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# Physiological Responses of Men During the Continuous Use of a Portable Liquid Cooling Vest

by

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of the requirements for the degree of
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# Physiological Responses of Men During the Continuous Use of a Portable Liquid Cooling Vest

Theresa J. Medina

## ABSTRACT

Heat stress is a well documented hazard across industries. The combination of environmental conditions, work demands, and clothing contribute to heat strain. Left unchecked, heat strain causes changes in an individual's physiological state that can lead to serious and fatal conditions with little warning. Although engineering and administrative controls are the first choice to abate this hazard, they frequently are not feasible. In these cases, personal cooling is often employed. There are three main types of personal cooling: liquid, air, and passive. Each has its own advantages and disadvantages.

This study focuses on continuous cooling using a portable liquid cooling system (LCS). The LCS used a vest with tubes circulating water from an ice heat sink. The experiment consisted of five males each completing seven tests in random order. The subjects wore work clothes as the control then in conjunction with a firefighter, vapor barrier, and bomb suits. Each suit was tested with and without the benefit of the LCS. All of the tests took place at 35°C dry bulb and 50% relative humidity while attempting to walk 90 minutes on a treadmill at a 300 W metabolic rate.

The study found continuous use of the LCS significantly reduced heat storage (S) and the rate of rise of heart rate (rrHR), core temperature ($rrT_{re}$), and mean skin

temperature ($rrT_{sk}$) for the firefighter and vapor barrier suits as compared to no-cooling. Although the LCS didn't significantly affect the rate of rise for physiological responses with the bomb suit, it did however, significantly increase the endurance time. Interestingly, the study also found when wearing either the vapor barrier or firefighter suits in conjunction with the LCS that the rrHR and $rrT_{re}$ were not significantly different from only wearing work clothes.

# INTRODUCTION

A wide range of occupations including firefighters, HAZMAT workers, and explosive ordinance technicians have potentially dangerous heat stress exposures. Heat stress is the net load on the worker from the metabolic demands, environmental factors, and clothing. Increasing the work load will increase the metabolic rate and in turn generate heat in the body. Air temperature, movement, and humidity along with radiant heat exchange are all environmental factors that contribute to heat stress. Clothing can drastically alter the heat stress an individual experiences. Unfortunately, many occupations require additional layers of personal protective equipment (PPE) as a barrier against hazards that cannot otherwise be controlled. PPE is often multilayered, impervious to water vapor and air, encapsulating, and thermally insulated. This drastically affects heat stress by significantly reducing the ability of the body to cool itself through the evaporation of sweat.

The internal temperature of the human body remains fairly constant even when exposed to widely varying environmental conditions. Safe limits for the fluctuation of core temperatures are small, and therefore, the body must get rid of excess heat to keep the internal temperature within safe limits. The primary mechanisms the body uses to maintain heat balance are to vary the rate and amount of blood circulating to the skin by increasing the heart rate and to release water onto the skin through sweat glands. As the sweat evaporates, the skin cools thereby eliminating large quantities of heat from the body. In order to achieve the cooling effects from sweating, sweat must be removed by evaporation. High humidity environments or protective clothing with high evaporative resistance may significantly diminish evaporation and the body's ability to dissipate excess heat. These defensive mechanisms of the body can also cause adverse effects. With large amounts of blood going to the skin and less to active muscles and the brain, muscle strength and alertness may decline. Left unchecked, heat strain can lead to serious and even fatal conditions sometimes with little warning.

The exchange of heat between the body and the environment is governed by the fundamental laws of thermodynamics. A common equation employed to express heat stress is the heat balance equation(1):

$$S = M + C + R - E \qquad (1)$$

The change in body heat storage (S) is a function of the metabolic rate (M), convective heat exchange (C), radiant heat exchange (R), and evaporative heat loss (E). Whenever the change in body heat storage is positive, the individual is gaining heat.

Engineering controls are often employed to control heat gains. In the case of metabolic heat gains, work stations can be designed to limit the physical effort the employee must use to perform the job. Convective heat gain can be reduced by lowering the air temperature so that the environmental temperature is less then the skin temperature and increasing air velocities. Radiant heat gain is typically controlled with shielding to block heat flow. In addition, administrative controls are used. These include frequent breaks and monitoring both environmental and physiological conditions. The American Conference of Governmental Industrial Hygienists (ACGIH) has published guidelines to determine work-rest cycles when evaluating work load and environmental conditions. Unfortunately, as in all disciplines of industrial hygiene, it is not always technically or economically possible to limit excessive heat stress by the use of engineering and administrative controls. When engineering and administrative controls do not adequately reduce heat stress, personal protective equipment is necessary. Cooling garments are typically used to meet this need.

It is often impossible to implement adequate engineering and administrative controls for firefighters who must wear insulating turnout gear, enter extremely hot environments, and perform heavy labor. The same can be said of explosive ordinance personnel who are required to wear heavy bomb suits to protect from flying debris and the impact of an explosion. Many jobs require the use of a chemical resistance suit to protect the skin. This vapor barrier causes evaporative resistance which reduces cooling by evaporation. When wearing turnout gear, a bomb suit, or vapor barrier suit, a cooling garment is one approach to decrease heat strain. This would allow the individual to perform work longer with reduced risk of excessive heat strain.

## LITERATURE REVIEW

Since effective engineering and administrative controls are often not feasible for chemical, physical and biological agents, numerous industries require personal protective equipment (PPE) to protect their workers. Although PPE can protect an individual from dangerous environments, it frequently has high insulating and low moisture permeability properties. Therefore, the use of PPE often introduces or increases the potential of a heat stress hazard. This is especially true when working in hot environments and under a heavy work load. Guidelines have been developed to help employers determine safe working conditions by recommending work-rest cycles based on environmental conditions, degree of worker activity, and the use of PPE.(2) This approach is not always desirable, because it extends the time to complete work, increases the need for more manpower, and can require excessively long rest periods. Additionally, as in the case of an explosive ordinance technician, mission requirements can interfere with taking breaks at the recommended intervals. One approach to this dilemma is to use a personal cooling system. Ideally the cooling system maintains the body’s heat balance or at least extended endurance time by slowing the physiological responses to heat stress. In general there are three types of personal cooling systems: liquid, air, and passive.

