A COMPARISON OF ACTIVE AND PASSIVE COOLING METHODS IN FIREFIGHTERS DURING FIREGROUND REHABILITATION FOLLOWING A LIVE BURN TRAINING

by

Deanna Colburn Hostler

B.S., Ohio University, 1996
MPT, Ohio University, 2001
DPT, Temple University, 2011

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This dissertation was presented

by

Deanna Colburn Hostler

It was defended on

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and approved by

Joe Suyama, MD Associate Professor School of Medicine, University of Pittsburgh

Steve Reis, MD, Associate Vice Chancellor School of Medicine,

University of Pittsburgh

Robert Robertson, PhD Professor Emeritus

Health and Physical Activity, University of Pittsburgh

Dissertation Advisor: Fredric L Goss, PhD, Associate Professor

Health and Physical Activity, University of Pittsburgh

A COMPARISON OF ACTIVE AND PASSIVE COOLING METHODS IN FIREFIGHTERS DURING FIREGROUND REHABILITATION FOLLOWING A LIVE BURN TRAINING

Deanna Colburn Hostler, PhD

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Objective We compared two active cooling devices to passive cooling in a moderate (≈22°C) temperature environment on heart rate, core temperature, and perceptions of recovery when applied to firefighters following 20 min. of fire suppression. **Methods** Firefighters (23 male, 2 female) performed 20 minutes of fire suppression at a live fire evolution. Immediately following the evolution, the subjects removed their thermal protective clothing and were randomized to receive forearm immersion (FI), ice water perfused cooling vest (CV), or passive cooling (P) in an air-conditioned medical trailer for 30 minutes. Heart rate and deep gastric temperature were monitored every five minutes during recovery. OMNI rating of perceived exertion, thermal comfort, thermal stress, sweating, and comfort ratings were all reported every five minutes during recovery. **Results** A single 20-minute bout of fire suppression resulted in near maximal HR (175±13 - P,172±20 - FI, 177±12 beats•min^{-1} - CV) when compared to baseline ($p < 0.001$), a rapid and substantial rise in Tc (38.2±0.7 - P, 38.3±0.4 - FI, 38.3±0.3° - CV) compared to baseline ($p < 0.001$), and mass lost from sweating of nearly one kilogram. Cooling rates (°C/min) differed ($p = 0.036$) by device with FI (0.05±0.04) providing higher rates than P (0.03±0.02) or CV (0.03±0.04) although differences over 30 minutes were small and recovery of body temperature was incomplete in all groups. There were no differences in perceptual ratings by cooling method, but there were significant effects based on time ($p=0.0$). **Conclusions** During 30

min. of recovery following a 20-minute bout of fire suppression in a training academy setting, there is a slightly higher cooling rate for FI and no apparent benefit to CV when compared to P cooling in a moderate temperature environment.

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PREFACE

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1.0 INTRODUCTION AND RATIONALE

Work in hot environments is common for firefighters and other public safety personnel. Specialized thermal protective clothing (TPC) and self-contained breathing apparatus (SCBA) are required for safety. TPC changes the microclimate for the worker insulating them from the external environment but reducing the capacity for normal thermoregulation (McLellan & Selkirk, 2006; Richmond VL, 2008). There is a growing body of work evaluating the effect of prolonged exposure to heat and subsequent rise in core temperature on the ability to perform tasks and the adverse health effects to individuals who repeatedly work under these conditions (McLellan & Selkirk, 2006; D. L. Smith, Manning, & Petruzzello, 2001). Currently there are no set safety standards based on physiologic data while working in TPC. Firefighters perform work in TPC that often results in maximal heart rates and dangerously high core temperatures requiring a rehabilitation period (McLellan & Selkirk, 2004). Rehabilitation at a fire scene includes rest, removal of TPC, rehydration, and may include active cooling techniques. Rapid return to resting core temperature and heart rate is the goal of rehabilitation and multiple devices have been developed in an attempt to accelerate a return to baseline core temperature. The purpose of this study will be to compare the effectiveness of three rehabilitation protocols involving commercially available cooling devices and rest in a controlled environment of moderate temperature and humidity following a live burn training session to determine which method is most effective in reducing the post-evolution elevated core temperature and heart rate.

Perceptual variables including thermal sensation, thermal comfort, sweating and perceived exertion will also be examined during rehabilitation.

1.1 RATIONALE

During prolonged work or exercise, endogenous heat production results in an increase in core temperature. In normal environmental conditions the body dissipates heat to the surrounding environment in an attempt to maintain core temperature within normal limits. In a hot, humid environment (>36° C) this is not possible, as the body will gain heat via radiation and convection and is unable to compensate with evaporative heat loss (Wendt, Van Loon, & Lichtenbelt, 2007). Thermoregulation is impaired by TPC and heat loss from evaporation, convection, radiation, and conduction is reduced or eliminated. When the body cannot effectively dissipate heat due to the characteristics of TPC or environmental conditions, hyperthermia may occur. This physiologic outcome has negative acute and possibly chronic effects in firefighters as demonstrated by statistically higher than normal cardiovascular disease (Holder, Stallings, Peeples, Burress, & Kales, 2006; Kales, Soteriades, Christophi, & Christiani, 2007).

