perceived exertion (χ^2 (1, n = 10) = 0.4, p = 0.5); thermal sensation (χ^2 (1, n = 10) = 1.6, p = 0.2); sweat sensation (χ^2 (1, n = 10) = 0.0, p = 1.0); and clothing comfort (χ^2 (1, n = 10) = 1.3, p = 0.3). Wearing COLD (< 0 °C) bunker gear did not differentially affect measures of thermal strain, cardiovascular strain, or perception during 30 min of work compared to wearing HOT bunker gear.

Key Words: protective clothing, micro-E, personal cooling

INTRODUCTION

Intense physical work in a hot ambient environment (macro-E) reduces the heat removal rate and increases rectal temperature (T_{re}) leading to decreased work output [10, 11] and increased risk of injury.[12] Protective clothing (PC, e.g. bunker gear) protects firefighters from extreme ambient heat due to its multi-layered, insulative, characteristics; but these characteristics also restrict both dry and evaporative heat loss (the primary avenue of heat dissipation). [13-15] Furthermore, the encapsulating nature of the bunker gear reduces the water vapor pressure gradient between the skin and the surrounding micro-environment (micro-E)—the small layer of air between the inside of the clothing and the outside of the clothing, [16]—which reduces the rate of evaporative heat loss. As the vapor pressure gradient between the skin and micro-E approaches zero, sweat evaporation is increasingly slowed and continued sweating leads to dehydration. [17] Heat stress is amplified not only by decreased evaporative sweat but the macro-E (from the fire and ambient environment), and increased metabolic heat production from physical work. [16, 18] To facilitate cooling, various devices and techniques have been utilized during firefighting.

For example, devices using liquid, ice, air, carbon dioxide, and fan cooling have been investigated [8, 9, 19-24] for micro-E firefighter cooling. These devices attenuate heat strain, [8, 9] enhance work capacity, and increase safety; however, such techniques and devices tend to be expensive and most have low practical utility on the fire field. Therefore, the high cost and low convenience of using these devices in the field remain problematic. With limited field-useful methods to aid heat dissipation, pre-cooling—cooling the body prior to an event (or during

recovery from one event prior to subsequent activity) to reduce heat strain—has become important, along with cooling during rehabilitation periods for self-contained breathing apparatus change out. [25] Pre- and rehabilitation cooling typically utilize cold-water immersion, ice vests, or cold wet towels to reduce the heat strain. [25] These methods of pre-cooling are good for workers in planned work in a hot macro-E, though they are not usually practical for firefighters who must respond rapidly to unplanned events and emergencies. Rehabilitation cooling can be effective, but is limited to helping firefighters after they have had an initial heat exposure. Consequently, cooling methods that can be implemented quickly are in need of research and development.

However, further research with a more robust treatment is necessary to substantiate these findings. Accordingly, the purpose of this study was to investigate the effects of pre-cooling firefighter bunker gear on firefighter T_{re} and micro-E WBGT while working in a hot environment (29 °C WBGT; 27 °C wet bulb, 32 °C globe). We hypothesized that cold bunker gear (COLD) would blunt the rise of T_{re} and micro-E WBGT compared to bunker gear that was not pre-cooled (HOT).

METHODS

Research Design

Participants

Ten men completed one familiarization and two counterbalanced treatment trials in a hot macro-E (32 °C dry bulb). A power analysis revealed that the sample of n = 10 was sufficient to detect an effect of 0.35 SD, assuming $\alpha = 0.05$ and power = 0.80 (G*Power- Universität, Kiel, Germany). The mean ± SD age, height, weight, and estimated body fat [26] percentage of the

subjects were as follows: 25 ± 6 yr, 175.0 ± 7.7 cm, 85.4 ± 13.9 kg, and 15.2 ± 4.6% body fat (determined from skinfolds), respectively.

Familiarization Trial

Approval was obtained from the local Institutional Review Board. Participants provided written informed consent. Prior to the first trial, participants were instructed to avoid eating 2 hours prior to coming to the laboratory; to drink 1 L of water before sleep, 0.5 L of water upon waking, and 0.5 L of water throughout the day until coming to the laboratory; abstain from alcohol, non-prescription drugs, caffeine intake, and exercise during the 36 hours prior to coming to the laboratory; and to sleep approximately 8 hours the night before the trial. Upon arrival, participants completed medical and 24-h history questionnaires to verify adherence to pre-test instructions.

Next, height was measured, and body composition was assessed via the thickness of skinfolds at 3 sites.[27] Participants were then instructed to provide a urine sample and measure nude body weight using a digital scale (Tanita Corporation of America, Inc., Arlington Heights, IL). Urine was analyzed for urine specific gravity to determine hydration status using a hand-held refractometer (Atago Co., Ltd., Japan). Urine specific gravity values < 1.020 were considered adequately hydrated. [28, 29] Participants whose values were > 1.020 were given fluids for 60 min (one instance of this occurred) and then re-evaluated. After obtaining nude body weight, participants put on a heart rate monitor (T-31 encoded, Polar Electro, Inc. Lake Success, NY, USA), underwear, socks, shoes, and a polyester/cotton shirt and pants (Roebuck Perma Press, Sears, Hoffman Estates, IL) that were provided. Participants donned bunker gear and a self-contained breathing apparatus (SCBA) and performed the first trial by walking on a

treadmill with oxygen uptake ($\dot{V}O_2$) continuously measured via open circuit spirometry using a metabolic measurement system (Parvo Medics, Sandy, UT) to determine the percent grade needed to elicit a $\dot{V}O_2$ of 1.7 L/min. Immediately following the treadmill walking they curled an 8.3-kg barbell to determine the number of curls needed to elicit a $\dot{V}O_2$ of 0.6 L/min. [8]

Experimental Trials

A minimum of two days (but no more than five) after completing the familiarization trial, participants returned to the laboratory. Like the familiarization trial, the 24-h history questionnaire was administered to verify adherence to pre-test instructions, which were identical to those provided before the first visit. Next, a urine sample was provided and nude body weight was measured. Then, participants instrumented with a heart rate (HR) monitor strap worn around the chest and inserted a rectal thermocouple (RET-1, Physitemp Instruments Inc., Clifton, NJ) covered by a sheath (TDI Products, Neenah, WI) 8 cm beyond the anal sphincter. Skin thermocouples (Physitemp, Clifton, New Jersey) were taped on the right chest, right forearm, and right calf to obtain mean skin temperature ($\overline{T}_{sk}$). [30] Thermocouples were adhered to the skin using adhesive athletic tape in such a way to minimize added insulation.

Micro-E WBGT under the bunker gear was continuously recorded using iButtons (DS1923#F5, Maxim Integrated Products Sunnyvale, CA). Four iButtons were attached inside the bunker gear at the following locations: right chest, right scapula, groin, and right calf. Micro-E WBGT was calculated using the method described by Bernard [31] from temperature and rH.

After all instrumentation, participants donned either hot (32 °C dry bulb; HOT) or cold (< 0 °C dry bulb; COLD) firefighter bunker gear. HOT was unfolded and heated inside an environmental chamber (set to 32 °C dry bulb temperature) with the temperature at the center of

t-he bunker gear measured using a thermocouple (Physitemp, Clifton, New Jersey) connected to an electronic thermometer (Omega Engineering Inc., Stamford, CT). HOT was heated for ~ 60 min using an electric heater placed at the sides of the bunker gear to accelerate heating. COLD was cooled in a freezer, with the temperature measured via the same method as above. Once the participant donned the bunker gear in 22 °C, a clothed body weight was obtained.

Next, the participant entered the environmental chamber, mounted the treadmill, inserted a mouthpiece attached to the metabolic system and began walking. The time-weighted work rate for each trial was 450 kcal/h and consisted of 12 min (80% of total work-cycle time) of walking at 1.34 m/s km/h^{-1} and a sufficient grade to elicit a metabolic rate of ($\dot{V}O_2$ = 1.7 L/min) combined with 3 min of arm curls (20% of total work-cycle time) at a metabolic rate of 180 kcal/h ($\dot{V}O_2$ = 0.6 L/min), performed two times for a total of 30 min. $\dot{V}O_2$ was continuously measured throughout each trial to verify metabolic rate. All other measures [T_{re}; $\overline{T}_{sk}$; HR; perceptual measures—ratings of perceived exertion (RPE), thermal sensation, sweating sensation, and clothing comfort] were measured every 5 min. Micro-E WBGT was measured continuously and averaged every 5 min. Nude and clothed body weights were obtained pre-exercise and post-exercise. No fluid was given between the pre-exercise and post-exercise body weight measurements. Sweat production rate was calculated from the difference of pre-exercise and post-exercise nude body weight, divided by trial duration. Sweat evaporation rate was calculated from the difference of pre-exercise and post-exercise clothed body weight, divided by the trial duration. Evaporative efficiency, the percentage of sweat evaporation relative to sweat production, could not be determined due to the sweat volume dripped.

Trials would have been terminated if any of the following criteria were reached: T_{re} of 39 °C, HR within 10 beats per min of the participant's age-predicted HR maximum, or rating of

perceived exertion of 19 or 20 on the 6-20 scale, [32] however no instances occurred. At the end of each trial, the participant exited the environmental chamber, measured clothed body weight, and then removed the helmet, jacket, and gloves while investigators removed the skin thermocouples. Then the participant proceeded to a private room, measured nude body weight, removed the rectal probe and dressed in their own clothes. Lastly, instructions were provided for the next trial. Each trial required approximately 1.5 to 2 h total and was scheduled at approximately the same time of day and separated by a minimum of 48 h.

Statistical Analysis

Data are reported as mean ± SD. A repeated-measures multiple analysis of variance (MANOVA) was performed to determine if mean differences existed between treatments for any variables (micro-E WBGT, T_{re}, $\overline{T}_{sk}$, and HR). Assumptions of sphericity were met, and post hoc analyses used a Bonferroni-adjusted alpha level. Sweat production rate, and sweat evaporation rate, were analyzed using pair sample t-tests and presented as mean ± SD. Perceptual measures (RPE, thermal sensation, clothing comfort, and sweat sensation) were analyzed using Friedman's two-way ANOVA. Data analyses were performed using SPSS v. 22.0 (SPSS Inc., Chicago, IL), and all hypothesis tests used an alpha level of 0.05.

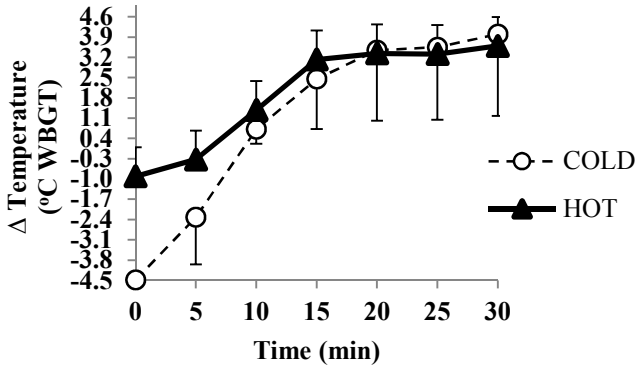
RESULTS

All participants (n = 10) successfully completed two 30-min bouts of high intensity (480 kcal/h) work in hot and cold bunker gear. The mean ± SD for work rate of all trials was 1.6 ± 0.15 L/min. The average macro-E WBGT for the two bouts was 28.9 ± 0.5 °C and was not statistically different between treatments ($p = 0.08$). No significant omnibus treatment effect was

observed in the MANOVA analysis (Wilk's Lamda; p = 0.45), so treatments were not different for any of the measured variables and no post hoc univariate analyses were conducted. Nonetheless, results of individual analyses are detailed in the following paragraphs.