### Liquid Cooling Systems

Liquid cooling systems (LCS) operate on the principle of conduction. The cooling potential varies by design and is determined by the heat exchange characteristics of the liquid and by thermal capacity (product of mass flow and specific heat). LCS conduct heat from the skin to cooler liquid contained in tubes sewn throughout fabric garments. The liquid then travels by a powered pump through the garment to a heat sink (usually ice). The style of the garment can be a vest, suit, or shirt which may or may not include a hood. Studies have shown increasing the body surface area covered by the LCS; that is, increasing the area of conduction, increases the heat transfer rate.(3-4) Higher flow rates help to maintain the temperature gradient between the skin and the liquid. Increasing the flow rate assists in maximizing cooling by conduction and the rate of heat transfer.(4) Similarly, the temperature gradient is widened and the cooling potential is increased by lowering the inlet temperature of the liquid.(3-4) Since the amount of heat generated in the body is proportional to the workload, the LCS is likely limited by the rate of heat transfer and the capacity of the heat sink.(4) When the air temperature is higher than the liquid coolant, the coolant can gain heat from the air. This reduces the cooling efficiency of the LCS. Clothing has an insulating effect and can reduce the heat transfer from the environment to the cooling system.(3-4) Although each LCS's design can affect the degree of cooling potential, several studies found LCS significantly lowered physiological responses and heat storage while increasing endurance time.(5, 6) Constable et al. studied the effects of a LCS vest during the resting phase, and found it significantly reduced heat storage, nearly doubled endurance time, and developed a perceived cooling effect for the participants.(5) Cadarette et al. studied a shirt and hood configured LCS. The test took place at moderate metabolic rates, in hot environmental conditions, and during short work and rest periods. The study compared two types of toxicological suits (both similar to a level B HAZMAT suit). The newer type suit weighed 4.5 kg less and used a LCS, the traditional type suits used no cooling. The study found that although the metabolic rate was greater for the newer type suits, the endurance time was twice as long and the physiological responses to heat stress were reduced.(6) Heled et al. also performed a study using a LCS, this time consisting of a vest plus a hood with dry ice as the heat sink. The study compared the effects of the LCS to a passive cooling system (see below). The experimental conditions were in a hot environment with a long work period. The study did not compare the results to a control nor did it mention the work load.(7) Harrison et al., studied continuous cooling from a LCS, but the subjects were in a resting phase and tethered to a stationary cooling system during the entire experiment.(3)

### Air Cooling Systems

Air cooling systems (ACS) operate on the principle of convection and sweat evaporation by using a power source to circulate air under clothing. The circulating air temperature must be lower then the skin temperature for cooling to occur by convection. As the temperature gradient between the skin and air increases, the rate of cooling increases. If the skin is wet, evaporative cooling can also occur. A vortex is often employed to generate cooler air and assist in the cooling. As the inlet temperature of the circulating air lowers, heat transfer improves between the skin and air. This is also true when lowering the water vapor pressure. As the water vapor pressure gradient between the skin and air increases, the rate of evaporation increases leading to enhanced cooling.(4, 8) ACS have been compared to LCS when in a hot environment (50°C, 30% RH) with resting metabolic rates. After four hours, both systems significantly reduced physiological responses to heat stress and both had similar core temperatures.(9) Another study found ACS and passive cooling systems when under moderate temperatures (28°C, 22°C wet bulb) and a high metabolic rate (430 W) provide similar physiological responses which were both significantly better than no-cooling.(10)

**Passive Cooling Systems**

Passive cooling systems (PCS) do not require power. Two PCS designs are the ice vest and water spray suit.

Ice vests are the most common type of PCS and operate on the principle of conduction, by placing a heat sink in direct contact with the body. Body heat is conducted directly to the heat sink (usually water ice). As the surface area between the skin and heat sink increases so does the rate of heat transfer.(11-12, 4) The metabolic rate is inversely proportional to the service time of the heat sink. The quicker the metabolic rate increases and generates heat the quicker the heat sink is spent.(13) Also, the heat sink service time is directly proportional to its heat absorbing capacity.(11-12) The insulating factor of clothing helps to reduce the loss of cooling potential to the environment. This is why many vests are insulated.

Water spray suits operate on the principle of cooling by evaporation. This procedure requires a water evaporative cotton suit to be wetted periodically with water. Unlike the majority of cooling systems, the suit is worn over protective equipment rather then under. The attenuation of heat strain using this method was found to be comparable to the LCS during the first hour of exercise and better during the second hour.(7) It was suggested the evaporative suit was more effective in the second hour because the heat sink may have been exhausted in the LCS.

### Intermittent Versus Continuous Cooling

Highly mobile jobs make cooling through a stationary cooling system connected by a tether impractical. Therefore, many studies were conducted on intermittent cooling during the resting phase only. Portable LCS have increased the potential for continuous cooling. Subjects have shown they are better able to maintain thermal equilibrium with continuous cooling.(8)

### Advantages and Disadvantages of the Different Systems

Each cooling system type has inherent advantages and disadvantages. LCS minimizes the potential for a contamination risk, because they are a closed loop system and are often portable. On the other hand, LCS can weigh more than other cooling systems. ACS will keep users drier and depending on design may reduce facial sweating and eye irritation. Unfortunately, ACS usually do not have a portable unit to cool air and require individuals to connect to a stationary unit during rest. PCS are inexpensive, simple, and easy to maintain. The main disadvantage, in the case of the ice vest, is users must doff any clothing over the PCS to switch out the heat sinks. This could be time consuming, especially if decontamination procedures are required before doffing. The water spray PCS requires access to enough water to take periodic 30 second showers. In addition, clothing worn under the evaporative suit will affect the cooling potential.

### Previous Reports

There are many reports testing the effectiveness of the different cooling systems. Since the effectiveness of a cooling system is influenced by many different variables, it is important to know and understand each when comparing studies. The cooling type must be known, because as discussed above, there are advantages and disadvantages in the application of each type. In addition to knowing the cooling type, the style should be known. This is needed since it helps determine which areas are exposed to the cooling elements. The clothing worn during the experiments can either assist in cooling by reducing the loss of the heat sink potential to the environment or hinder cooling by preventing evaporation. For this reason clothing must be evaluated. Heat sinks can be exhausted quicker by higher metabolic rates; therefore, it is imperative to know the metabolic rate along with the length of the test, and length of the work/rest cycles. Obviously, hot environments will require more cooling; therefore, the environmental conditions should be known. Finally, differences in physiological responses can occur if continuous or intermittent cooling is performed. Although Table 1 is not an exhaustive list of studies, it helps compare the different types of research conducted on cooling systems by summarizing the study, type and style of cooling systems, the clothing worn, if cooling was continuous or intermittent, work load, length of work-rest cycles, total length of test, and environmental conditions. All of the reports in Table 1 found cooling systems can increase endurance time and reduce physiological responses to heat stress.

### Need for Further Research

The primary purpose of this study was to determine the efficacy of the Med-Eng CardioCOOL$^{TM}$ liquid cooling system in a hot environment while wearing different types of PPE and performing long uninterrupted work. A secondary purpose was to compare the physiological responses and endurance time of wearing a LCS and PPE to wearing work clothes only.