The majority of time working as a firefighter includes maintenance and cleaning of equipment and quarters at the firehouse but they must always be prepared to answer emergency calls. The amount and types of calls for assistance can vary greatly among departments based on the area covered by the department and population. Firefighters respond to calls for fire emergencies, EMS first responder, automobile accidents, and hazardous material spills. They are required to don TPC for all non-medical emergency calls due to the protective nature of the ensemble. Work at an active fire scene can last for hours in high heat conditions with intermittent periods of intense aerobic work. This includes fire suppression, searching a structure for victims, ventilation, and overhaul, which consists of pulling down ceilings and walls to ensure the fire is extinguished. This type of effort requires frequent periods of rest and rehabilitation in order to safely continue working.

It has been hypothesized that active rehabilitation at fire scenes will reduce heart rate, respiratory rate, blood pressure, and core temperature at a faster rate than passive cooling consisting of only rest, TPC removal, and hydration. Active rehabilitation includes a variety of strategies that are designed to accelerate a return to a normal core temperature, resting heart rate and respiration rate. Subjects may return to a resting physiological state in a shorter time when using active cooling methods like fans, body submersion in cool water, or a cooling vest than under passive cooling conditions (Bennett, Hagan, Huey, Minson, & Cain, 1995; Carter JM, 2007; Giesbrecht, Jamieson, & Cahill, 2007). However, there is no consensus on the most effective method of active cooling rehabilitation to produce cooling, rehydration, or safe return to work at active fire scenes.

In addition to the acute effects of working in a high-risk profession that places firefighters at risk for trauma, burns, and asphyxiation, firefighters may suffer from chronic health problems. The majority of firefighter deaths are from cardiovascular disease (Kales, et al., 2007). Coronary heart disease is the cause of 45% of on-duty deaths in the fire department and the odds of cardiac related death are much higher during fire suppression (Angerer, Kadlez-Gebhardt, Delius, Raluca, & Nowak, 2008; Kales SN, 2003). Firefighters are exposed to unusual cardiovascular stress from intermittent high intensity physical exertion and environmental hazards like smoke and heat (Holder, et al., 2006; Kales, et al., 2007). Effective and efficient rehabilitation at a fire scene may reduce cardiovascular strain thereby reducing acute incidents of myocardial infarction and cardiac arrest.

This study will compare two commercially available active cooling methods to a passive cooling method in moderate environmental conditions. Moderate conditions include ambient temperature less than 35° C and low humidity (Wendt, et al., 2007). Firefighters will participate in a live fire evolution followed by a 30- minute rehabilitation period. A laboratory based study of active and passive cooling in a 24°C, moderate humidity environment found that active cooling methods did not reduce core temperature or heart rate of firefighters after working in a hot environment faster than passive cooling (Hostler, Reis, Bednez, Kerin, & Suyama, 2010). However, active and passive cooling strategies have not been adequately examined in a live burn field study after fire suppression. Therefore the results of the present investigation may have practical application in designing rehabilitation interventions that promote a rapid recovery allowing a safer return to work for firefighters.

1.2 PURPOSE

The purpose of this study is to compare the effectiveness of three cooling methods (cooling vest, seated arm immersion in cool water, and passive sitting) administered in a controlled fire scene environment to reduce heat stress in firefighters following fire suppression. This study will gather data at a live fire training performed by firefighters who will then participate in one of three rehabilitation protocols. These recovery protocols will use methods and equipment that are practical to use at an actual fire scene.

1.3 SPECIFIC AIMS

This investigation is a randomized controlled trial that will use a live fire training session to produce the physiologic responses typical for firefighters engaged in structural fire suppression. Three methods of cooling (cooling vest, seated arm immersion, and passive sitting) to promote recovery of core temperature and resting heart rate will be evaluated.

1. Measure core temperature, heart rate, blood pressure and subjective measures including rating of perceived exertion (RPE), sweating sensation, thermal sensation, and thermal comfort during rehabilitation following fire suppression.

2. Determine if either core temperature recovery or heart rate recovery is differentially affected by the cooling method.

3. Determine if rating of perceived exertion, sweating sensation, thermal sensation, or thermal comfort is differentially affected by the cooling method.

1.4 SIGNIFICANCE

The adoption of rehabilitation at fire scenes is relatively recent. Multiple effective methods to return to a resting physiologic state have been identified for hot weather conditions but little is known about moderate environmental conditions (McLellan & Selkirk, 2006; Selkirk, McLellan, & Wong, 2004). Given the financial, logistic, and workforce costs associated with deploying active cooling devices it is important to determine if the benefits seen in hot (35 C°/95 F°) are realized at more moderate temperatures (Selkirk & McLellan, 2004). An evaluation of cooling methods during rehabilitation will allow recommendations to be made to fire departments to promote recovery of firefighters during work.