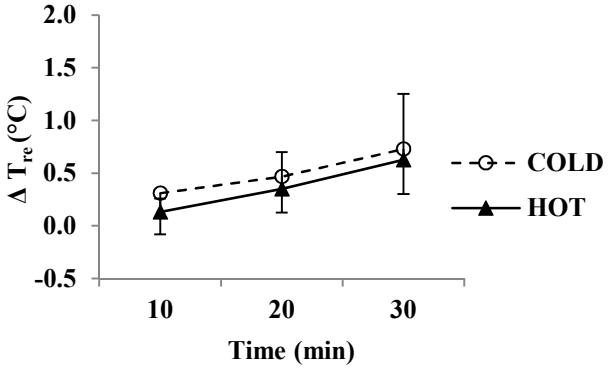
Micro Environment (micro-E)

Figure 1.1 depicts the Δ temperature (^{o}C WBGT) between micro- and ambient environments for COLD and HOT across time.



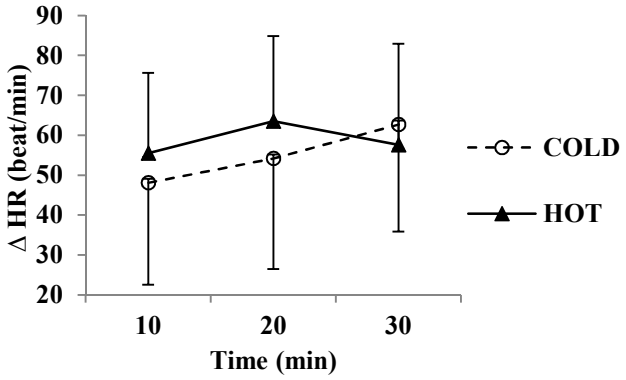
Core and Mean Skin Temperatures

Figure 1.2 displays the results for Δ T_{re} °C across time from baseline (0 min) to 10, 20, and 30 min. The COLD treatment was insufficient to differentially affect T_{re} relative to HOT. Likewise, there were no significant differences (34.7 ± 0.3(COLD) vs. 35.0 ± 0.7 (HOT); p = 0.28) for $\overline{T}_{sk}$ between treatments.



Heart Rate

Delta HR across time is presented in Figure 1.3.

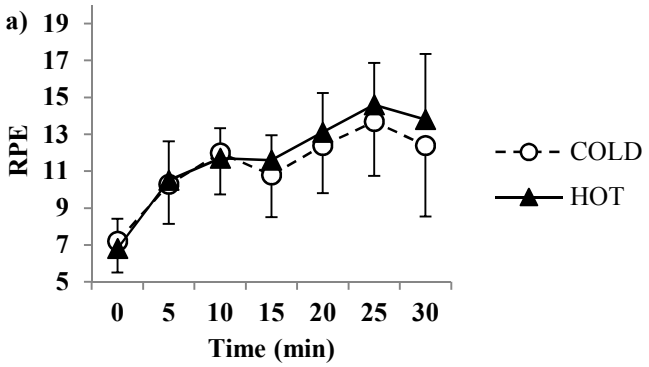


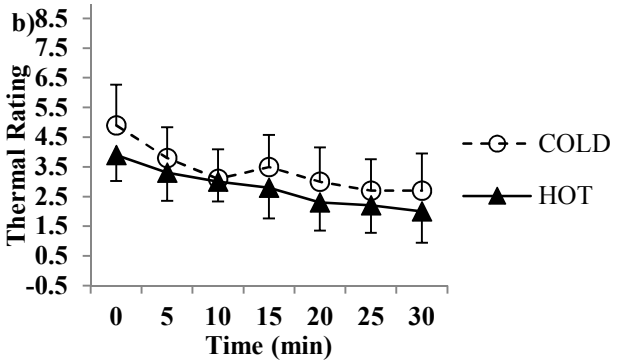
Sweat Production and Evaporation Rate

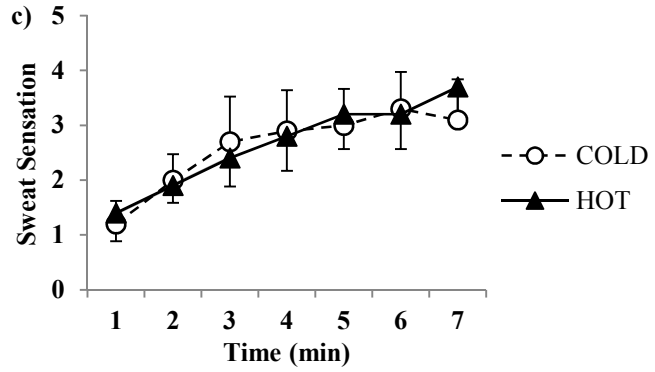
Sweat production was not statistically significantly different between treatments (COLD 1754.4 ± 785.5 g/h^{-1}; HOT 1261.6 ± 696.6 g/h^{-1}; $p = 0.06$). Sweat evaporation rate was not significantly different between treatments (COLD 630.8 ± 290.9 g/h; HOT 551.9 ± 259.5 g/h; $p = 0.44$).

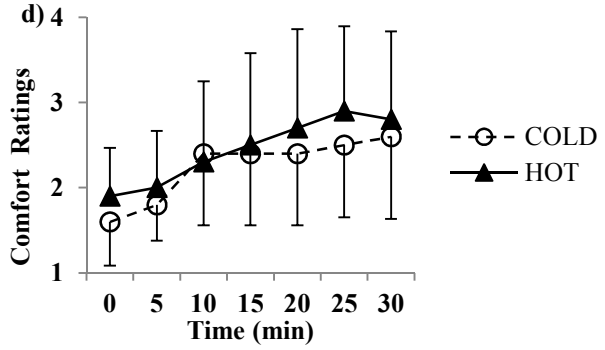
Mean Perceptual Measures

Figure 1.4 (a-d) shows mean perceptual measures across time for each treatment. A lower score indicates: increased comfort (how comfortable the participant is wearing the bunker gear), decreased sweat sensation (decreased perception of sweating), increased thermal sensation (how hot the participant perceives it to be under the bunker gear), and increased perceived exertion. RPE was not different between treatments (χ^2 (1, n=10) = 0.400, $p = 0.53$). Likewise, thermal sensation was not different between treatments (χ^2 (1, n=10) = 1.6, $p = 0.21$), nor was sweat sensation (χ^2 (1, N=10) = 0.00, $p = 1.00$). Finally, clothing comfort also was not different between treatments (χ^2 (1, N=10) = 1.286, $p = 0.257$).


a)
RPE
19
17
15
13
11
9
7
5
0 5 10 15 20 25 30
Time (min)
COLD
HOT


b)
Thermal Rating
8.5
7.5
6.5
5.5
4.5
3.5
2.5
1.5
0.5
-0.5
0 5 10 15 20 25 30
Time (min)
COLD
HOT


c)
Sweat Sensation
5
4
3
2
1
0
1 2 3 4 5 6 7
Time (min)
COLD
HOT


d)
Comfort Ratings
4
3
2
1
0 5 10 15 20 25 30
Time (min)
COLD
HOT

DISCUSSION

The purpose of this study was to investigate the effects of COLD (< 0 °C) vs. HOT (32 °C) bunker gear on micro-E WBGT, core and mean skin temperatures, and perceptual measures during a 30-min bout of work in a climate controlled macro-E of 29 °C WBGT at 480 kcal/h. Contrary to our hypothesis, the primary finding is that COLD treatment did not affect any of the measured outcomes.

The findings of the current study are in line with Gao et al. [33] who found a mean difference between macro- and micro-E of 6 °C is necessary to promote cooling while working in a hot macro-E. Working in a warm to hot macro-E after donning bunker gear causes heat stress to increase [4, 34] more rapidly and with greater magnitude than when not wearing bunker gear. However, the micro-E surrounding the body, [1] can reduce the effects of heat stress. [5]

Donning the bunker gear prior to each treatment was standardized, the iButtons were immediately attached, and the participant donned the bunker gear and proceeded into the environmental chamber. Despite efforts to hasten the standardized procedure, it may have been the low thermal mass of the bunker gear, donned in 22 ºC that caused most of the heat loss in the case of HOT, and most of the cold in the case of the COLD trial as the clothing reached rapid equilibrium with the macro-E.

While the time required to put on the bunker gear may have allowed thermal equilibrium between the bunker gear and 22 °C macro-E before entering the environmental chamber, this method is ecologically valid since firefighters are not given a specialized macro-E in which to don their bunker gear.

CONCLUSIONS

In conclusion, COLD did not blunt thermal, cardiovascular, or perceptual strain vs. HOT while working in a hot environment. Combine with other research in this area, our findings suggest that to be effective, cooling methods which are sustained are likely necessary to result in reduced micro-E and T_{re} values after donning bunker gear and working in a hot macro-E. Otherwise, the low thermal mass of the clothing allows rapid equilibrium with the macro-E in which it is donned, which negates any benefits of the prior garment cooling process. Sustained cooling methods likely avoid this complication.

REFERENCES

1. **Sullivan, P.J. and I.B. Mekjavić**, Temperature and humidity within the clothing microenvironment. Aviat. Space. Environ. Med., 1992. 63*(3)*: p. 186-192.

2. **Bishop, P., D. Gu, and A. Clapp**, Climate under impermeable protective clothing. Int. J. Ind. Ergo., 2000. 25*(3)*: p. 233-238.

3. **Muir, I., P. Bishop, and J. Kozusko**, Micro-environment changes inside impermeable protective clothing during a continuous work exposure. Ergonomics, 2001. 44*(11)*: p. 953-961.

4. **Reneau, P. and P. Bishop**, A review of suggested WBGT adjustments for encapsulating protective clothing. Am. Ind. Hyg. Assoc. J., 1996. 57*(1)*: p. 58-61.

5. **Bishop, P., K. Crew, and A. Al-Nawaiseh,** Heat Stress and Heat Strain in Protective Clothing: Micro-environmental Considerations., in Protective Clothing: Managing Thermal Stress F. Wang and C. Gao, Editors. Sawston, Cambridge, UK: Woodhead Publishing, 2014.

6. **Cadarette , B.S., et al.**, Intermittent microclimate cooling during exercise-heat stress in US army chemical protective clothing. Ergonomics, 2006. 49*(2)*: p. 209-219.

7. **Cadarette , B.S., et al.**, Upper body cooling during exercise-heat stress wearing the improved toxicological agent protective system for HAZMAT operations. [Evaluation Studies]. Am. Ind. Hyg. Assoc. J., 2003. 64*(4)*: p. 510-515.

8. **Zhang, Y., et al.**, A new hand-cooling device enhance firefighter heat strain recovery. J. Occup. Environ. Med., 2009. 6*(5)*: p. 283-288.

9. **Zhang, Y., et al.**, Evaluation of a novel personal cooling device for workers in hot environments. J. Occup. Environ. Med., 2010. 7: p. 389-396.

10. **González-Alonso, J., et al.**, Influence of body temperature on the development of fatigue during prolonged exercise in the heat. J. Appl. Physiol., 1999. 86*(3)*: p. 1032-1039.

11. **Walters, T., et al.**, Exercise in the heat is limited by a critical temperature. J. Appl. Physiol., 2000. 89: p. 799-806.

12. **Cheung, S.S., T. McLellan, and S. Tenaglia**, The thermophysiology of uncompensable heat stress. Sports Med., 2000. 29*(5)*: p. 329-359.