Table 1. Reports of Personal Cooling Types and Experimental Conditions

| **Study** | **Clothing** | **Type** | **Style** | **C/I**[a] | **M**[b] | **W/R**[c] | **Time**[d] | **Temp/RH**[e] |
|---|---|---|---|---|---|---|---|---|
| Harrison & Belyavin(3) | Flight suit | LCS | Suit | C | Resting | Rest only | 60-240 | ------------- |
| Speckman et al.(4) | CDE[f] | LCS | Varied | C/I | Varied | Varied | Varied | 29/85 to 52/25 |
| | | ACS | | | | | | |
| Constable et al.(5) | CDE | LCS | Vest | I | 400/475 | 30/30 | 286 | 38/26wb[g]<br>31wbgt[h] |
| Cadarette et al.(6) | Army A+B[i] | LCS | Shirt + hood | C | 222-278 | 20/10 | 120 | 38/30 |
| Heled et al.(7) | CDE | LCS | Vest + hood | C | ---------- | 55/10 | 125 | 35/40 |
| | | PCS-spray | Suit | | | | | |
| Bomalaski et al.(8) | CDE | ACS | Vest | C/I | ---------- | 45/15 | 240 | 28/22wb |
| | | | | | | 30/30 | | 38/26wb |
| Epstein et al. (9) | Coverall, helmet, boots | LCS | Vest/ hood | C | Resting | Rest only | 240 | 50/30 |
| | | ACS | Vest/ hood | | | | | |
| | | PCS | Vest | | | | | |
| Bishop et al.(10) | CDE | LCS | Vest | I | 430 | 45/15 | 240 | 28/22wb<br>26wbgt |
| | | ACS | | | | | | |
| Konz et al.(11) | None/ Jacket | PCS | Vest | C | Resting | Rest only | 100-240 | 43.5/45 or 55 |
| Kamon et al.(12) | Coverall | PCS | Shirt | C | 200-300 | 5/5 | 135 | 55/28 |

a. Intermittent or continuous cooling
b. Metabolic Rate in watts
c. Work/Rest cycle in minutes
d. Time in minutes
e. Temperature in degrees Celsius and relative humidity in percent
f. Air Force chemical defense ensemble
g. Wet bulb temperature in degrees Celsius
h. Wet bulb global temperature in degrees Celsius
i. Level A and B hazardous material suits

# METHODS

Clothing has a large impact on how the body responses to heat stress. Light weight, loose fitting clothing is ideal for cooling by evaporation and conduction, because it permits air to circulate over the skin. On the other hand, PPE often has high insulating and impermeable properties. These properties not only prevent cooling from environmental air, but can increase the humidity and temperature underneath the PPE. As the temperature and humidity increase, the physiological responses to heat stress will also increase. This study implemented a LCS to see how it affected the physiological responses and endurance time. It also compared heat strain responses between wearing work clothes only, and work clothes plus PPE and the LCS.

## Subjects

Five healthy males completed all seven tests in the study. The mean ± standard deviation (SD) age, height, weight, and body surface area were 32.5 ± 9.8 years, 179.6 ± 3.6 cm, 91.2 ± 8.1 kg, and 2.1 ± 0.08 $m^2$, respectively. This research project was approved by the Institutional Review Board of the University of South Florida according to the guidelines of the National Institutes of Health to ensure subject safety. Prior to this experiment each volunteer signed an informed consent and underwent a physical examination by a physician.

## Experimental Conditions

Tests were performed in a controlled environmental chamber with the ambient air temperature of 35°C ± 0.5°C, relative humidity of 50% ± 2%, and a target metabolic rate of 300W.

## Equipment and Materials

The PPE selected for this study not only represents a wide range of industries, but also a wide range of insulating and permeability properties. Listed below is the equipment worn in the experiments.

- Undergarments
    - T-shirt
    - Athletic shorts
    - Men's underwear
    - Men's Athletic socks
    - Athletic Shoes
- Work clothes
    - Undergarments
    - Long sleeve shirt
    - Pants
- Protective Clothing Ensembles
    - Explosive ordnance disposal suit including helmet (Bomb Suits): Med-Eng Systems Canada, model EOD 8, NATO Stock # 8470-21-920-2137
    - Firefighter turnout suit and hat: Morning Pride Manufacturing, model 1430, meets NFPA 1971 (1986 Edition)
    - Vapor barrier suit: Polyethylene-coated Dupont Tychem ® QC coverall with hood
- Cooling System
    - Cooling vest: Med-Eng CardioCOOL$^{TM}$
    - Portable cooling unit: Med-Eng PortaCOOL$^{TM}$

The seven tests performed and the combinations of clothing and cooling condition are listed in Table 2. Undergarments and work clothes were worn for all tests.

Table 2. Types of Test Performed and Cooling Condition

| Protective Clothing | Cooling Garment | Acronym |
|---|---|---|
| Work Clothes | No | WC-NC |
| Vapor Barrier | No | VB-NC |
| Vapor Barrier | Yes | VB-C |
| Firefighter Turnout | No | FF-NC |
| Firefighter Turnout | Yes | FF-C |
| Bomb Suit | No | BS-NC |
| Bomb Suit | Yes | BS-C |

### Experimental Protocol

Participants completed a heat acclimatization protocol prior to performing tests. The heat acclimatization protocol consisted of walking on a treadmill at 2.5 mph at 0% grade while wearing undergarments for 5 consecutive days. This occurred at approximately the same time each day in an environmental chamber set to 50°C and 20% relative humidity. Subjects were allowed to drink water at will. During this protocol, the initial treadmill speed was set to obtain the target 300 W metabolic rate for the experimental tests. As an alternative to acclimatization, one subject performed tests at intervals no more frequent then than every other day. The time lapse was to prevent acclimatizing from the tests and changing the individual's response to heat stress.

The experimental protocol involved seven tests per participant. The first test was WC-NC for four of the five participants. The first test allowed participants to become familiar with the testing protocol without the extra burden of the protective gear. The six remaining tests were performed in random order. Respirators were not worn during the tests, because they would interfere with equipment used to measure metabolic rate.

Each subject was instructed to avoid moderate to high-level exercise 24 hours prior to each test. They were also instructed not to take stimulants or diuretics 12 hours prior to testing or large meals 2-3 hours prior to testing. In addition, they were instructed to maintain normal hydration.