2.0 REVIEW OF LITERATURE

2.1 THERMOREGULATION AND HOMEOSTASIS

Humans need to maintain temperature homeostasis within a narrow margin for optimal safety and function. The body can employ multiple mechanisms to maintain temperature while interacting with the environment. During physical activity metabolic processes produce heat, and excess heat must be dissipated into the surroundings. If heat cannot be completely dissipated there will be a rise in core temperature. A hot external environment or insulating clothing impedes thermoregulation resulting in hyperthermia and can lead to cessation of work, heat illness, or death.

Heat loss is accomplished in humans by transporting heat from the core to skin to be dissipated into the environment. The three most important methods of heat loss from skin to the surrounding environment under normal circumstances are convection, radiation, and evaporation (Havenith, 1999). Convective heat loss occurs as air cooler than skin moves across the skin, transferring heat to the air. Heat loss via radiation occurs when the body is warmer than the environment. Evaporative cooling occurs as humans sweat and moisture evaporates off the body.

Sweating is a very effective method for heat loss in humans and is the most important, especially under hot conditions (Havenith, 1999). Conductive heat loss occurs when the body is directly in contact with a cooler surface allowing heat to exchange; however this is negligible in a person wearing insulating clothing in a standing position (Havenith, 1999). Respiration also contributes to heat loss as inspired air is usually cooler and less humid than air inside the lungs. The body will heat and moisten inspired air; this transfer of heat can produce up to 10% of heat loss (Havenith, 1999).

Heat storage in humans can be described by the equation: Metabolism ± Radiation ± Conduction ± Convection – Evaporation = Heat storage (Wendt, et al., 2007). All of these variables except evaporation can either add or remove heat from the body. There are multiple mechanisms for temperature regulation in humans. There are centrally located thermodetectors, mainly in the hypothalamus, that monitor blood temperature in the brain and detect changes in core temperature (Gisolfi & Wenger, 1984; Wendt, et al., 2007). Humans have a set point around 37° C and will initiate mechanisms to produce or lose heat when there are abnormal deviations from this set temperature.

When the body is overheated, skin blood flow (SkBF) is increased to help dissipate heat. Vasodilatation will increase SkBF to allow blood to cool via radiation, conduction and convection. This cooler blood returns centrally reducing core temperature (Gisolfi & Wenger, 1984). Sweating is the other main process to decrease temperature when temperature reaches a critical threshold. Eccrine sweat glands are activated causing sweat to be excreted onto the skin where evaporation will allow cooling of the skin. Peripheral blood will then be cooled by the cooler skin and returned centrally reducing overall core temperature (Wendt, et al., 2007).

In order to maintain core temperature homeostasis humans mainly rely on convection, radiation, and evaporation for heat loss and metabolic activity for heat production. In normal resting conditions core temperature is 37° to 37.5 C° (Havenith, 1999). Heat loss at rest in moderate temperature and humidity conditions (50%) consists of 20% evaporation, 25% conduction, 45% radiation and 10% respiration (Rossi, 2003). If the ambient temperature exceeds 35 C° then evaporation is the primary method used to cool the body as humans will gain heat via radiation and convection (Rossi, 2003; Wendt, et al., 2007). When environmental conditions drastically reduce or eliminate the body's normal cooling strategies core temperature raises until it reaches a level that may force the individual to stop work or result in heat related illness. Even when humans perform work in moderate heat and humidity their core temperature will rise (Richmond VL, 2008; Rossi, 2003). As firefighters are exposed to hot environments while doing heavy work a rise in core temperature is inevitable. This is further impacted when protective clothing adversely affects normal mechanisms of heat loss. In addition, TPC is heavy and the extra weight increases the metabolic load of any activity. It is also insulating and has poor vapor permeability, restricting heat loss.

2.2 HEAT STRESS AND STRAIN

Increased core temperature results in increased stress on the cardiovascular system during activity. There are multiple factors contributing to this stress (Crandall & Gonzalez-Alonso, 2010). Tachycardia produced by hyperthermia will reduce stroke volume in exercising humans (Crandall & Gonzalez-Alonso, 2010). Increased core temperature results in an increased SkBF for temperature regulation and activity requires increased blood flow to working muscle and the myocardium (Crandall & Gonzalez-Alonso, 2010). Vasodilatation in conjunction with increased SkBF will cause blood pooling in the periphery and reduce blood volume available for cardiac filling. (Gisolfi & Wenger, 1984). Total blood volume limits the amount of circulation available for both muscle and skin simultaneously. Peripheral vasodilatation typically will increase with core temperature increase during exercise. This effect is limited with SkBF not continuing to increase at around a core temperature of 38°C (Crandall & Gonzalez-Alonso, 2010; Nose, Mack, Shi, Morimoto, & Nadel, 1990). This is possibly due to cardiopulmonary mechanoreceptors responding to decreased central venous pressure (Nose, et al., 1990).