13. **McLellan, T., I. Jacobs, and J. Bain**, Influence of temperature and metabolic rate on work performance with Canadian forces NBC clothing. Aviat. Space. Environ. Med., 1993. 64*(7)*: p. 587-594.

14. **Nadel, E.R., et al.**, Mechanisms of thermal acclimation to exercise and heat. J. Appl. Physiol., 1974. 37*(4)*: p. 515-20.

15. **Nunneley, S.A.**, Heat stress in protective clothing: Interactions among physical and physiological factors. Scand. J. Work Environ. Health, 1989. 15: p. 52-57.

16. **Sullivan, P.J. and I.B. Mekjavić**, Temperature and humidity within the clothing microenvironment. Aviat. Space. Envirom. Med., 1992. 63*(3)*: p. 186-192.

17. **Cheung, S., S. Petersen, and T. McLellan**, Physiological strain and countermeasures with firefighting. Scand. J. Med. Sci. Sports, 2010. 20*(s3)*: p. 103-116.

18. **Smith, D., et al.**, The effects of different thermal environments on the physiological and psychological responses of firefighters to a training drill. Ergonomics, 1997. 40*(4)*: p. 500-510.

19. **Armstrong, L.E., et al.**, Whole-body cooling of hyperthermic runners: comparison of two field therapies. Am. J. Emerg. Med., 1996. 14*(4)*: p. 355-358.

20. **Bishop, P.A., S.A. Nunneley, and S.H. Constable**, Comparisons of air and liquid personal cooling for intermittent heavy work in moderate temperatures. Am. Ind. Hyg. Assoc. J., 1991. 52*(9)*: p. 393-397.

21. **Carter, J.**, Effectiveness of rest pauses and cooling in alleviation of heat stress during simulated fire-fighting activity. Ergonomics, 1999. 42*(2)*: p. 299-313.

22. **Constable, S.H., et al.**, Intermittent microclimate cooling during rest increases work capacity and reduces heat stress. Ergonomics, 1994. 37*(2)*: p. 277-85.

23. **Duffield, R., et al.**, Effect of wearing an ice cooling jacket on repeat sprint performance in warm/humid conditions. Br. J. Sports Med., 2003. 37*(2)*: p. 164-169.

24. **Epstein, Y., Y. Shapiro, and S. Brill**, Comparison between different auxiliary cooling devices in a severe hot/dry climate. Ergonomics, 1986. 29*(1)*: p. 41-48.

25. **Booth, J., F. Marino, and J.J. Ward**, Improved running performance in hot humid conditions following whole body precooling. Med. Sci. Sports Exer., 1997. 29*(7)*: p. 943-949.

26. **Jackson, A.S. and M.L. Pollock**, Generalized equations for predicting body density of men. Br. J. Nutr., 1978. 40*(3)*: p. 497-504.

27. **Pollock, M.L., D.H. Schmidt, and A.S. Jackson**, Measurement of cardiorespiratory fitness and body composition in the clinical setting. Clin. Ther., 1980. 6: p. 12-27.

28. **Cheuvront, S.N. and M.N. Sawka**, Hydration assessment of athletes. Sports Sci. Exchange, 2005. 18*(2)*: p. 1-6.

29. **Kavouras, S.A.**, Assessing hydration status. Curr. Opin. Clin. Nutr. Metab. Care, 2002. 5*(5)*: p. 519-24.

30. **Burton, A.C.**, Human calorimetry II. The average temperature of the tissues of the body three figures. J. Nutr., 1935. 9*(3)*: p. 261-280.

31. **Bernard, T.E.**, Prediction of workplace wet bulb global temperature. App. Occup. Envion. Med., 1999. 14*(2)*: p. 126-134.

32. **Borg, G.**, Psychophysical bases of perceived exertion. Med. Sci. Sports Exerc., 1982. 14*(5)*: p. 377-381.

33. **Gao, C., K. Kuklane, and I. Holmer**, Cooling vests with phase change material packs: the effects of temperature gradient, mass and covering area. Ergonomics, 2010. 53*(5)*: p. 716-723.

34. **Bishop, P., et al.**, Limitations to heavy work at 21 degrees C of personnel wearing the US military chemical defense ensemble. Aviat. Space. Environ. Med., 1991. 62*(3)*: p. 216-220.

Figure Captions

FIGURE 1.1. Mean ± SD wet bulb globe temperature (WBGT) difference between micro- and macro- E across time for HOT and COLD treatments (n = 10).

FIGURE 1.2. Mean ± SD ΔT_{re} (°C) from baseline (0 min) to 10, 20, and 30 min for HOT and COLD treatments (n = 10).

FIGURE 1.3. Mean ± SD HR (beats/min) across time for HOT vs. COLD (n = 10).

FIGURE 1.4 (a-d). Mean ± SD responses for rating of perceived exertion (RPE), thermal sensation, sweat sensation and comfort rating for HOT and COLD treatments (n=10). Higher values (1-10 scale) for RPE, thermal ratings, and sweat sensation represent increased perception rating. Higher values for comfort rating equals decreased perceived comfort.

CHAPTER III

IMPACT OF WORK RATE ON MICRO-E UNDER FIREFIGHTER BUNKER GEAR AT 29 °C WBGT

ABSTRACT

This study described the impact of three work rates on rectal temperature (T_{re}) and micro-environment (micro-E) under firefighter bunker gear in a hot ambient environment (macro-E). Ten men completed one familiarization trial and three counterbalanced experimental trials on separate days, consisting of 30 min of exercise at either ~100 (LO), ~330 (MOD), or ~450 kcal/h (HI) in 29 °C WBGT (27 °C wet bulb, 32 °C globe, and 32 °C dry bulb) macro-E. Every 5 min during exercise, T_{re}, mean skin temperature ($\overline{T}_{sk}$), macro-E, perceptual measures (perceived exertion, thermal sensation, thermal comfort, and sweating sensation), oxygen uptake ($\dot{V}O_2$), and heart rate (HR) were recorded. Micro-E temperature and rH were collected every 30-s for each trial. For LO, participants stood quietly. For MOD and HI trials, participants walked at 1.34 m/s km/h for 12 min (80% of total work-cycle time), with the treadmill grade adjusted to achieve the desired work rate, followed by arm curls for 3 min (20% of total work-cycle time). Walking and curls was repeated twice. MANOVA analysis revealed a significant ($p = 0.008$) omnibus effect of work rate. Post hoc univariate analysis revealed no differences among trials for micro-E WBGT (LO: 29.8 ± 1.9 °C; MOD: 29.9 ± 2.4 °C; HI: 31.1 ± 1.0 °C; $p = 0.2$). T_{re} was lower during LO than MOD (36.8 ± 0.4 °C vs. 37.3 ± 0.4 °C, respectively). Friedman's analysis revealed significant main effects for RPE (χ^2 (2, n = 10) = 16.7, $p < 0.001$). RPE during LO (7.6 ±

1.6) vs. MOD (10.4 ± 1.8; p = 0.007) and vs. HI (11.6 ± 1.4; p = 0.005). RPE during MOD was lower than that during HI (p = 0.03). Sweat sensation (Friedman's analysis χ^2 (2, n = 10) = 9.680) was lower during LO compared to HI (p=0.01) and during MOD compared to HI (p= 0.04). T_{re} and perceptual measures were higher as exercise intensity increased. Understanding work rate's effect on micro-E WBGT can aid in maintaining acceptable T_{re} values while working in hot/humid environments, lowering the risk for exertional heat illness or death.

Key Words: protective clothing, micro environment, heat stress

INTRODUCTION

After donning protective clothing (bunker gear) such as firefighter bunker gear, a micro-environment (micro-E) (a small layer of air between the inner clothing and the outer wear) is formed, which increases heat stress in warm environments. More specifically, bunker gear allows little air exchange between the micro-E [(1)] and the ambient environment (macro-E), resulting in the micro-E being heated by metabolic heat and humidified by sweat evaporation. [(2)]

In hot conditions, metabolic heat is most effectively dissipated via sweat evaporation at the skin, [(3)] which is influenced by the water vapor pressure gradient between the skin and the surrounding environment. As the water vapor pressure gradient approaches zero, sweating becomes increasingly ineffective, and voluminous sweating with little or no evaporative heat loss leads to dehydration with no cooling benefit. This restriction in evaporative heat loss is especially hazardous during work while wearing protective clothing in a hot macro-E because the insulative nature of the bunker gear affords limited dry heat loss. [(4)]

To decrease the risk of heat illness in hot and humid working environments, Threshold Limit Values have been set by the American Conference of Governmental Industrial Hygienists (ACGIH). [(5)] These are based on normal cotton shirt and trousers, work rate, and ambient wet bulb globe temperature (WBGT), which is a computed index of the environment that includes the potential for sweat evaporation as well as heat gain and loss from conduction, convection, and radiation. These guidelines aid occupational hygienists in estimating safe levels of exposure to heat stress. The current environmental thresholds expressed as WBGT are established for different metabolic rates (work demands) while wearing typical cotton work clothing that does

not encapsulate the body. Given the difference between bunker gear and cotton clothing, the current standards are not directly applicable to bunker gear since it encapsulates more than 50% of the body's surface area, is more insulative, and transmits water vapor more slowly than cotton.

Not all firefighting duties are done in the extremely hot environment of the fire field. Firefighter work is also performed at auto accidents and around fire fields without direct exposure to the high radiant conditions of the fire itself. Therefore, there is a need to further investigate the micro-E temperature and relative humidity (rH) under bunker gear to better understand the changes that take place during low, moderate, and high intensity work. This study is part of a series of studies with the intent to collect data that will be used to develop a model that will describe micro-E temperature and relative humidity under bunker gear under all expected macro-E conditions. The model will be useful for making adjustments to the ACGIH Threshold Limit Values for work while wearing firefighter bunker gear. In the present study the effect of different work rates on micro-E WBGT was investigated at a set macro-E WBGT. Accordingly, we hypothesized that for a given macro-E WBGT, a higher work rate would result in a significantly higher micro-E WBGT due to the encapsulating nature of bunker gear coupled with physiological responses such as increased heart rate (HR), cardiac output, and metabolic rate.

METHODS

Research Design

Participants

A power analysis revealed a sample of n = 10 was sufficient to detect an effect of 0.28 SD, assuming $\alpha = 0.05$ and power = 0.80 (G*Power, Universität Kiel, Germany). Participants

were male, with mean ± SD age = 25 ± 6 yr, height = 175.0 ± 7.7 cm, weight 85.4 ± 13.9 kg, and estimated body fat percentage 15.2 ± 4.6%. Approval was obtained from the local Institutional Review Board, and all participants provided written informed consent prior to beginning any study procedures. A repeated measures design was used in which all participants completed all trials, which were performed in a counterbalanced order (separated by a minimum of 48 h) and consisted of 30 min of exercise while wearing firefighter bunker gear and performed at either: 1) 100 kcal/h 9 (LO), 2) 330 kcal/h (MOD), or 3) 450 kcal/h (HI) in 29 °C WBGT (27 °C wet bulb temperature, 32 °C globe temperature).