Individuals were weighed semi-nude (undergarments only) before each test. They were then connected to probes to measure rectal core temperature, heart rate, and skin temperature. Eight skin sites specified by ISO 9886 (forehead, right scapula, left upper chest, upper right arm, lower left arm, left hand, right anterior thigh, and left posterior calf) were measured. If the test included the cooling garment, the individual selected the best fit size and donned the vest over the t-shirt. Next the subject put on the work pants and the appropriate protective clothing ensemble. The subjects were able to select the size of the vapor barrier and firefighter turnout gear. If the protocol included the cooling garment, the portable cooling unit (pump and heat sink) was attached over the protective garments. This allowed for easy access during the test. The portable cooling unit's bottle was filled with 1650 – 1800 ml of water and frozen. Just prior to the test, the remaining 2 L volume in the bottle was filled with cool water. The participant was weighed with the cooling garment, cooling unit, and clothing ensemble to obtain the clothed weight.

Next the subject entered the environmental chamber and was connected to the monitoring devices. The heart rate and temperatures were noted. The treadmill was set to obtain the target metabolic rate and the individual began exercising. The heart rate (HR), core temperature ($T_{re}$), and skin temperatures ($T_{sk}$) were recorded every five minutes. The intent was to change the heat sink when the ice completely melted in the bottle. Due to the configuration of the bottle inside the pouch it was difficult to determine when all the ice had melted. In actuality, the heat sinks were always changed with ice remaining in the bottle. The heat sink change occurred while the subject continued to walk. If the HR exceeded 95% of the age predicted maximum or if the $T_{re}$ exceeded 38.5°C before 90 minutes, the exercise phase was terminated. It was also stopped if the subject reported excessive fatigue, faintness, headache, disorientation, or if the subject requested to stop.

The metabolic rate was measured at 15 minutes into the exercise phase and then every 30 minutes thereafter. The subject's metabolic rate was calculated by capturing and measuring the exhaled air over approximately two and a half minutes using the Douglas Bag method.(14)

After the termination of the exercise, there was a 30 minute recovery phase. The recovery phase took place while sitting inside the environmental chamber. The individuals undid zippers, opened the protective suit, and removed protective head gear to assist in cooling. If the test consisted of cooling, the subject continued to wear the LCS during the resting phase. The HR, $T_{re}$, and $T_{sk}$ were still measured and recorded every five minutes. If the HR exceeded 95% of the age predicted value or if the $T_{re}$ rose above 39.0°C, the test was terminated. The metabolic rate was measured midway through the recovery phase. The individual was allowed to drink up to 350 ml of cool water with no ice. Theoretical amount consumed was recorded.

The participant was weighed to get the post-test clothed weight. The subject then doffed the protective gear, work clothes, and probes to obtain the post semi-nude weight.

# RESULTS

Three major factors influence heat stress: environmental conditions, workload, and clothing. In this study, environmental conditions remained constant. This ensured significant changes in physiological responses to heat stress between tests could not be contributed to the environment. In an attempt to control for the workload, the treadmill speed was set for a target 300 W metabolic rate. With similar metabolic rates, differences in physiological responses between tests were not likely a result of the workload. The clothing ensembles were quite different between protocols. The vapor barrier suit had a much higher evaporative resistance, the firefighter turnout suit was more insulating, the 75 lbs bomb suit was heavier, and the work clothes was the least of all these properties. The different properties of the clothing could affect the metabolic rate and in turn the level of heat strain. To compare among clothing types the metabolic rates had to be similar. Therefore knowing the environment, workload, and clothing did not significantly contribute to changes in physiological responses to heat stress, the changes could then be contributed to the use of the cooling garment.

The workload was determined by measuring the metabolic rate(14) and dividing it by the subject's body surface area (MSA). A three way analysis of variance (ANOVA) was performed with cooling condition, clothing type, and subject identification as the three independent variables. An $\alpha = 0.05$ level of significance was selected. The analysis found the MSA was not significantly different when comparing cooling status ($p=0.64$), but significantly different when comparing clothing type ($p=0.002$) and subject ($p<0.001$). A Tukey's hsd analysis was performed for the MSA when looking at clothing type. The analysis found work clothes, the vapor barrier suit, and the firefighter gear to have similar MSA's, but not similar to the bomb suit. Therefore, knowing the environmental conditions did not change and there was no statistically significant change in workload between cooling conditions, any significant difference in the subject's response to heat stress could then be contributed to the cooling unit when comparing similar clothing types (work clothes, vapor barrier suit, and firefighter turnout).

The mean $T_{sk}$ (mean skin temperature) was calculated using the ISO 9886 Standard$^{(15)}$:

$$T_{sk} = 0.7\ T_{forehead} + 0.175\ T_{chest} + 0.05\ T_{hand} + 0.19\ T_{thigh} + 0.175\ T_{scapula} + 0.2\ T_{calf} + 0.07\ T_{arm} + 0.07\ T_{forearm} \qquad (2)$$

Due to malfunction of the skin probes in some trials, data were missing for one site during six tests and two sites during one test. When there were missing data during a no-cooling test, values were assigned to the missing data by taking the sum of the recorded values times the respective weighting factor and dividing the sum by the total of the weighting factors. During tests using the LCS, all of the missing data were in areas not in contact with the LCS. In these cases, values were assigned to the missing data by taking the sum of the recorded values not in contact with the LCS (i.e. excluding the chest and scapula) times the respective weighting factor and dividing the sum by the total of the weighting factors for the no-cooled sites. After values were assigned to the missing data, the $T_{sk}$, using ISO equation was calculated.

The average heat storage (S) in W * $m^{-2}$ for each clothing type and cooling condition was calculated using the formula$^{(16)}$:

$$S = [(m_b * c_d)/A_D] *(\Delta T_b/\Delta t) \quad (3)$$

Where $m_b$ is the mean body weight [kg]; $c_d$ is the specific heat constant 0.965 [W * $h^{-1}$ * $°C^{-1}$ * $kg^{-1}$]; $A_D$ is the DuBois surface area [$m^2$]; $\Delta T_b$ is the change in mean body temperature [°C] where $T_b = 0.2\ T_{sk} + 0.8\ T_{re}$; and $\Delta t$ is the elapsed time [h].

The null hypothesis of this work is that the LCS does not reduce heat strain. It was tested by checking for significant differences in the subjects' endurance time and physiological responses to heat stress when wearing the LCS as compared to no-cooling for each clothing type. The physiological responses evaluated were mean heat storage (S) and mean rate of rise in heart rate (rrHR), core temperature ($rrT_{re}$), and skin temperature ($rrT_{sk}$). The rates of rise in the physiological responses were calculated by measuring the response at the termination of the exercise and subtracting the response recorded after the initial five minutes then dividing the difference by the elapsed time. The physiological responses at five minutes were used to allow a physiological steady state due to work rather than heat stress.