Dehydration during aerobic activity is also a concern in hot environments. As humans loose around 2% of body mass before they are stimulated to drink, and may not tolerate drinking the total volume lost dehydration frequently accompanies activity in heat (Selkirk, McLellan, & Wong, 2006; Wendt, et al., 2007). Dehydration during activity will reduce SkBF and blood flow to muscle (Crandall & Gonzalez-Alonso, 2010). Stroke volume decreases with dehydration and heart rate does not fully compensate for this decrease resulting in a reduced cardiac output (Crandall & Gonzalez-Alonso, 2010). These factors all contribute to exhaustion and limit work.

At a core temperature of around 38.7° humans predictably become unable to continue activity because of fatigue with 40° C as a typical maximum before voluntary cessation of activity (Cheung & Sleivert, 2004; Gonzalez-Alonso, 2007). There are multiple triggers for cessation of activity due to heat stress. Increased heat promotes muscle fatigue and decreased strength of contraction by impairment of acute neuromuscular function (Cheung & Sleivert, 2004).

An elevated core temperature at around 40° C and above produces heat stroke in humans (Wendt, et al., 2007). These core temperatures can cause severe problems including confusion and loss of consciousness. In extreme cases hyperthermia can cause an increase in gastrointestinal permeability leading to leakage of bacteria producing sepsis (Broessner, et al., 2005) . Hyperthermia can also lead to multiple organ dysfunction or failure requiring emergent medical attention (Broessner, et al., 2005).

Fire protective equipment reduces environmental heat loss as it forms an insulative barrier around the body that is impermeable to water (McLellan & Selkirk, 2006). This limits evaporation, radiation, and convection as heat loss methods. The hot external environment present at a live fire also promotes an increase in core temperature through radiated heat and convection. It also prevents heat loss through these methods and the TPC prevents evaporative heat loss via sweating due to its low vapor permeability. This combination of environment and clothing produces uncompensatable heat stress in firefighters, increasing risk for developing heat related illness (Cheung & Sleivert, 2004).

2.3 CORE TEMPERATURE AND MEASUREMENT

Heat stress in humans is diagnosed by clinical signs and symptoms including core temperature. Accurate measurement of core temperature is necessary for safety when exercising or working in hot environments. The National Athletic Trainers Association recommends use of rectal temperature for determining exertional heat stroke (Binkley HM, 2002). Other methods of temperature monitoring have been evaluated for use during prolonged activity. In one study subjects had core temperatures measured at 60, 120, and 180 minutes during outdoor sports activities (Casa, et al., 2007). This investigation compared the use of rectal, oral, axillary, temporal, aural and gastrointestinal temperature with various thermistors to determine core temperature. Gastrointestinal temperature was measured with an ingested thermistor and was the only method that accurately measured core temperature when compared to rectal temperature (Casa, et al., 2007). A similar study performed in a controlled laboratory environmental chamber also found that the ingested thermistor was the only accurate temperature when compared to rectal temperature (Gagnon, Lemire, Jay, & Kenny, 2010; Ganio, et al., 2009). The ingested thermistor has the advantage of being able to record temperature while fully clothed in TPC and other situations when need for temperature monitoring is known in advance but obtaining a rectal temperature is not practical.

Another investigation required subjects exercise to achieve hyperthermia (39.5°C) while measuring aural, rectal and esophageal temperature and then undergo a cooling scenario. Aural temperature was lower than esophageal throughout the exercise and cooling. Rectal temperature increased and decreased at a slower rate than esophageal temperature. This was attributed to the large amount of dense tissue in the pelvis and decreased blood flow to this area when compared to the esophagus (Gagnon, et al., 2010). They concluded that among these three methods of temperature measurement rectal was the most reliable measure of core temperature that can be taken during emergency situations (Gagnon, et al., 2010).

2.4 THERMAL PROTECTIVE CLOTHING

According to the National Fire Protection Association (NFPA) regulations firefighters must wear specific thermal protective clothing when working at active fire scenes. This includes boots, gloves, coat, pants, helmet, and self-contained breathing apparatus (SCBA) that add to work performed by adding weight. The ensemble also adds a layer of insulation to decrease the chance of burn injuries but decreases vapor permeability so that evaporation, radiation and convection are severely restricted (Rossi, 2003).

Multiple studies have demonstrated that work while wearing TPC will lead to higher cardiovascular stress and core temperature (Baker, Grice, Roby, & Matthews, 2000; McLellan & Selkirk, 2006; Richmond VL, 2008; D. L. Smith, et al., 2001). The effects of wearing TPC during activity have been studied under a variety of environmental conditions. In trials that simulate search and rescue duties in moderate temperature and humidity (27°C, 50%) where firefighters were not exposed to live fire situations the burden of TPC and carrying equipment causes on average a rise in core temperature greater than 39 C° (Richmond VL, 2008). Treadmill walking while wearing TPC causes a significantly greater increase in heart rate and VO_2

requirements at moderate work levels than if only shorts and t-shirt are worn demonstrating the increased cardiovascular load caused by TPC (Baker, et al., 2000).