Experimental Protocol

After arriving for the first trial, participants completed a Medical History Form, Risk Classification Flow Chart, and a 24-h history form (to describe the participant's sleep pattern, dietary habits, and participation in physical activity in order to confirm adherence to pre-test instructions). Thereafter, the thickness of skinfolds at 3 sites was measured and used to estimate body fat percentage. [6] After body fat percentage was estimated, participants were instructed to enter a private room, provide a urine sample to measure urine specific gravity and obtain a nude body weight (Tanita Corporation of America, Inc., Arlington Heights, IL). The participant's urine specific gravity was assessed to determine hydration status using a hand-held refractometer (Atago Co., Ltd., Japan). Urine specific gravity values were required to be < 1.020 for the participant to be considered adequately hydrated. [7, 8] A participant whose urine specific gravity was ≥ 1.020 was given fluids for 60 min and then re-evaluated (this occurred on one instance). After they obtained a nude bodyweight, participants donned a heart rate monitor strap (T-31 encoded, Polar Electro Inc., Lake Success, NY, USA) at the level of the sternum and inserted a

rectal thermocouple (RET-1, Physitemp Instruments Inc., Clifton, NJ) that was covered with a thermocouple sheath (TDI Products, Neenah, WI) 8 cm beyond the anal sphincter to measure rectal temperature (T_{re}). Then they clothed in a standard ensemble consisting of underwear, polyester/cotton shirt and pants (Roebuck Perma Press, Sears, Hoffman Estates, IL), socks, and shoes.

Next, participants put on firefighter bunker gear in the laboratory area, mounted a treadmill, and began walking at 1.34 m/s with grade adjusted to elicit steady state oxygen uptake ($\dot{V}O_2$; open circuit spirometry; Parvo Medics, Sandy, UT) values equal to 1.2 followed by 1.7 L/min. This process required approximately 17 min. After the grades for 1.2 and 1.7 L/min $\dot{V}O_2$ were determined, arm curls were performed with a weight of 8.3 kg [9] to elicit a $\dot{V}O_2$ of 0.6 L/min, (these preliminary measurements for number of arm curls and $\dot{V}O_2$ values were used for all exercise trials). After completing the initial trial, participants removed the bunker gear, entered a private room, removed the rectal probe, obtained a nude body weight, dressed in their own clothes and returned to the laboratory area. Once back in the laboratory area, the participant was scheduled for the next trial and was given instructions concerning physical activity, hydration, and eating habits before the next visit.

The participants returned to the laboratory for three experimental trials, each separated by a minimum of 48 h. Upon arrival, participants entered a private room, provided a urine sample, obtained a nude body weight (kg), and inserted a rectal thermocouple like on the first visit. Participants then donned a heart rate monitor, underwear, the same polyester/cotton shirt and pants that were provided on the first visit, socks, and shoes. After returning to the laboratory area, thermocouples (Physitemp, Clifton, New Jersey) were taped to the skin (right chest, right

forearm, and right calf) to measure skin temperature at each site for calculation of mean skin temperature ($\overline{T}_{sk}$).[10]

Micro-E temperature and humidity were continuously recorded (and averaged every 5 min) using iButtons (DS1923#F5, Maxim Integrated Products Sunnyvale, CA). Four iButtons were attached to the inner layer of the bunker gear at the right chest, right shoulder blade, groin, and right calf. Micro-E WBGT was calculated using the method described in Bernard [11] from temperature and rH humidity.

After being instrumented, participants donned bunker gear in the 22 °C laboratory environment. The bunker gear had been heated to a temperature of 32 °C dry bulb in an environmental chamber prior to being worn, as part of another study. The bunker gear was heated for ~ 60 min with an electric heater placed at the head and both sides of to accelerate heating. The temperature of the bunker gear was confirmed using a thermocouple (Physitemp, Clifton, New Jersey) placed at the center of the ensemble with temperature displayed on a digital thermocouple meter (Omega Engineering, Inc., Stamford, CT).

Next, clothed body weight was measured. Then the participant entered the environmental chamber, mounted the treadmill, inserted a mouthpiece for measurement of $\dot{V}O_2$, and stood quietly for ~ 2 min while baseline measures were obtained. Then the following procedures were performed depending on which counterbalanced treatment trial was scheduled for that day.

For LO, participants stood quietly for 30 min to elicit a metabolic rate of 100 kcal/h ($\dot{V}O_2$ = 0.35 L/min). For the other two trials, participants walked on the treadmill at 1.34 m/s km/h (3 mph) for 12 min (80% of total work-cycle time). The grade was adjusted to elicit a metabolic rate of either 330 kcal/h ($\dot{V}O_2$ ~ 1.2 L/min) or 450 kcal/h ($\dot{V}O_2$ ~ 1.7 L/min), determined during the initial trial. After 12 min of walking, arm curls were performed for 3 min (20% of total work-

cycle time) at a metabolic rate of 180 kcal/h ($\dot{V}O_2$ of 0.6 L/min). Each set of walking and curls was performed two times for a total of 30 min. The following measures were collected every 5 min during each trial: T_{re}, $\bar{T}_{sk}$, micro-E temperature and rH, perceptual measures [ratings of perceived exertion (to what extent the participant felt he was exerting himself), thermal sensation (how hot the participant felt inside the clothing, thermal comfort (how comfortable the participant felt inside the clothing), and sweating sensation (how much sweat the participant felt he was producing)], and HR.

At the end of each trial, the participant exited the chamber and measured clothed body weight. Then the helmet, jacket, gloves, and skin thermocouples were removed and the participant was instructed to enter a private room, remove the rectal probe, obtain a nude body weight, dress in their own clothes, and return to the laboratory area.

Nude and clothed body weights were obtained pre-exercise and post-exercise and used to calculate sweat rate. No fluid was given or urine lost between the pre-exercise and post-exercise body weight measurements. Sweat production rate was calculated from the difference of pre-exercise and post-exercise nude body weight, divided by trial duration. Sweat evaporation rate was calculated from the difference of pre-exercise and post-exercise clothed body weight, divided by the trial duration. Evaporative efficiency, the percentage of sweat evaporation relative to sweat production, could not be determined due to the sweat volume dripped.

After returning to the laboratory area, instructions and scheduling of the next trial were discussed. Each trial required approximately 1.5 to 2.0 h total and was scheduled for the same time of day a minimum of 48 h later.

Statistical Analysis

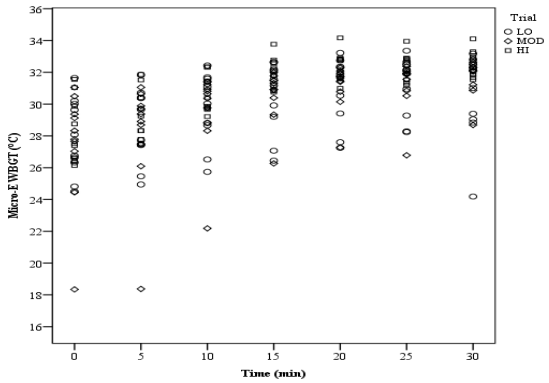
Data are reported as mean ± SD. A repeated measures multiple analysis of variance (MANOVA) was performed to determine if mean differences existed among treatments for any variables (micro-E WBGT, T_{re}, $\overline{T}_{sk}$, and HR) combined in a single analysis. Assumptions of sphericity were met. In the event of a significant omnibus test, further analyses were conducted for individual variables using univariate ANOVA. Significant omnibus ANOVA tests were further analyzed using paired samples t-tests with Bonferroni-adjusted alpha levels to determine individual differences. Perceptual measures (RPE, thermal sensation, clothing comfort, and sweat sensation) were analyzed using Friedman's analysis, and significant findings were then further analyzed using Wilcoxon Signed Ranks Test. All hypothesis tests used an alpha level of 0.05 and data analyses were conducted using SPSS v. 22.0 (SPSS Inc., Chicago, IL).

RESULTS

All participants (n = 10) successfully completed three 30-min bouts of work at low, moderate, and high intensities. The work rates for each trial were: LO 0.4 ± 0.1 L/min, 120 kcal/h; MOD 1.3 ± 0.1 L/min, 390 kcal/h; HI 1.6 ± 0.2, 480 kcal/h. The macro-E WBGT averaged 28.9 ± 0.5 °C for the three trials. A significant omnibus treatment effect was observed in the MANOVA analysis (Wilks Lamda; $p = 0.008$). Results of individual outcome variable analyses are detailed in the following paragraphs.

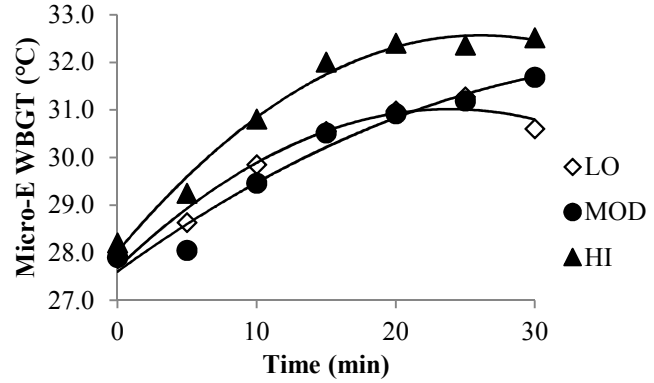
Micro Environment (micro-E)

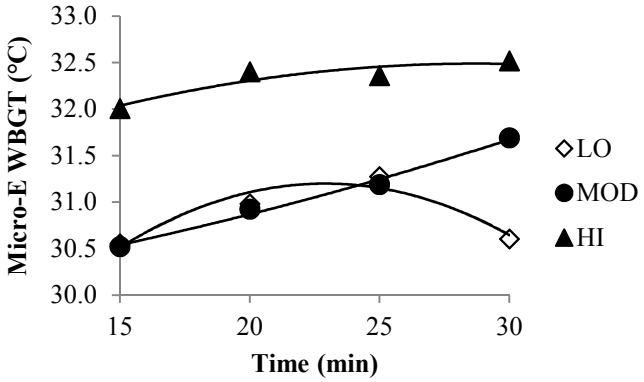
Figure 2.1 depicts micro-E WBGT for each participant across time and trial.



Regression Analysis

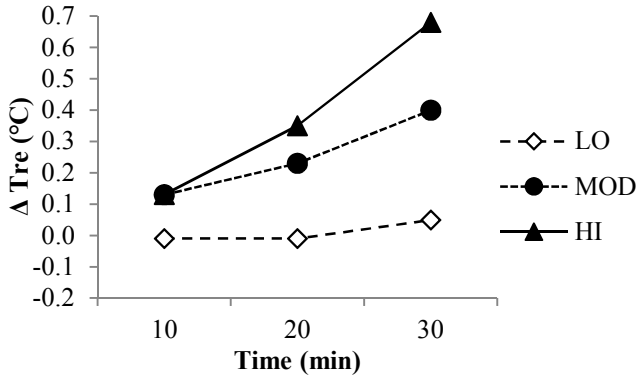
Figure 2.2 depicts polynomial regressions (second order) for Micro-E WBGT (°C) during the entire work bout. Figure 2.3 depicts polynomial regressions (second order) for Micro-E WBGT (°C) beginning at 15 min. These figures serve as depictions of what the regression analysis might look like after more data have been collected.





Core and Mean Skin Temperatures

Figure 2.4 displays results for Δ T_{re} (°C) from baseline (0 min) across time (10, 20, and 30 min). A significant omnibus effect of treatment was observed ($p = 0.02$), and post hoc analysis revealed T_{re} was lower during LO than during MOD ($p = 0.006$). $\overline{T}_{sk}$ was not different among treatments (LO 34.5 ± 0.6 °C vs. MOD 34.4 ± 1.2 °C; $p = 1.0$), (MOD 34.4 ± 1.2 °C vs. HI 35 ± 0.7 °C; $p = 0.33$).