In reviewing the results, a univariate analysis was performed on the data to check for frequency consistency and to identify extreme outliers. The frequencies were as expected and no outliers were identified. Next, the physiological responses and endurance time were checked for interactions of clothing (3 levels: vapor barrier, firefighter, and bomb suit) by cooling (2 levels: No and Yes) using an Analysis of Variance (ANOVA). Work clothes were not included in the interaction analysis, because there was only a no-cooling trial. There were no significant interactions. The lack of significance showed there were no synergistic effects between clothing type and cooling condition.

Once again a three way ANOVA was performed, this time using the work clothes as the control in the clothing types. This analysis was performed to determine if there was a significant difference in the endurance time and physiological responses when looking at the cooling status, clothing type, and subject. The results are listed in Table 3.

Table 3. Results of a 3 Way ANOVA for Cooling, Clothing, and Subject with Respective p-Values

| **Response** | **Cooling** | **Clothing** | **Subject** |
|---|---|---|---|
| rrHR | <0.0001[a] | <0.0001 | 0.0365 |
| $rrT_{re}$ | <0.0001 | <0.0001 | 0.0223 |
| $rrT_{sk}$ | <0.0001 | <0.0001 | 0.0648 |
| S | <0.0001 | <0.0001 | 0.1814 |
| Time | 0.0010 | <0.0001 | 0.1183 |

a. Shaded areas are significant p-values

There were statistically significant differences in the rrHR, $rrT_{re}$, $rrT_{sk}$, and endurance time in the cooling condition and clothing type. From this, it appears using the cooling ensemble affects the rrHR, $rrT_{re}$, $rrT_{sk}$, S, and time.

To further evaluate the significance of these differences, a paired t-test on the a priori comparisons of interest was performed. The paired t-test analyzed each clothing type against cooling condition, checking for significant differences in physiological responses and endurance time. The results are listed in Table 4.

Table 4. Results of an A Priori Paired t-Tests for Each Clothing Type Against Cooling Condition with Respective p-Values

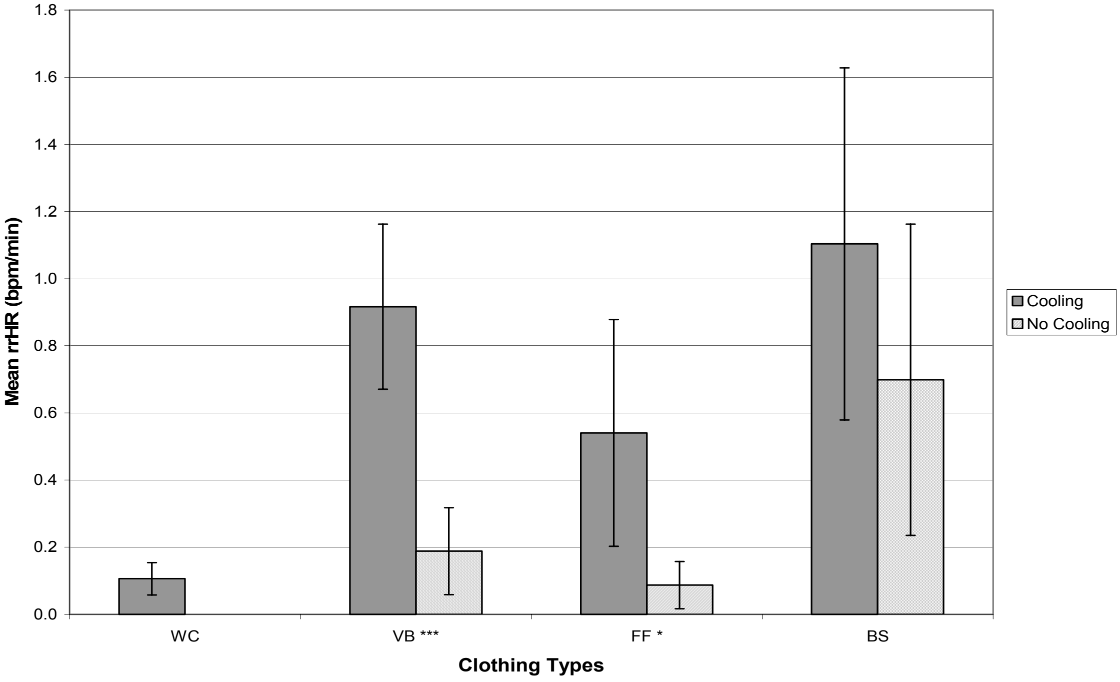
| **Response** | **Vapor Barrier** | **Firefighter** | **Bomb Suit** |
|---|---|---|---|
| rrHR | 0.0005[a] | 0.0458 | 0.2956 |
| $rrT_{re}$ | 0.0051 | 0.0111 | 0.1929 |
| $rrT_{sk}$ | 0.0281 | 0.0135 | 0.0634 |
| S | 0.0142 | 0.0080 | 0.1133 |
| Time | 0.0714 | 0.3739 | 0.0143 |

a. Shaded areas are significant p-values

The results revealed that the cooling ensemble significantly changed the rate of rise of heart rate, core temperature, and skin temperature for the firefighter and vapor barrier suits. It only had a significant impact on the endurance time for the bomb suit. Therefore, the null hypothesis was rejected for the firefighter and vapor barrier suits' physiological responses. The null hypothesis was accepted for the bomb suit's physiological responses, but was rejected for the response time.