TPC is required and necessary to prevent burns and trauma during firefighting activities. Changing its qualities to promote heat loss and still protect the wearer is difficult. As a result changing the uniform underneath TPC has been investigated. The standard firefighter's uniform includes long pants, and long sleeve shirt in winter with short sleeve shirts and long pants in summer. When this is modified to short sleeves and shorts treadmill walking time is prolonged under light and very light intensity work conditions of walking at 4.5 Km/hr and 2.5 Km/hr with no elevation, respectively (McLellan & Selkirk, 2004). This alternative ensemble worn under TPC extended exposure time by 10-15% (McLellan & Selkirk, 2004). This type of activity would apply to firefighters responding to automobile accidents where they would be required to wear protective gear, but most of the work is not strenuous. Wearing TPC coat and pants with long pants and short sleeve shirt underneath results in more physiologic strain when compared to wearing shorts and short sleeves, resulting in decreased ability to tolerate work at a high aerobic intensity. Firefighters wearing TPC and walking on a treadmill at a workload equal to 50% of VO_2 max extended their exercise time when wearing uniform shorts instead of pants (Malley, et al., 1999). Allowing shorts to be worn as part of the standard uniform may increase work tolerance while wearing TPC at both low and high levels of activity.

2.5 WORK IN FIRE SUPRESSION

There have been multiple investigations that demonstrate that firefighters experience an increased core temperature while performing fire suppression activity (McLellan & Selkirk, 2004; Richmond VL, 2008; Rossi, 2003). Most of these interventions have been performed in laboratory settings but there are some data from live fire training sessions (Rossi, 2003; D. L. Smith, et al., 2001). In measurements taken inside a live fire training building the temperature ranged from 50°C to 278°C and temperature and humidity inside subject's TPC were 48°C and100%, respectively (Rossi, 2003). At these environmental temperatures the human body will absorb, not dissipate heat. Core temperature after 15 minutes of firefighting has been found to increase .6° to 1° C (Rossi, 2003). Search and rescue exercises performed wearing TPC and SCBA in 27°C produced a core temperature increase rate of 0.047°C/min. This resulted in ending core temperature of 38.6° to 39.1°C depending on the scenario performed (Richmond VL, 2008). These temperature increases must be counteracted with rehabilitation in order for firefighters to safely return to work. However, core temperature is typically not monitored in firefighters performing fire suppression and there no safety recommendation for core temperature levels specific to firefighting.

There are also multiple studies that have investigated methods to alleviate hyperthermia including length of rest after heat exposure, clothing, active cooling methods, and hydration strategies. There is no agreement on the most effective way to reduce the heat load during recovery as each study examined work under different temperature and humidity conditions and utilized different cooling methods. The various methods of rehabilitation strategies are most commonly studied under laboratory conditions and may not be easily applicable to field work. A summary of these studies is presented in Table 8.

2.6 REHABILITATION

Rehabilitation is required at fire scenes by the NFPA but there is little guidance for what rehabilitation should include. The NFPA recommends firefighters use a maximum of two air cylinders before undergoing rehabilitation (about 50 minutes). This rehabilitation generally includes a rest period of about 20 minutes and the opportunity to drink fluids for hydration and nutrition. An exchange of air cylinders will occur, and a medical officer should evaluate heart rate and blood pressure before the firefighter returns to work. Rehabilitation may also involve active cooling methods designed to reduce core temperature rapidly. The importance of rehabilitation or recovery for safety and improved performance is recognized in athletics, (Wendt, Clements McDermott, Binkley) and as firefighting duties commonly produce maximal HR and effort, similar recovery standards are appropriate (Binkley HM, 2002; Clements, et al., 2002; McDermott, et al., 2009; Wendt, et al., 2007). Recommendations include providing rest breaks, hydration, ice for cooling and a method to measure core temperature (Binkley HM, 2002).

2.7 HYDRATION

Hydration status during work affects performance in both exercise and fire suppression. Hypohydration is a potential side effect of work or exercise in hot environments that is detrimental to cardiovascular performance. Aerobic work capacity is reduced following only 1-2 % loss of total water (Wendt, et al., 2007). Water loss through sweating reduces blood plasma volume. This volume loss results in increased blood viscosity and tachycardia is necessary to compensate for falling stroke volume in order to maintain cardiac output. Excessive fluid loss may eventually contribute to reduced or stopped work. Dehydration may also lead to hyperthermia and heat illness. Maintaining adequate hydration status is necessary to safely continue physical activity.