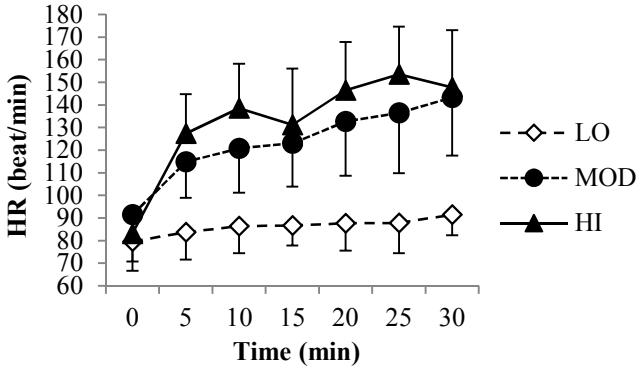


Sweat Production and Evaporation Rate

There was no statistical significant difference among trials for sweat evaporation (LO: 295.7 ± 338.2 g/h; MOD: 492.8 ± 139.4 g/h; HI: 551.9 ± 259.3 g/h; $p = 0.09$). A significant main-effect was observed for sweat production (LO: 225.3 ±130.1 g/h; MOD: 1636.1 ± 708 g/h; HI: 1261.6 ± 696.7 g/h; $p < 0.001$). A significant individual difference was observed between LO vs. MOD, and HI; $p < 0.001$ and $p = 0.001$, respectively.

Heart Rate

HR for all three trials across time is presented in Figure 2.5. Not surprisingly, HR was lower during LO than MOD and HI; $p < 0.001$ and $p < 0.001$, respectfully.



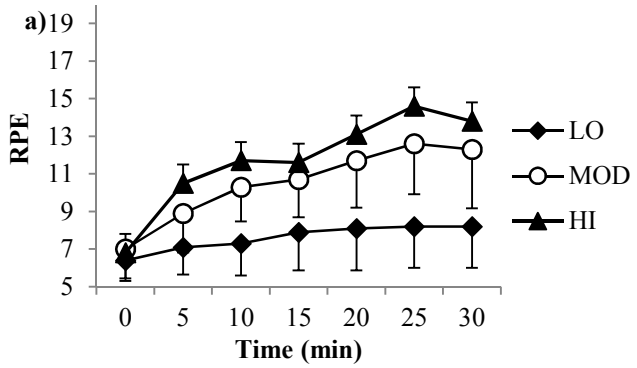
Perceptual Measures

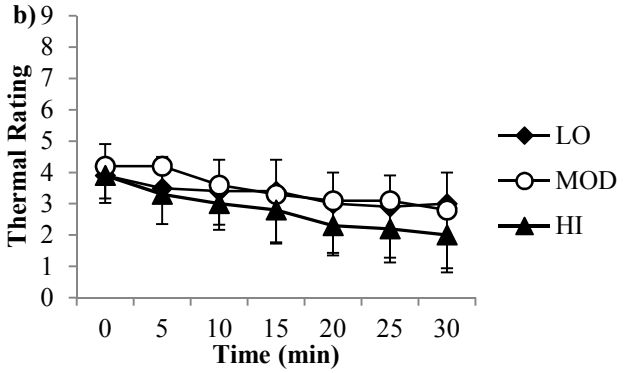
Figure 2.6 (a-d) depicts the results of the perceptual measures across time for all three trials. Friedman's analysis revealed a significant omnibus effect of treatment (χ^2 (2, n = 10) = 16.722, $p < 0.001$) on RPE. LO was significantly different than MOD and HI; p = 0.007 and p = 0.005, respectfully. MOD was significantly different that HI; p = 0.03.

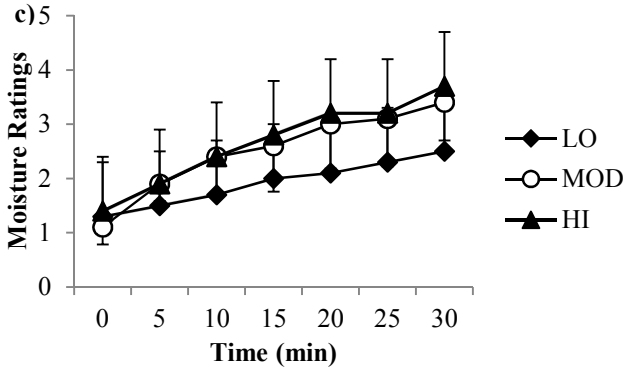
In contrast to RPE, thermal sensation (χ^2 (2, n = 10) = 4.174; p = 0.12; Fig 6b) was not different among trials.

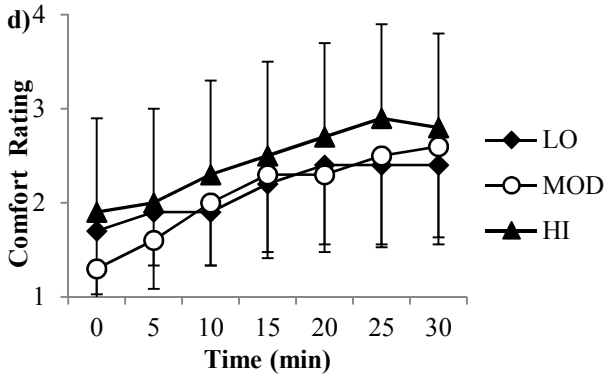
An omnibus effect of treatment on sweat sensation was detected (χ^2 (2, n = 10) = 9.680; p = 0.008; Fig 6c). Post hoc analysis utilizing a Wilcoxon Signed Ranks Test indicated individual differences between LO and HI; p = 0.01; and MOD vs. HI; p = 0.04.

Finally, clothing comfort was not different among treatments (χ^2 (2, n = 10) = 4.333; p = 0.11; Fig 6d).


a)
RPE
19
17
15
13
11
9
7
5
0 5 10 15 20 25 30
Time (min)
LO
MOD
HI


b)
Thermal Rating
9
8
7
6
5
4
3
2
1
0
0 5 10 15 20 25 30
Time (min)
LO
MOD
HI


c)
Moisture Ratings
5
4
3
2
1
0
0 5 10 15 20 25 30
Time (min)
LO
MOD
HI


d)
Comfort Rating
4
3
2
1
0 5 10 15 20 25 30
Time (min)
LO
MOD
HI

DISCUSSION

The purpose of this study was to determine the effect of work rate on micro-E WBGT and contribute data to a larger data set aimed at modeling the micro-E during different work rate and macro-E perturbations. The primary finding was that, contrary to our hypothesis, work rate did not influence the micro-E WBGT.

Clothing Adjustment Factors (CAFs) have been created to attempt to account for the heat stress of the micro-E under protective clothing [12] and are currently used by ACGIH[13] and the National Institute of Occupational Safety and Health (NIOSH). The micro-E becomes stable after 20-30 min of exposure to a given macro-E while working at a fixed rate.[12] Under our study conditions, after about 15 min of exertion the micro-E WBGT was almost plateaued. Furthermore, these findings indicate that the micro-E could be expressed as a higher macro-E WBGT once micro-E stability occurs [12] for a particular macro-WBGT. While CAFs have been beneficial, evidence suggests that they would be constantly changed as work rate, and both micro-and macro-E, fluctuate.[12]

Findings from the current study suggest that the mean micro-E WBGT environments were not practically different at the two highest work rates. The differences between micro- and macro-E WBGT in the present study were about 3 °C for the two highest work rates at 29.8 °C macro-E WBGT. This finding is in contrast to Bishop et al. [2], who tested workers wearing impermeable clothing during exertion at 26.9 °C macro-E WBGT and found a difference of 5.7 °C between the macro- and micro-E. The nearly two-fold difference between our finding and that of Bishop et al. [2] is likely attributable to the lower macro-E WBGT and use of bunker gear used in the present study compared to sealed impermeable encapsulating clothing in Bishop et al. [2].

The mean and end-point micro-E WBGTs of the current study were 23.8 °C WBGT and 31.7 °C WBGT, respectively, for MOD. These findings differed from Muir et al. [14] who had

participants work at 300 kcal/h for 60 min in a Saranex®-coated Tyvek® fabric suit (Kappler, Inc., Guntersville, AL, USA) for slightly over an hour in a macro-E of 30.1 °C WBGT. In both studies, micro-E increased across time, but in the Muir et al. [15] study at the end of work the mean micro-E WBGT was 34.6 °C [14] (at approximately the same work rate). This gave a micro- to macro-E difference of 4.5 °C WBGT for Muir et al. [14] compared to 2.7 °C WBGT for the present study. One possible explanation for this contrast is the different duration of exercise in the two studies. Another reason for the difference in micro-E is that Muir et al. [14] used sealed impermeable coveralls whereas the present study used bunker gear with multiple layers which allowed some limited exchange of air between the micro- and macro-E, and does have some permeability.

T_{re} was lower during LO compared to MOD suggesting that the increase in work rate was large enough to cause the body to increase heat storage. This finding further suggests that a larger increase in work rate was needed between MOD and HI to see a significant increase in T_{re}. Also, an increase in trial duration may be needed to see a significant difference in T_{re}. Given that 450 kcal/hr represents the practical ceiling of sustained work rates, for practical purposes work rate seemed to not have a major impact on heat strain under these conditions.

CONCLUSIONS

We conclude that low, moderate, and high intensities of work in ~29 °C macro-E WBGT do not differentially affect micro-E WBGT under protective firefighter bunker gear. Understanding the effect work rate and duration has on micro-E WBGT should aid in estimating acceptable, dynamic Threshold Limit Values while working in hot/humid environments, which could lower the risk of an exertional heat illness or death. These data will be combined with data

from other, parallel studies utilizing different macro-E WBGT temperatures for development of a full model to predict the micro-E WBGT from work rate and ambient WBGT.

REFERENCES

1. **Sullivan, P.J. and I.B. Mekjavić**, Temperature and humidity within the clothing microenvironment. Aviat. Space. Environ. Med., 1992. 63*(3)*: p. 186-192.

2. **Bishop, P., D. Gu, and A. Clapp**, Climate under impermeable protective clothing. Int. J. Ind. Ergo., 2000. 25*(3)*: p. 233-238.

3. **Nadel, E.R., et al.**, Mechanisms of thermal acclimation to exercise and heat. J. Appl. Physiol., 1974. 37*(4)*: p. 515-20.

4. **Cheung, S., S. Petersen, and T. McLellan**, Physiological strain and countermeasures with firefighting. Scand. J. Med. Sci. Sports, 2010. 20*(s3)*: p. 103-116.

5. **ACGIH.** *TLVs and BEIs. American Confrence of Governmental Indurtrial Hygienists* in *ACGIH*. 2012.

6. **Pollock, M.L., D.H. Schmidt, and A.S. Jackson**, Measurement of cardiorespiratory fitness and body composition in the clinical setting. Clin. Ther., 1980. 6: p. 12-27.

7. **Cheuvront, S.N. and M.N. Sawka**, Hydration assessment of athletes. Sports Sci. Exchange, 2005. 18*(2)*: p. 1-6.

8. **Kavouras, S.A.**, Assessing hydration status. Curr. Opin. Clin. Nutr. Metab. Care, 2002. 5*(5)*: p. 519-24.

9. **Zhang, Y., et al.**, A new hand-cooling device enhance firefighter heat strain recovery. J. Occup. Environ. Med., 2009. 6*(5)*: p. 283-288.

10. **Burton, A.C.**, Human calorimetry II. The average temperature of the tissues of the body three figures. J. Nutr., 1935. 9*(3)*: p. 261-280.

11. **Bernard, T.E.**, Prediction of workplace wet bulb global temperature. App. Occup. Envion. Med., 1999. 14*(2)*: p. 126-134.

12. **Bishop, P., K. Crew, and A. Al-Nawaiseh,** Heat Stress and Heat Strain in Protective Clothing: Micro-environmental Considerations., in Protective Clothing: Managing Thermal Stress F. Wang and C. Gao, Editors. Sawston, Cambridge, UK: Woodhead Publishing, 2014.