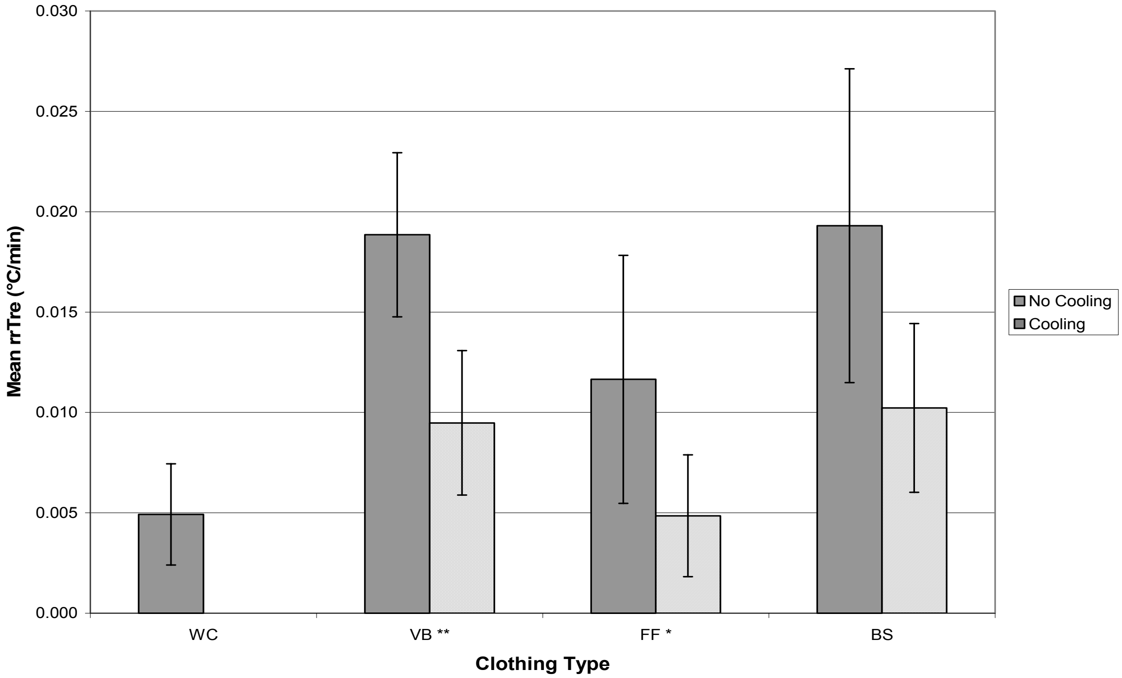
The mean ± one standard deviation were calculated for each of the above physiological response and depicted in Figures 1– 5. The figures show there was a large variation among the subjects for the endurance time and physiological responses while wearing the bomb suit. The large standard deviation among subjects while wearing the bomb suit may have contributed to the lack of significant between cooling statuses.

Figure 1: Mean Rate of Rise in Heart Rate (rrHR) When Comparing Each Clothing Ensemble Without Cooling to Cooling.



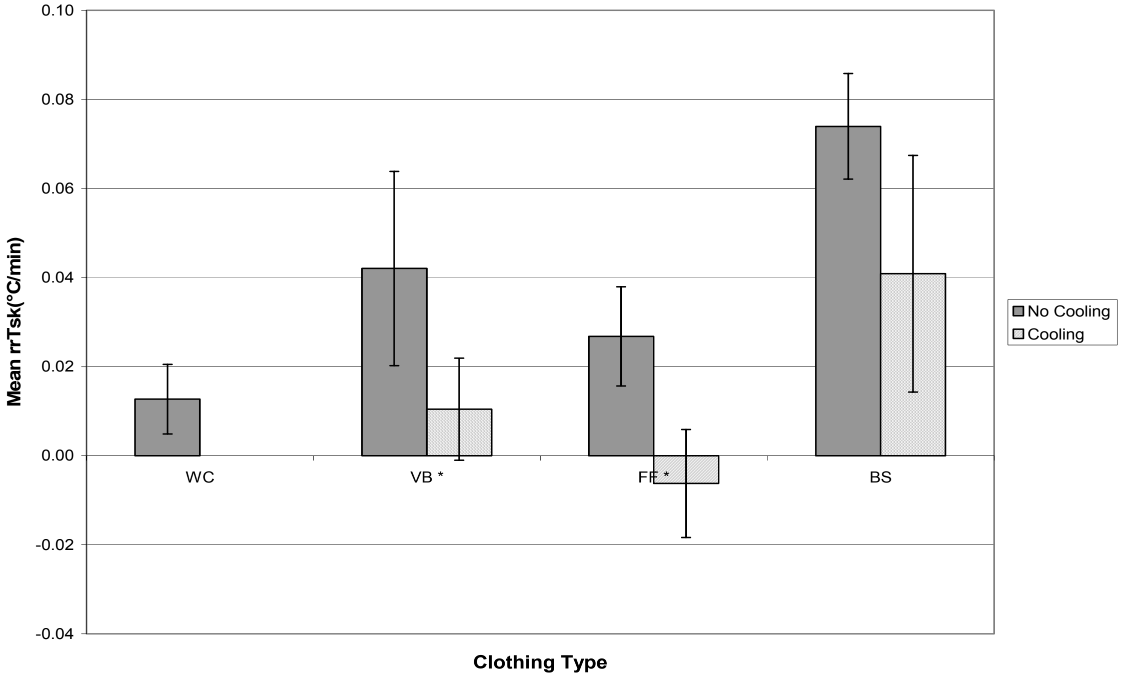
Note: * (0.01 < p < 0.05); ** (0.01 < p < 0.001); *** (p < 0.001)

Figure 2: Mean Rate of Rise in Core Temperature ($rrT_{re}$) When Comparing Each Clothing Ensemble Without Cooling to Cooling.



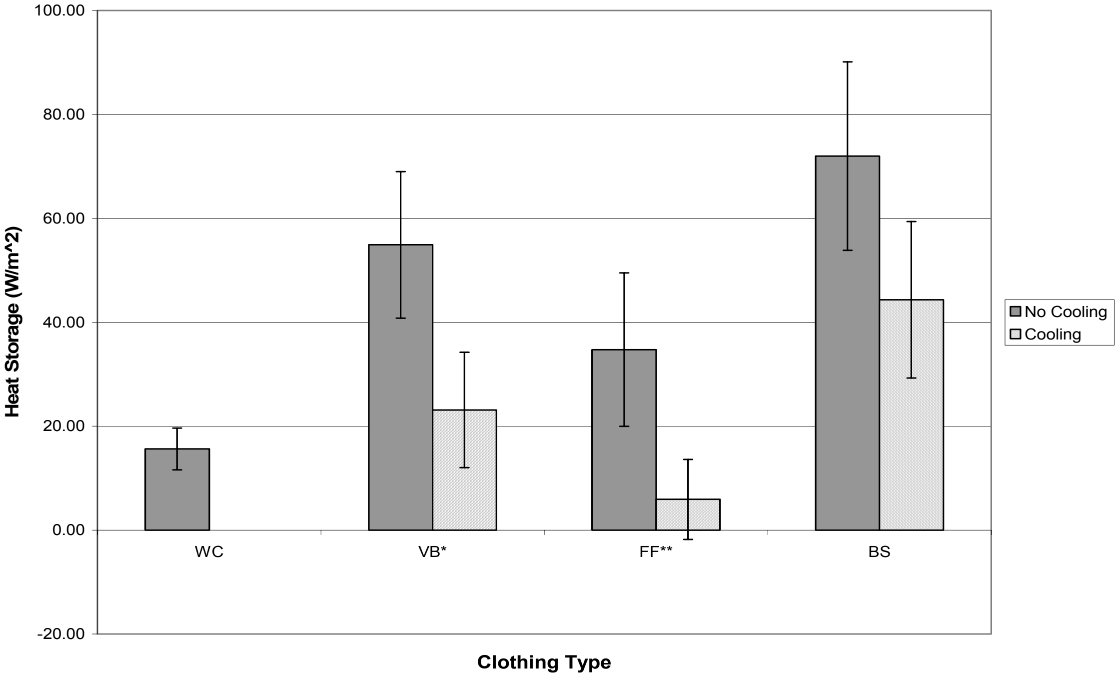
Note: * (0.01 < p < 0.05); ** (0.01 < p < 0.001)

Figure 3: Mean Rate of Rise in Skin Temperature ($rrT_{sk}$) When Comparing Each Clothing Ensemble Without Cooling to Cooling.