Various levels of fluid intake during treadmill walking while wearing TPC have been investigated. Subjects wearing TPC walked on a treadmill at 4.5 Km/h for 20 minutes then had a 10 minute "bottle change simulation" in a room at 35° C, 50% humidity. A second walking stage was followed by 30 minutes of rest. When drinking 15°C water equal to the volume lost via sweat is attempted subjects are unable to tolerate this high amount of liquid (Selkirk, et al., 2006). Replacing at least 65% of fluid lost during exercise enabled the subject to continue work for 15% longer compared to no fluid (Selkirk, et al., 2006). Also there is a greater rise in core temperature and heart rate when no fluids are consumed during work when compared to any of the fluid replacement conditions (Selkirk, et al., 2006).

Hydration is encouraged during rehabilitation, but there is not a standard test to ensure euhydration of firefighters. Hydration is necessary to maintain function and thermoregulation during physical activity. Studies have shown .5 L or greater of water loss when wearing TPC during treadmill walking at 4.5 km/hr at 2.5% grade for 20 minutes followed by a short rest then 20 more minutes of walking (Hostler, Bednez, et al., 2010). This demonstrates the need for fluid consumption at the fireground. Fluids are normally provided *ad libitum* at fire rehabilitation but there is not a requirement to drink and no recommended amount to consume. The type of rehydration fluid (i.e. water, sports drink, or IV fluid at 37°C) does not affect performance (Hostler, Bednez, et al., 2010). Replacing fluid lost by sweating did not necessarily increase work time (Hostler, Bednez, et al., 2010) but fluid replacement (15°C water) during work in TPC has been found to attenuate the increase in core temperature (Selkirk, et al., 2006).

2.8 PERCEPTUAL MEASURES

Perceptual measures of exertion and thermal sensation have been compared to physiologic strain in subjects working in chemical and fire protective ensembles (Hostler, Gallagher, et al., 2009; D. L. Smith, et al., 2001). Commonly used rating of perceived exertion (RPE) scales include the Borg or OMNI. The OMNI scale has been validated for use in graded treadmill exercise, which is a modality frequently used in laboratory investigations of firefighting work (Utter, et al., 2004).

Scales have been developed for thermal sensation including the Bedford Thermal scale and Gagge scale. Visual analog scales are recommended for thermal perception, which allows for more sensitivity to change in thermal perception (Leon, Koscheyev, & Stone, 2008). Overall, subject perception of thermal sensation has not been found to be accurate at extreme external temperatures (Leon, et al., 2008). Therefore thermal perceptions while working in a live fire environment may not be an accurate representation of thermal stress.

Sweating sensation has also been measured with a 3-point scale during activity (Hostler, Reis, et al., 2010). In warm environments or during exercise, thermal discomfort is positively correlated to sweating (Fukazawa & Havenith, 2009). An index to measure the overall level of wetness on the skin (w) was developed by Gagge (Fukazawa & Havenith, 2009). Level of moisture on the skin is known as an index (w) and is defined as $w = (q_{sw}/q_{emax}) + 0.06$ when q_{sw} is heat flux from the body due to sweating and q_{emax} is the maximal evaporative heat flux. Skin wetness in different locations affects ratings of thermal comfort differently (Fukazawa & Havenith, 2009). For example wetness on arms and thighs produces ratings of discomfort at a lower threshold that trunk wetness. However if the total body wetness (w) remains below .36 w then thermal comfort levels can be maintained even if some areas of the body have increased levels of wetness (Fukazawa & Havenith, 2009).

Perceptual levels of heat strain (PeSI) have been quantified using the equation

$$PeSI = 5(TS_t - 0) * (8)^{-1} + 5(RPE_t) * (20)^{-1}$$

where TS is thermal sensation and RPE is measured using the Borg Scale ((Tikuisis, McLellan, & Selkirk, 2002). A modified method of measuring PeSI was developed and compared to physiologic strain (PhSI) using data from one laboratory and one field study which both provided measures of HR, rectal temperature, RPE, and thermal sensation (D. L. Smith, et al., 2001). The laboratory study resulted in increased PeSI and PhSI during treadmill walking wearing different configurations of TPC with the highest levels of strain recorded with the most protective TPC. The PeSI was consistently lower than PhSI during the laboratory exercise studies. There was a strong positive correlation between PeSI and PhSI during the field study performed at live fire training with significant increases in both measures (D. L. Smith, et al., 2001).

Measures of PeSI and PhSI have also been compared in subjects performing treadmill exercise (4.8 km/hr, 5% grade carrying 8.1kg bar) while wearing chemical resistant personal protective equipment (Hostler, Gallagher, et al., 2009). The subjects were either euhydrated or hyperhydrated and PhSI did not differ between groups, but PeSI was higher during exercise in the euhydrated group (Hostler, Gallagher, et al., 2009).