13. **Reneau, P.D., P.A. Bishop, and C.D. Ashley**, A comparison of physiological responses to two types of particle barrier, vapor permeable clothing ensembles. Am. Ind. Hyg. Assoc. J., 1999. 60*(4)*: p. 495-501.

14. **Muir, I., P. Bishop, and J. Kozusko**, Micro-environment changes inside impermeable protective clothing during a continuous work exposure. Ergonomics, 2001. 44*(11)*: p. 953-961.

15. **Muir, I.H., P.A. Bishop, and P. Ray**, Effects of a novel ice-cooling technique on work in protective clothing at 28 °C, 23 °C, and 18 °C WBGTs. Am. Ind. Hyg. Assoc. J., 1999. 60*(1)*: p. 96-104.

Figure Captions

FIGURE 2.1. Micro-E WBGT (°C) scatterplots for each participant across time and trials (n = 10).

FIGURE 2.2. Regression equations created from micro- and macro-E temperatures (30.3 °C WBGT) among trials for the entire trial(n = 10). LO ($y = -0.0058x^2 + 0.279x + 27.677$, $R^2 = 0.97$). MOD ($y = -0.0025x^2 + 0.212x + 27.6$, $R^2 = 0.96$). HI ($y = -0.0067x^2 + 0.3488x + 28.017$, $R^2 = 0.98$).

FIGURE 2.3. Regression equations created from micro- and macro-E temperatures (°C WBGT) among trials beginning at 15 min (n = 10). LO ($y=0.001x^2 + 0.0316x + 29.8$, R^2 0.99). MOD ($y = 0.0011x^2 + 0.5048x + 25.417$, $R^2 = 0.9023$. HI ($y = -0.0024x^2 + 0.1383x + 30.503$, $R^2 = 0.8602$.

FIGURE 2.4. Mean ± SD ΔT_{re} from baseline (0 min) to 10, 20, and 30 min respectively (n = 10).

FIGURE 2.5. Mean ± SD heart rate (HR) across time (n = 10).

FIGURE 2.6 (a-d). Mean ± SD responses for all perceptual measures (RPE, thermal sensation, sweat sensation and comfort rating) (n=10). RPE was significantly different for : LO vs. MOD ($p = 0.007$), LO vs. HI ($p = 0.005$), and MOD vs. HI ($p = 0.031$). Sweat sensation was significantly different for: LO vs. HI ($p = 0.01$) and MOD vs. HI ($p < 0.04$).

CHAPTER IV

COOLING TECHNIQUES FOR FIRE FIGHTERS: A BRIEF REVIEW

ABSTRACT

Firefighter bunker gear is donned by firefighters (FF) responding to the fire field or other emergencies. Bunker gear's encapsulating nature makes cooling the micro environment (micro-E) useful to reduce the risk of exertional heat illness and increase work capacity. Due to varying modes of work, work rates, and ambient environments, synthesis of the research literature is difficult. This paper briefly reviewed some of the challenges FF experience on the fire field and as a result of donning bunker gear. In addition, some of the cooling strategies currently used to reduce heat stress of those working in protective clothing are also discussed. Liquid, chemical, phase change materials, and cooling devices have proven beneficial either while working on the fire field or during recovery from a work bout. Additional research is needed to improve the current methods of micro-E cooling and develop new methods that are more cost-effective, ergonomic, and effective at reducing the negative effects FF experience during work while wearing bunker gear.

Key Words: micro environment, protective clothing, heat stress

INTRODUCTION

Firefighters (FF) are challenged in many ways, especially while working in a hot ambient (macro) environment (macro-E). Protective clothing (e.g. bunker gear) encapsulates firefighters, protecting them from high macro-E temperatures but simultaneously causing uncompensable heat stress, [1] which leads to increased heat storage. Stressors caused by hot macro- and micro-environments (micro-E) (the small layer of air that surrounds the body[2] between the skin and protective clothing) reduce the cardiovascular system's ability to meet competing demands of skeletal muscle blood flow (for muscle O_2 delivery) and skin blood flow (for heat dissipation) during physical exertion. Cardiovascular strain coupled with increased rectal temperature (T_{re}) can increase the risk of heart attack, exertional heat stroke, and death.

Due to bunker gear's bulky and encapsulating nature, additional weight is added to the FF leading to increased physical exertion and increased ergonomic challenges. Though various techniques and strategies for FF cooling have been utilized, several obstacles limit their feasibility and practicality. However, there are solutions being developed to increase the utility of many of the cooling techniques and strategies. The purpose of this review was to synthesize the current literature on FF cooling strategies and techniques to meet the physiological challenges of FF in or around the fire field.

Physiological Challenges of Firefighters

With the physical demands of firefighting comes a significant demand on the cardiovascular system. Smith et al.[3] utilized bunker gear that met the National Fire Protection Association (NFPA) requirements (NFPA 1500) and found that heart rate (HR) rose to near maximal values while performing heavy exercise. Additionally, as HR increased so did T_{re}, further challenging the cardiovascular system. A HR of ~150 beats/min is common for FF entering a burning structure.[4] Core body temperature was also increased by ~1.3 °C during 24 min of firefighting in one report.[4] Additional research indicates that a Lead Hand FF (those individuals who first enter the burning structure) have near maximal HR during fire suppression activities,[4-9] resulting in heart attacks being the most frequent cause of death for FF during active duty.[10]

Indeed, the stress and anxiety,[11] physical demands,[12, 13] and physiological strain caused by firefighting and bunker gear,[14] individually or compounded, increase the risk of a myocardial infarction . Therefore, a better understanding of cooling strategies and techniques are needed for FF working on or around the fire field.[1] A FF's ability to dissipate heat [which is primarily determined by micro-E temperature and relative humidity (rH)] is greatly reduced after donning bunker gear. In addition more than 70% of metabolic energy is converted to heat during movement [15] while working in bunker gear.[16, 17] As heat dissipation of the FF is inhibited, metabolic heat gain increases.[1] Furthermore, since FF bunker gear is typically resistant to air penetration, convective heat loss is also reduced. That said, minimizing convection is useful on the fire field because the macro-E temperatures can be extremely high.[1]

Muir, Bishop, and Kozusko[18] found that micro-E temperature and rH increase to a plateau within 20-30 min of donning a hooded Saranex 23-P one-piece impermeable coverall.

Furthermore, when the mean difference of the micro-E and macro-E wet bulb globe temperature (WBGT) was measured at multiple locations (thigh, hip, and shoulder) the rise in the micro-E proved to be consistent across locations.[18] Additionally, when exposed to a hot macro-E WBGT, the micro- E increased rapidly at the beginning of the trial and then plateaued over time.[18] These findings are also characteristic of the demands and challenges placed on FF while working in bunker gear.

Demands and Challenges caused by Bunker Gear

Firefighting is characterized as one of the most strenuous occupations due to the physical demands placed on FF by their working environments.[12, 13, 19, 20] Demands on the body are drastically increased after donning bunker gear, carrying a self-contained breathing apparatus (SCBA), and numerous tools. FF bunker gear is designed to protect the FF from high temperatures, steam, and the toxic fumes associated with exposure to a live fire environment.[21, 22] Bunker gear weighs approximately 10–15 kg and consists of (in addition to the standard underwear and uniform) a jacket and trousers, a fire-resistant hood, a respirator, helmet, impermeable rubber boots, and gloves.[15] Bunker gear fully encapsulates the body and significantly inhibits heat transfer due to its high insulation and low water vapor permeability.[10]

In addition to bunker gear, a SCBA weighing approximately 10 to 12 kg, is also worn.[10]

The additional weight and location of the SCBA hinders normal movement mechanics, especially when climbing steep grades or stairs.[16, 17] With FF weighing approximately 82 kg,[23] bunker gear and SCBA increase their mass by 30%.[10] The tools and equipment FF need on the fire field were reported by Gledhill and Jamnik[24] to greatly exceed the mass of the bunker gear

and SCBA, which further increases the metabolic rate and heat production when compared to the bunker gear alone.

FF experience various impediments such as bunker gear, head protection, and SCBA while on the fire field. In addition, the uncertainty of when an emergency will occur also prevents FF pre-cooling. With FF facing maneuverability and logistical obstacles while on the fire field, cooling methods and techniques must function with existing equipment, be portable, ergonomic, and economically feasible while not requiring a lot of space or power to operate. [10]

Techniques and Strategies of Firefighter Cooling

The fire field and the equipment used by FF pose several challenges to FF cooling. Challenges include cost of the cooling techniques or devices, which limits their dispensability to many FF. Techniques and devices used while working can also increase the physical load that the FF must carry, which further inhibits breathing, [10] movement, and maneuverability.

The harsh conditions of the fire field make FF cooling during recovery the most practical option. Cooling during recovery allows FF to recover while seated in a less harsh environment, lessening FF heat stress, and lowering the risk of damage to the cooling devices compared to cooling during fire field work. Recharging a personal cooling device to continue facilitating cooling has historically been difficult due to the lack of resources (cold water supply, chemical recycling, and the need for electricity). However, overcoming the challenges of recharging a personal cooling system can be achieved for workers in a defined area on a planned schedule.

Cooling techniques[25, 26] and devices[27-30] have been shown to attenuate heat strain, enhance work capacity, and increase safety. Though the devices using liquid, phase-change

material, air, carbon dioxide, and fan cooling systems have been investigated, [27, 28, 31-36] such devices tend to be expensive.

Solutions

Economical, Lightweight, and Effective Mobile Cooling Devices

Current portable cooling devices use complicated and expensive equipment that are cumbersome, and add to the already elevated metabolic demand for a given activity. [28, 37, 38] To meet this need, an alternative approach to micro-E cooling using the vaporization of liquefied CO_2 (Porticool Personal Cooling Systems, Porticool, Inc. Morrisville, NC) was developed. Using this cooling shirt, heat storage was significantly reduced [cooling shirt (mean ± SD) = 54 ± 41 W vs. no cooling 72 ± 40 W], while ΔT_{re} (°C/h) was significantly different over time compared to no cooling 0.7 ± 0.4 °C/h; 1.0 ± 0.4 °C/h, respectfully.[36]

Kim et al. [39] investigated the effects of a liquid cooling garment on performance time and recovery while exercising on a treadmill for three 15-min stages at 75% $\dot{V}O_2$max with 10 min of rest between each stage. Environmental conditions were 35 °C, 50% rH. Six male participants were recruited for this study and performed each trial after donning FF bunker gear and SCBA. Each participant performed six trials in randomized order. Treatments included no cooling, air ventilation rerouted into the protective clothing, and liquid cooling garments worn under the bunker gear. The liquid cooling garment was used in two ways; one condition covered only the head and forearms (top cooling garment), while another condition covered the head, torso, forearm, and thigh region (shortened cooling garment). Performance time was increased ($p < 0.05$) using the shortened cooling garment (38 min) and shortened cooling garment plus air ventilation (40 min), compared to no cooling (25 min), air ventilation (22 min), top cooling

garment (26 min), and liquid cooling garment plus air ventilation (24 min). [39] Delta T_{re} averaged for the three rest stages were significantly different among the short cooling garment (0.0 °C), and short cooling garment plus air ventilation (-0.1 °C) vs. no cooling (0.28 °C), air ventilation (0.2 °C), top cooling garment (0.21 °C), top cooling garment plus air ventilation (0.23 °C). [39] Compared to no cooling (40 ± 4 beats/min), cooling treatments resulted in a smaller change in HR from rest: liquid cooling garment: 50 beats/min, top cooling garment plus air ventilation: 53 beats/min, shortened cooling garment: 57 beats/min, and shortened cooling garment plus air ventilation (59 beats/min).