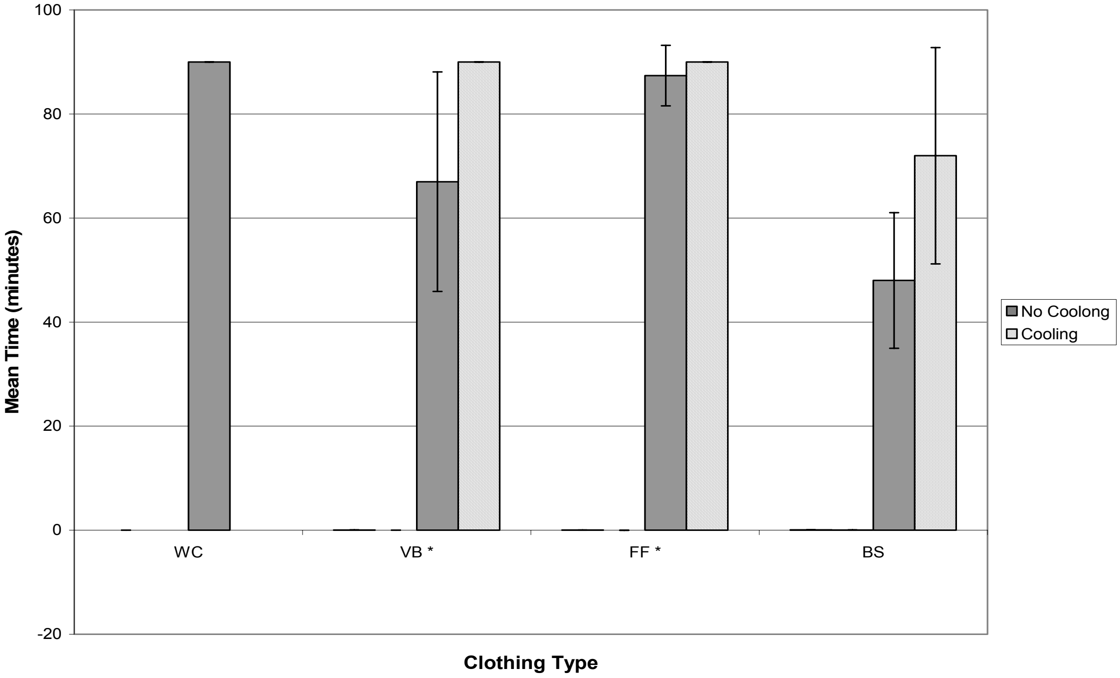
Note: * (0.01 < p < 0.05)

Figure 4: Mean Heat Storage (S) When Comparing Each Clothing Ensemble Without Cooling to Cooling.



Note: * (0.01 < p < 0.05); ** (0.01 < p < 0.001)

Figure 5: Mean Endurance Time When Comparing Each Clothing Ensemble Without Cooling to Cooling.



Note: * (0.01 < p < 0.05)

This study found the portable cooling vest significantly reduced the subjects' heat strain by reducing rrHR, $rrT_{re}$, $rrT_{sk}$, and S for the vapor barrier and firefighter suits and significantly increased the endurance time for the bomb suit.

Next, an interesting comparison was performed between the work clothes and cooling with the firefighter and vapor barrier suits. Since the bomb suit did not have a MSA similar to work clothing it was not included in this evaluation. A paired t-test was used to perform this analysis. The results are listed in Table 5.

Table 5. Results of an A Priori Paired t-Test Comparing Work Clothes to PPE Plus LCS with Respective p-Values

| **Response** | **Work Clothes Versus Vapor Barrier** | **Work Clothes Versus Firefighter** |
|---|---|---|
| rrHR | 0.3190 | 0.7150 |
| $rrT_{re}$ | 0.1222 | 0.9593 |
| $rrT_{sk}$ | 0.5906 | 0.0008[a] |
| S | 0.2782 | 0.0342 |
| Time | NA | NA |

a. Shaded areas are significant p-values

Except for the rate of rise for skin temperature, both the firefighter and vapor barrier suits in conjunction with cooling were similar to wearing work clothing. That is, the worker had approximately the same physiological stress wearing cooling with the firefighter or vapor barrier suits as if they were only wearing work clothes. Also, they could work for about as long.

# DISCUSSION

Engineering and administrative controls are the preferred method to eliminate or reduce occupational hazards. Unfortunately, this isn't always feasible. The age-old hazards of fire and explosion along with the development of OELs and more recently the insurgence of biological agents has created a trend of increasing need for PPE. Traditionally, heat stress may not have been a concern in warm work environments, but the addition of PPE has increased the hazard. The risks of heat stress are of particular concern when working in hot environments with PPE. One approach to combat heat stress is the use of a personal cooling garment.

The main emphasis of this study was to evaluate the cooling performance of the Med-Eng CardioCOOL$^{TM}$ liquid cooling system. This was done by comparing subjects' physiological responses and endurance time to heat stress while wearing various protective clothing, with and without the use of the portable liquid cooling vest. This comparison could be made because there was no significant difference in metabolic rates for each clothing type when comparing cooling to no-cooling. In other words, the work demand was similar between the cooling statuses. The three protective ensembles evaluated were a vapor barrier suit, firefighter turnout gear, and bomb suit.

## Vapor Barrier Suit

This LCS significantly reduced the rrHR, $rrT_{re}$, $rrT_{sk,}$ and S when wearing the vapor barrier suit. This supports previous studies with LCS, where significant reductions in $T_{re}$ were seen when comparing no-cooling to intermittent cooling.(5, 10) These same studies conflicted on the significance of reduction in $T_{sk}$ at the end of the final exercise phase. The conflict in the significance of reduction in $T_{sk}$ likely resulted because cooling only occurred during the resting phases of the previous studies and was performed continuously during this study. Although an alternate method of personal cooling, air cooling supports the importance of continuous cooling in the significant reduction of $T_{sk.}$ during the exercise phase.(8) The significant reduction in rrHR was not supported by previous studies.(5, 10) The metabolic rates in the previous studies were much higher (over 400 W) than the target 300 W used in this study.