Scales for RPE, thermal sensation and skin wetness have been used during a wide variety of activities. However there has been less research on scaling metrics during recovery. Swank reports that changes in VO_2, HR and RPE were not strongly related during recovery. These findings may be related to directions given on use of the scales as these are usually used for describing sensation during activity.

2.9 PASSIVE COOLING METHODS

Passive cooling methods imply that no special measures or devices are used to promote a return to a baseline heart rate, core temperature, or respiratory rate. In a firefighter work setting this typically would include rest, hydration, and removal of outer garments (TPC).

Rest periods are normally used in both athletic events and occupational settings to maintain performance and prevent injury especially under conditions of high temperature and humidity (Binkley HM, 2002). Rest periods should take place in areas of moderate temperature and humidity to allow for the rapid return to a resting temperature, heart rate, and respiratory rate. However, when recovery periods occur in hot environments with no enhanced means of cooling the normalization of core temperature or heart rate cannot occur, causing a continuous increase in core temperature even if there is a decrease in heart rate (J. B. Carter, Banister, & Morrison, 1999; Malley, et al., 1999; Selkirk, et al., 2004).

As a part of passive cooling, removal of TPC eliminates the insulated air and humidity trapped inside the clothing. This allows a more normal thermoregulatory interaction with the surrounding environment. Evaporative, convective, and radiant cooling can occur and unless the ambient temperature and humidity are high the body will lose heat to the surroundings. Over time heart rate and core temperature will decrease allowing the individual to return to work (Hostler, Reis, et al., 2010). Passive cooling in moderate temperature and humidity conditions is more effective than in high temperatures (Carter JM, 2007; Selkirk, et al., 2004; Y. Zhang, Bishop, Casaru, & Davis, 2009). Increased temperature and humidity reduces potential heat loss from the body resulting in continued elevated core temperature.

2.10 ACTIVE COOLING METHODS

In addition to clothing variants and rest periods active methods of cooling have also been utilized to alleviate hyperthermia. Total body immersion in ice water has been found to be the most effective method of reducing core temperature (McDermott, et al., 2009; J. E. Smith, 2005) but is not practical at an active fire scene or during typical firefighting activities. Therefore there have been investigations on the use of various cooling methods that include fans, partial submersion in cool water, cooling vests and other commercial devices (Bennett, et al., 1995; Selkirk, et al., 2004).

There are multiple cooling devices that are marketed to fire departments. A few include the Cool Shirt 2010 Shafer Enterprises, LLC. 170 Andrew Drive, Stockbridge, GA 30281 a water -cooled vest to cool firefighters during rehabilitation. GelCool packs by GelCool Systems © 2006-2010 are frozen packs to be worn on the head inside the helmet to promote cooling. Fans like Cool Draft (3829 Noble Street Bellaire, OH, 43906) are also marketed towards firefighter rehab. The limited research that has been conducted on these devices has primarily been completed in a laboratory setting; therefore ecological validation of these devised has not been established.

Forearm and hand immersion in cool water has been used in a laboratory setting as it is easy to remove the fire coat and expose the arms. As an extremity is cooled the blood perfusing it will decrease in temperature and as this cooler blood returns centrally it produces a decrease in core temperature (McDermott, et al., 2009). One concern about cold-water immersion is that regional vasoconstriction may result in reducing the cooling effect as there would be less blood flow through the immersed limb. This peripheral hemodynamic response has generally not been found to have a negative impact on hyperthermic subjects (Clements, et al., 2002; McDermott, et al., 2009). While vasoconstriction and shivering are responses to cold water immersion in normothermic individuals they do not affect hyperthermic individuals (core temperature > 38.5° C) (McDermott, et al., 2009).

Cool water immersion of hands and forearms has been found to prolong work time when compared to passive cooling during a period of 50 minutes of treadmill walking with 30 minutes of rest (Selkirk, et al., 2004). Hand and forearm immersion is more effective at a water temperature of 10° C when compared to only hand immersion or immersion in 20° C water. In one study subjects performed stepping exercise in a hot room (40°C, 40% humidity) wearing TPC. During rest periods the subjects immersed either their hands or hands and forearms in 10° or 20° C water, the most effective reduction of core temperature was found with hand and forearm immersion at 10°C (Giesbrecht, et al., 2007). Vasoconstriction was not found to be a limiting factor even in immersion at 10° C (Giesbrecht, et al., 2007). Currently these cooling methods have only been studied in laboratory conditions.

Specialized cooling vests which are garments worn during work that utilize cool liquid or air to prevent hyperthermia have been examined for both military and firefighting purposes. For this method to be effective the cooling properties must outweigh the increased work resulting from adding another garment to the ensemble. The liquid filled vests add weight and insulation so the benefits of cooling produced by the vest must overcome the added work.