The purpose of these studies was to determine the effect cooling garments could have on heat strain. Variations were made to the cooling methods, such as: the region of the body that was cooled, chemicals used during cooling, and coupling the liquid cooling garment with other methods of cooling such as air ventilation. These alterations in cooling resulted in varying findings as shown above that are beneficial when deciding upon which method of micro-E cooling to utilize.

Pre-Cooling

During recovery periods (between work bouts), FF pre-cooling (cold water immersion, ice vests, or cold/wet towels) prepares the body for a thermally stressful macro-E [40] and reduces heat stress.[41] Pre-cooling increases one's capacity to store metabolic and environmental heat, which leads to improved performance. [42, 43] Pre-cooling also combats heat-stress-induced fatigue to enhance exercise performance.[40] However, certain modes of pre-cooling are difficult to implement due to the uncertainty of an emergency.

During recovery periods (typically 10-20 min) between bouts of firefighting or after the mission has been completed, reducing core body temperature is vital. Core body temperature was decreased from 39.5 °C (at the end of exercise in the heat) to below 37.5 °C in ~10 min after whole-body water immersion (2 °C). [44] Intermittent (10–20 °C) or continuous (20 °C) whole-body water immersion during a 15-min recovery period reduced thermal strain and attenuated the reduction in work output during a second bout of exercise when compared to active recovery (cycling at 40% $\dot{V}O_2max$). [45] Whereas whole-body immersion shows positive results, logistical difficulties involved with transporting and erecting water baths and supplying cold water on the fire field, along with removing and donning clothing and equipment, limit the practicality of this technique.

Recovery periods during work bouts afford FF the opportunity to pre-cool before returning for another bout of firefighting. This method of cooling has many benefits, one being the ability for the FF to return to a lower temperature macro-E. In addition, the FF doesn't have to carry additional gear to facilitate cooling and the cooling system doesn't have to overcome a very high temperature macro-E as it cools.

Regional Cooling

Recovery periods may be better utilized when combining regional immersion of the limbs or extremities into cold or cool water to speed up cooling. [10] Though full removal of bunker gear may not be practical, partial doffing (helmet, mask, SCBA, jacket, gloves, and pants) during FF recovery periods have been utilized. [10] Regions of the body such as the forearm, hands, and feet have a high surface area to volume ratio, and have the ability for strong vasodilation during hyperthermic conditions, increasing the potential for heat exchange. [38] Heat exchange is also

improved via anastomoses (a connection between two blood vessels allowing multiple arteries and veins to serve the same tissue). This allows a larger quantity of blood that was exposed to cooling to reach the tissue.

Zhang et al. [35] investigated a hand cooling device designed to reduce physiological strain, enhance heat loss, increase safety, and increase work capacity. This device is small, portable, and battery operated with a temperature controlled cone inside of a vacuum chamber. A water bottle filled with ice and water is connected to the vacuum chamber to supply ice water pumped to the cooling cone creating a thermal gradient with the palm of the hand. When the hand grips the cone, heat is extracted from the hand circulation and cooled blood is returned to the body's core.[35] This study indicated that cooling one palm was more effective at reducing T_{re} than passive cooling.[35] T_{re} at 35 min had decreased by 0.5 ± 0.2 °C (passive cooling) vs. 0.8 ± 0.3 °C (hand cooling). At 40 min, T_{re} had decreased by 0.6 ± 0.2 °C (passive cooling) vs. 0.8 ± 0.3 °C (hand cooling) ($p < 0.03$). This indicates that hand cooling efficacy plateau around 35 min during these conditions.

Fifteen male FF participated in heat stress trials that compared active vs. passive cooling during intermittent work after donning FF bunker gear and SCBA. [14] The work-rest cycle for each trial was 50 to 30 min. All trials were performed in a macro-E of 35 °C, 50% rH. Each trial continued until any of the following occurred: $T_{re} \geq 39.9$ °C, 95% of HR max, or exhaustion. Trials were performed in randomized order, with the cooling modalities including forearm submersion (forearms submersed in a calorimetry tank filled with water (17.4 ± 0.2 °C up to the elbow for 20 min), mister with the participant seated 5 ft away, a fan propelling a fine mist at 2000 cubic ft per min for 20 min, or passive cooling (seated rest with no clothing for 20 min). Tolerance time and work time were significantly longer for forearm submersion (178.7 ± 13.0

and 124.7 ± 7.9 min) and mister (139.1 ± 8.3 and 95.1 ± 4.9 min) vs. passive cooling (108.0 ± 3.6 and 78.0 ± 3.6 min). There was no significant difference for $\overline{T}_{sk}$ for forearm submersion vs. mister. However, a significantly lower hand temperature resulted from forearm submersion (20 °C) vs. mister (32 °C). HR for passive cooling (113 beats/min) was significantly higher across time than forearm submersion (99 beats/min) and mister (93 beats/min). HR was lower with forearm submersion vs. mister during the first rest session (93 beats/min vs. 98 beats/min), work session two (120 beats/min vs. 131 beats/min), and rest session two (97 beats/min vs. 118 beats/min). T_{re} decreased 0.4 °C during forearm submersion compared with mister (~0.08 °C), while during passive cooling T_{re} increased (~0.2 °C). During the second rest period, T_{re} was 0.9 °C lower in forearm submersion vs. mister. These findings indicate that when compared to a mister during the specified conditions, forearm submersion decreased physiological strain more and allowed longer work tolerance.

Liquid cooling (circulating liquid cooled garments worn in varied configurations (i.e. whole body, upper body only, or torso vest only) was investigated in regards to micro-E cooling.[46] During this study, intermittent (2 min off-on) vs. constant cooling were also investigated. [46] Core body temperature increased more (1.6 ± 0.2 °C) during the no cooling than for intermittent cooling (0.5 ± 0.2 °C) and continuous cooling (0.5 ± 0.3 °C). Mean skin temperature was also higher during no cooling (36.1 ± 0.4 °C) compared to intermittent cooling (33.7 ± 0.6 °C) and continuous cooling (32.6 ± 0.6 °C). These results indicate that compared to no cooling, a circulating liquid cooled garment blunts the rise of T_{re} and T_{sk} while working in a US Army chemical protective clothing at 30 °C, 30 rH.

Being able to cool the body effectively while exposing less of the body's surface area to the cooling treatment is beneficial since the resources on the fire field are limited and often times

the firefighter is recovering from a work bout in a harsh macro-E (high temperature, lack of shaded area, etc.). Utilizing hands, forearms, and lower limbs for cooling also keeps the firefighter from having to doffing clothing that they will don shortly afterwards. Therefore, cooling the upper extremities saves some time and energy during the recovery period.

Gas Cooling

Gas cooling reduces heat storage and increases performance. [47, 48] Use during recovery periods [35, 36] makes gas cooling a more practical technique to reduce heat strain; however, challenges exist for most gas cooling systems because they are tethered to a cooling source. [1]

The effectiveness of reducing heat strain by a portable open-circuit carbon dioxide cooling device was investigated by Zhang et al. [36] Ten participants completed two trials in a 30 °C WBGT (75% rH) ambient environment with either a liquid carbon dioxide cooling shirt or no cooling. When the cooling shirt was worn, work time was significantly increased by 32% (97 ± 35 min) compared to no cooling (74 ± 26 min). After 50 min, T_{re} was lower while wearing the cooling shirt vs. no cooling (38.1 °C vs. 38.3 °C). Carbon dioxide cooling also resulted in a lower HR, delta T_{re} from rest, and heat storage at 55 min vs. no cooling. This technique could be used by FF on the fire field (during recovery) to reduce heat storage and increase work time.

Phase Change Materials

Ice packs and phase change materials (PCM) (a highly productive thermal storage medium) have been used to decrease heat stress. Chou et al. [49] had subjects cycle on a cycle ergometer while wearing FF bunker gear. Four trials were performed in a 30 °C, 50% rH macro-

E. During each trial subjects rested pre-test in a 25 °C (dry bulb) room for 10 min, then they proceeded to the testing room and rested for an additional 10 min, then they exercised for 30 min at 55% $\dot{V}O_2max$. After exercise they recovered for 10 min. Treatments included: a control (CON) during which no cooling was administered; ice pack (ICE) (5 packs in a vest); [PCM(5)] 16 packs of PCM placed in a CoolVest^{TM} at 5 °C; and [PCM(20)] which used 16 PCM packets cooled to 20 °C. Based on the results, investigators concluded that the increase in T_{re} was smaller using PCM (5 and 20) (0.8 °C) vs. CON (1.0 °C) and ICE (1.1 °C). The increase in skin temperature was smaller for PCM (2.2 °C) than ICE (2.4 °C). There was no significant difference between PCM (5) and PCM (20) for skin temperature.

PCM in a cooling vest (MicroClimate Systems, Inc., Sanford, MI) was compared to no cooling, liquid cooling, and air cooling (powered by external portable chiller units) at the region of the torso while participants walked on a treadmill at 3.5 km/h in a 40 °C macro-E. [50] Seven male participants performed five trials to determine total time of exercise and change in T_{re} while wearing a nuclear, biological, and chemical overgarment. Total trial time was set at 3 h, or until any of the following occurred: T_{re} = 39.3 °C, 95% peak HR for 3 min, presence of nausea or dizziness. While no cooling was given, the tolerance time was 100 min and the final T_{re} was 39.1 °C. Both PCM trials resulted in 130 min of walking and a T_{re} of 38.0 °C. Liquid cooling and air cooling resulted in 180 min of walking while T_{re} remained below 38.0 °C. These findings suggest PCM was effective at increasing total exercise time but less beneficial than air and liquid cooling for decreasing heat strain.

CONCLUSIONS

For FF on the fire field, the potential for exertional heat illness is always present; therefore, mitigating heat gain while allowing FF to remain functional is important. FF cooling techniques and strategies are limited. Various techniques and strategies (liquid, chemical, PCM, and pre-cooling) have been investigated for their ability to aid micro-E cooling under protective clothing. In general, cooling methods are superior to no cooling. For example, carbon dioxide used in a cooling shirt reduces heat storage vs. no cooling.[36] Likewise, micro-E cooling reduces heat storage, though several devices require recharging to continue to be effective, which has proven problematic. PCM has been effective at reducing heat stress vs. ice vests and no cooling. Like cooling devices, however, recharging PCM poses some challenges; since resources on the fire field are limited.

With numerous techniques and strategies available for cooling while wearing protective clothing, it is important to weigh the various factors (time, cost, ergonomics, durability, etc.) when selecting a method. As research and innovation continue, hopefully the current FF cooling methods will become more portable, cost-effective, and practical for use on the fire field. In addition to improvements in the current methods of firefighter and protective clothing cooling, perhaps new methods and devices will be developed to allow FF to work longer and be more effective while on the fire field.

REFERENCES

1. **Bishop, P., K. Crew, and A. Al-Nawaiseh,** Heat Stress and Heat Strain in Protective Clothing: Micro-environmental Considerations., in Protective Clothing: Managing Thermal Stress F. Wang and C. Gao, Editors. Sawston, Cambridge, UK: Woodhead Publishing, 2014.

2. **Sullivan, P.J. and I.B. Mekjavić**, Temperature and humidity within the clothing microenvironment. Aviat. Space. Environ. Med., 1992. 63*(3)*: p. 186-192.

3. **Smith, D., et al.**, Selected physiological and psychobiological responses to physical activity in different configurations of firefighting gear. Ergonomics, 1995. 38*(10)*: p. 2065-2077.