In this study, a statistical analysis did not find endurance time was significantly affected by the cooling system. This was to be expected, because the subjects completed the arbitrary 90 minute interval for all of the cooling trials and 2 out of 5 no-cooling trials rather then stopping due to heat strain. Although this study did not find the LCS significantly affected endurance time, LCS have been found to increases endurance time.(5) A longer exercise phase would be needed to determine the impact of this LCS on endurance time.

### Firefighter Turnout Gear

This LCS significantly reduced the rrHR, $rrT_{re}$, $rrT_{sk,}$ and S when wearing the firefighter turnout gear. This supports previous studies with LCS, where significant reductions in $T_{re}$ were seen when comparing no-cooling to intermittent cooling.(5, 10) These same studies conflicted on the significance of reduction in $T_{sk}$ at the end of the final exercise phase. The conflict in the significance of reduction in $T_{sk}$ likely resulted because cooling only occurred during the resting phases of the previous studies and was performed continuously during this study. Additionally in this study, as depicted in Figure 4, the LCS actually had a negative rr$T_{sk}$ for the firefighter suit. This means the mean $T_{sk}$ was actually lower at the end of the exercise phase then in the initial five minutes of the exercise. The reduction in $T_{sk}$ is mostly likely due to the firefighter suit's insulation. The insulation reduced the loss of the heat sink potential to the environment.(3) The negative rr$T_{sk}$ for the firefighter suit contributed to the differences seen between the protocols. The significant reduction in rrHR was not supported by previous studies but the metabolic rates in the previous studies were much higher (over 400 W) than the target 300 W used in this study.(5, 10)

In this study, a statistical analysis did not find endurance time was significantly affected by the cooling system. This was to be expected, because the subjects completed the arbitrary 90 minute interval for all of the cooling trials and all but one no-cooling trial rather then stopping due to heat strain. Although this study did not find the LCS significantly affected endurance time, LCS have been found to increases endurance time.(5) A longer exercise phase would be needed to determine the impact of this LCS on endurance time.

### Bomb Suit

This LCS did not significantly reduce the rrHR, rr$T_{re}$, rr$T_{sk}$, and S when wearing the bomb suit. This was not supported by previous studies with LCS, where significant reductions in $T_{re}$ were seen when comparing no-cooling to intermittent cooling.(5, 10) These same studies conflicted on the significance of reduction in $T_{sk}$ at the end of the final exercise phase. The bomb suit is very different from the types of protective clothing tested in other studies. It weighs 75 lbs and is quite cumbersome. Unfamiliarity of donning and wearing this unique suit added to the subject's metabolic rate. On average the donning time was 15 minutes longer then the other protocols. That along with the heavy weight of the suit likely elevated the subject's physiological response even before starting the exercise phase. The bomb suit increased the metabolic rate such that the LCS alone could not keep the body from experiencing excessive heat strain. The large deviation of each physiological response between subjects may have impacted the significance of physiological responses for this LCS. The lack of significant in reduction of rrHR was supported by previous studies.(5, 10) The metabolic rates in the previous studies were much higher (over 400 W) and were closer to the actual metabolic rate that occurred for the bomb suit.

The endurance time for the bomb suit was significantly affected by the cooling system. This was found with the bomb suit unlike the vapor barrier and firefighter suits, because the burden of the bomb suit prevented subjects from completing the arbitrary 90 minute exercise interval in all trials except two of the cooling trials. Had the exercise phase been longer the significance for increased endurance time might have been stronger. As expected, the LCS has been found to increases endurance time.(5)

## Comparing Work Clothes to PPE with Cooling

Since the mean normalized metabolic rates of the work clothes, vapor barrier and firefighter suits were similar, comparisons could be made between these test protocols. This allowed for an interesting analysis comparing the subjects' physiological responses to heat stress of the VB-C and FF-C to the WC-NC. Endurance time was not evaluated, because subjects completed the 90 minute exercise phase for all of the WC-NC, VB-C, and FF-C trials.

The rrHR, rr$T_{re}$, rr$T_{sk}$, and S were not significantly different when comparing work clothes to the vapor barrier suit while wearing this LCS. These results are quite unlike the results found in a study comparing a carbon impinged chemical protective garment used by the military.(5) That study found HR, $T_{re}$, $T_{sk}$, and S were significantly different when comparing work clothes to the chemical protective garment while wearing a LCS. The previous study's higher metabolic rates and intermittent cooling versus this study's continuous cooling could have caused the conflict in results.

The rrHR, rr$T_{re}$, and S were not significantly different when comparing work clothes to the firefighter turnout gear while wearing this LCS. These results are quite unlike the results found in a study comparing a carbon impinged chemical protective garment used by the military.(5) That study found HR, $T_{re}$, and S were significantly different when comparing work clothes to the chemical protective garment while wearing a LCS. The previous study's higher metabolic rates and intermittent cooling versus this study's continuous cooling could have caused the conflict in results.

This study found the rr$T_{sk}$ was significantly different when comparing the WC-NC to FF-C. The LCS actually had a negative rr$T_{sk}$ for the firefighter suit. This means the mean $T_{sk}$ was actually lower at the end of the exercise phase then in the initial five minutes of the exercise. The reduction in $T_{sk}$ is mostly likely due to the firefighter suit's insulation. The insulation reduced the loss of the heat sink potential to the environment.(3) As expected the reduction in $T_{sk}$ was similar to the previous study.(5)

## Conclusions

In summary, the Med-Eng CardioCOOL$^{TM}$ liquid cooling system effectively reduced subjects' heat strain while in the vapor barrier and firefighter suits. Since each individual can have a different response to heat stress, it is important to reduce heat strain. The cooling system had limited effectiveness in reducing physiological responses with high metabolic rates such as those that occurred with the bomb suit. Although the LCS was not effective in significantly improving the body's heat balance when experiencing high metabolic rates, it did increase endurance time. Increasing the endurance time will aide in lengthening the work phase of a work-rest cycle. Increasing the work phase will reduce manpower needs, production time, and costs. Increasing endurance time is crucial for explosive ordinance technicians as well as other workers who may be unable to take scheduled breaks due to mission requirements.

The study also found the Med-Eng CardioCOOL$^{TM}$ liquid cooling system reduced physiological response to heat stress when wearing vapor barrier and firefighter suits to that if only wearing work clothes. Employers and supervisors can often relate more with the affects of heat stress while in work clothes rather than in PPE. Therefore, being able to make this comparison can help employers more easily gauge workers' heat strain and more appropriately schedule necessary breaks. This in turn could help reduce the number of heat related injuries.

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