4. **Romet, T.T. and J. Frim**, Physiological responses to fire fighting activities. Euro. J. Apply.Physiol., 1987. 56*(6)*: p. 633-638.

5. **Malley, K., et al.**, Effects of fire fighting uniform (modern, modified modern, and traditional) design changes on exercise duration in New York City Firefighters. J. Occup. Environ. Med., 1999. 41*(12)*: p. 1104-1115.

6. **Manning, J.E. and T.R. Griggs**, Heart rates in fire fighters using light and heavy breathing equipment: similar near-maximal exertion in response to multiple work load conditions. J. Occup. Environ. Med., 1983. 25*(3)*: p. 215-218.

7. **Smith, D., et al.**, The effects of different thermal environments on the physiological and psychological responses of firefighters to a training drill. Ergonomics, 1997. 40*(4)*: p. 500-510.

8. **Smith, D.L. and S.J. Petruzzello**, Selected physiological and psychological responses to live-fire drills in different configurations of firefighting gear. Ergonomics, 1998. 41*(8)*: p. 1141-1154.

9. **Smith, D.L., et al.**, Physiological, psychophysical, and psychological responses of firefighters to firefighting training drills. Aviat. Space Environ. Med., 1996. 67*(11)*: p. 1063-1068.

10. **Cheung, S., S. Petersen, and T. McLellan**, Physiological strain and countermeasures with firefighting. Scand. J. Med. Sci. Sports, 2010. 20*(s3)*: p. 103-116.

11. **Kuorinka, I. and O. Korhonen**, Firefighters' reaction to alarm, an ECG and heart rate study. J. Occup. Environ. Med., 1981. 23*(11)*: p. 762-766.

12. **Gledhill, N. and V.K. Jamnik**, Characterization of the physical demands of firefighting. Can. J. Sport Sci., 1992a. 17*(3)*: p. 207-13.

13. **Williams-Bell, F.M., et al.**, Physiological demands of the firefighter Candidate Physical Ability Test. Med Sci Sports Exerc, 2009. 41*(3)*: p. 653-62.

14. **Selkirk, G., T.M. McLellan, and J. Wong**, Active versus passive cooling during work in warm environments while wearing firefighting protective clothing. J. Occup. Environ. Hyg., 2004. 1*(8)*: p. 521-531.

15. **Cheung, S.**, Advanced Enironmental Exercise Physiology. Advanced Exercise Physiology. 2010, Champaign, IL: Human Kinetics.

16. **Kang, J., et al.**, Physiological and biomechanical analysis of treadmill walking up various gradients in men and women. Euro. J. Apply.Physiol., 2002. 86*(6)*: p. 503-508.

17. **Santee, W.R., et al.**, A proposed model for load carriage on sloped terrain. Aviat. Space Environ. Med., 2001. 72*(6)*: p. 562-566.

18. **Muir, I., P. Bishop, and J. Kozusko**, Micro-environment changes inside impermeable protective clothing during a continuous work exposure. Ergonomics, 2001. 44*(11)*: p. 953-961.

19. **Lemon, P. and R.T. Hermiston**, The human energy cost of fire fighting. J. Occup. Environ. Hyg., 1977. 19*(8)*: p. 558-562.

20. **O'Connell, E.R., et al.**, Energy costs of simulated stair climbing as a job-related task in fire fighting. J. Occup. Environ. Hyg., 1986. 28*(4)*: p. 282-284.

21. **Prezant, D.J., et al.**, Impact of a design modification in modern firefighting uniforms on burn prevention outcomes in New York City firefighters. J. Occup. Environ. Hyg., 2000. 42*(8)*: p. 827-834.

22. **Prezant, D.J., et al.**, Impact of a modern firefighting protective uniform on the incidence and severity of burn injuries in New York City firefighters. J. Occup. Environ. Hyg., 1999. 41*(6)*: p. 469-479.

23. **Horowitz, M. and D.L. Montgomery**, Physiological profile of fire fighters compared to norms for the Canadian population. Can. J. Public Health, 1992. 84*(1)*: p. 50-52.

24. **Gledhill, N. and V. Jamnik**, Development and validation of a fitness screening protocol for firefighter applicants. Can. J. Sport Sci., 1992b. 17*(3)*: p. 199-206.

25. **Bennett, B.L., et al.**, Comparison of two cool vests on heat-strain reduction while wearing a firefighting ensemble. Euro. J. Appl. Physiol. Occu. Physiol., 1995. 70*(4)*: p. 322-328.

26. **Muir, I.H., P.A. Bishop, and P. Ray**, Effects of a novel ice-cooling technique on work in protective clothing at 28 °C, 23 °C, and 18 °C WBGTs. Am. Ind. Hyg. Assoc. J., 1999. 60*(1)*: p. 96-104.

27. **Bishop, P.A., S.A. Nunneley, and S.H. Constable**, Comparisons of air and liquid personal cooling for intermittent heavy work in moderate temperatures. Am. Ind. Hyg. Assoc. J., 1991. 52*(9)*: p. 393-397.

28. **Constable, S.H., et al.**, Intermittent microclimate cooling during rest increases work capacity and reduces heat stress. Ergonomics, 1994. 37*(2)*: p. 277-85.

29. **Muza, S.R., et al.,** Portable, ambient air microclimate cooling in simulated desert and tropic conditions, 1987, DTIC Document.

30. **Vallerand, A., et al.**, Heat balance of subjects wearing protective clothing with a liquid- or air-cooled vest. Aviat. Space Envirom. Med, 1991. 62*(5)*: p. 383-391.

31. **Armstrong, L.E., et al.**, Whole-body cooling of hyperthermic runners: comparison of two field therapies. Am. J. Emerg. Med., 1996. 14*(4)*: p. 355-358.

32. **Carter, J.**, Effectiveness of rest pauses and cooling in alleviation of heat stress during simulated fire-fighting activity. Ergonomics, 1999. 42*(2)*: p. 299-313.

33. **Duffield, R., et al.**, Effect of wearing an ice cooling jacket on repeat sprint performance in warm/humid conditions. Br. J. Sports Med., 2003. 37*(2)*: p. 164-169.

34. **Epstein, Y., Y. Shapiro, and S. Brill**, Comparison between different auxiliary cooling devices in a severe hot/dry climate. Ergonomics, 1986. 29*(1)*: p. 41-48.

35. **Zhang, Y., et al.**, A new hand-cooling device enhance firefighter heat strain recovery. J. Occup. Environ. Med., 2009. 6*(5)*: p. 283-288.

36. **Zhang, Y., et al.**, Evaluation of a novel personal cooling device for workers in hot environments. J. Occup. Environ. Med., 2010. 7: p. 389-396.

37. **Mclellan, T.M., et al.**, Effects of dehydration, hypohydration, and hyperhydration on tolerance during uncompensable heat stress. Can. J. Appl. Physiol., 1999. 24*(4)*: p. 349-361.

38. **Tipton, M., et al.**, Hand immersion as a method of cooling and rewarming: a short review. J. R. Nav. Med. Serv., 1992. 79*(3)*: p. 125-131.

39. **Kim, J.-H., et al.**, Effects of liquid cooling garments on recovery and performance time in individuals performing strenuous work wearing a firefighter ensemble. J, Occup, Environ, Hyg., 2011. 8*(7)*: p. 409-416.

40. **Ross, M., et al.**, Precooling methods and their effects on athletic performance. Sports Med., 2013. 43*(3)*: p. 207-225.

41. **Booth, J., F. Marino, and J.J. Ward**, Improved running performance in hot humid conditions following whole body precooling. Med. Sci. Sports Exer., 1997. 29*(7)*: p. 943-949.

42. **Marino, F.**, Methods, advantages, and limitations of body cooling for exercise performance. Br. J. Sports Med., 2002. 36*(2)*: p. 89-94.

43. **Quod, M.J., D.T. Martin, and P.B. Laursen**, Cooling athletes before competition in the heat. Sports Med., 2006. 36*(8)*: p. 671-682.

44. **Proulx, C.I., M.B. Ducharme, and G.P. Kenny**, Effect of water temperature on cooling efficiency during hyperthermia in humans. J. Appl. Physiol., 2003. 94*(4)*: p. 1317-1323.

45. **Vaile, J., et al.**, Effect of cold water immersion on repeat cycling performance and thermoregulation in the heat. Journal of sports sciences, 2008. 26*(5)*: p. 431-440.

46. **Cadarette , B.S., et al.**, Intermittent microclimate cooling during exercise-heat stress in US army chemical protective clothing. Ergonomics, 2006. 49*(2)*: p. 209-219.

47. **Cadarette, B.S., et al.,** Evaluation of three commercial microclimate cooling systems, 1990, DTIC Document.

48. **Cadarette, B.S., et al.**, Heat strain reduction by ice-based and vapor compression liquid cooling systems with a toxic agent protective uniform. Aviat. Space. Envirom. Med., 2002. 73*(7)*: p. 665-672.

49. **Chou, C., Y. Tochihara, and T. Kim**, Physiological and subjective responses to cooling devices on firefighting protective clothing. Eur. J. Appl. Physiol., 2008. 104*(2)*: p. 369-374.

50. **McLellan, T.M. and J. Frim,** Efficacy of liquid, air, and phase change material torso cooling during light exercise while wearing NBC clothing, 1998, DTIC Document.

APPENDIX

Office for Research
Institutional Review Board for the Protection of Human Subjects

THE UNIVERSITY OF ALABAMA RESEARCH

May 21, 2014

Jared Hornsby
Department of Kinesiology
College of Education
The University of Alabama

Re: IRB Protocol # 13-033-ME
"The Effects of Cold versus Hot Firefighter Bunker Gear on Physiological Measurements"

Mr. Hornsby:

The University of Alabama Medical Institutional Review Board has reviewed the revision to your previously approved full board protocol. The board has approved the minor change in your protocol.

Please remember that your approval period expires one year from the date of your original approval, December 12, 2013, not the date of this revision approval.

Should you need to submit any further correspondence regarding this proposal, please include the assigned IRB application number. Changes in this study cannot be initiated without IRB approval, except when necessary to eliminate apparent immediate hazards to participants.

Good luck with your research.

Sincerely,

John C. Higginbotham, Ph.D., MPH
Medical IRB Chair
The University of Alabama

352 Rose Administration Building
Box 870127
Tuscaloosa, Alabama 35487-0127
(205) 348-8461
fax (205) 348-7189
toll free (877) 820-3066

Office for Research
Institutional Review Board for the Protection of Human Subjects

THE UNIVERSITY OF ALABAMA RESEARCH

May 21, 2014

Jared Hornsby
Department of Kinesiology
College of Education
The University of Alabama

Re: IRB Protocol # 13-033-ME
"The Effects of Cold versus Hot Firefighter Bunker Gear on Physiological Measurements"

Mr. Hornsby:

The University of Alabama Medical Institutional Review Board has reviewed the revision to your previously approved full board protocol. The board has approved the minor change in your protocol.

Please remember that your approval period expires one year from the date of your original approval, December 12, 2013, not the date of this revision approval.

Should you need to submit any further correspondence regarding this proposal, please include the assigned IRB application number. Changes in this study cannot be initiated without IRB approval, except when necessary to eliminate apparent immediate hazards to participants.

Good luck with your research.

Sincerely,

John C. Higginbotham, Ph.D., MPH
Medical IRB Chair
The University of Alabama

358 Rose Administration Building
Box 870127
Tuscaloosa, Alabama 35487-0127
(205) 348-8461
fax (205) 348-7189
toll free (877) 820-3066