The use of air or liquid cooled vests to enhance work tolerance has been studied during exercise while wearing a chemical protective ensemble. This ensemble is similar to TPC as they both have poor vapor permeability preventing normal thermoregulation. This application was examined for flight crews in military aircraft and utilized a hot room (37° C, 50% humidity). Work of a flight crew was simulated by 10 minutes of treadmill walking at 4km/hr 0% grade to simulate walking to an aircraft, a 20-minute rest period in the hot room, then 10 minutes of intermittent arm ergometry at 50W alternating with 10 minutes of rest. The subjects had a goal of performing the protocol in the heated room for 150 minutes, however only subjects wearing a cooling vest were able to tolerate the full protocol time. They found the use of either the air or liquid cooled vests increased heat tolerance times (Vallerand, Michas, Frim, & Ackles, 1991). There was also a decrease in sweating and core temperature when wearing a vest compared to normal conditions (Vallerand, et al., 1991). Similar results were found using vests filled with frozen gel worn underneath TPC while walking on a treadmill using 30 minute exercise (1.12m/s 0% incline) and 30 minute seated rest intervals (Bennett, et al., 1995). In this case core and skin temperature were lower while wearing the vest during exercise in a 34.4° C room compared to no active cooling (Bennett, et al., 1995). Use of a cooling vest reduces evaporative cooling via sweating but the reduced skin temperature under the vest allows for cooling via conduction (Hasegawa, Takatori, Komura, & Yamasaki, 2005). Use of the cooling vests has been recommended when activity lasts for 60 minutes or more (Bennett, et al., 1995).

There have been investigations that do not support the use of cooling vests during firefighting activity. The vests will increase in temperature if they do not have a system that provides continuous cooling (i.e., frozen gel packs). Wearing a gel pack vest during simulated firefighting activity was not shown to improve work time (J. B. Carter, et al., 1999).

2.11 SUMMARY

Heat and exercise have been studied extensively but the prevention of normal heat loss due to thermal protective clothing is a relatively new area of study. The effects of hyperthermia are known to negatively impact the ability to perform work and may cause heat related illness, dehydration, and decreased cardiovascular function. The prevention of heat injury is needed to ensure the safety of firefighters and prolong work time. Working in the required fire TPC produces increases in HR and core temperature when compared to the same activity wearing regular clothing. Active cooling methods during work or recovery periods have been studied but no effective and easily used recommendations have been developed for active fire scenes.

3.0 METHODS

3.1 SUBJECTS

Subjects were recruited from local professional and volunteer fire departments. Both males and females were included. Power calculations for recruitment are included in the data analysis section. All potential subjects had completed required training to participate in “live burn” training where they extinguished fires intentionally set in a training building at the Allegheny County Fire Academy. Such training is standard for firefighters in Pennsylvania and is representative of work that is performed during firefighting duties. All subjects provided informed consent in accordance with University of Pittsburgh IRB requirements. Subjects were compensated for their participation provided by a grant.

3.2 SCREENING

All subjects did undergo a physical exam conducted by a physician prior to participation in the study and complete a PAR-Q. Subjects must be free of chronic health conditions including cardiovascular disease, diabetes, pulmonary disease and orthopedic injuries. Additional exclusion criteria included: 1) Any medication that would affect heart rate response or thermoregulation or 2) pregnancy. Anthropometric measurements will be recorded prior to participation in the training. Height was measured using a stadiometer, weight with a Health o Meter Professional Scale. Body fat was measured using the 3 site caliper method by an experienced researcher, and resting 12 lead ECG was included as part of the physical. ((Jackson & Pollock, 1976)) Female subjects completed a pregnancy test at their physical.

Subjects completed a progressively incremented treadmill test using a TMX425C treadmill (Full Vision, Newton, KS 67114) following a Bruce protocol to establish VO_{2max}. Open circuit spirometry (Parvomedics TrueOne 2400, Sandy UT) was used to determine respiratory rate, (RR) respiratory exchange ratio, (RER) oxygen consumption, (VO_2), ventilation (V_E), and carbon dioxide production (VCO_2). Subjects exercised to the point of voluntary exhaustion or until age predicted maximal HR were attained. Rating of perceived exertion was estimated using the OMNI walk/run scale (Figure 1.) at each stage of the protocol. Subjects were asked to estimate their RPE during the last 30 seconds of each phase of the Bruce protocol. Instructions for use of the OMNI walk/run scale are included in Appendix 1. A 12 lead ECG (GE Marquette MAC 6) was obtained at rest and during the last 30 seconds of each incremental stage of the protocol to monitor for cardiac abnormalities. Resting BP was measured prior to beginning the test and during the last 30 seconds of each incremental stage. Subjects wore their personal athletic clothing and shoes that they felt comfortable wearing to exercise. A cardiologist read the ECG of each participant to ensure only subjects with a normal ECG were permitted to participate in the study.

3.3 LIVE BURN TRAINING

The physical and treadmill test were completed in the 4 months prior to the fire training. Subjects were instructed to refrain from caffeine, alcohol, and exercise for 12 hours prior to participation in both the laboratory phase and the live fire training and to eat a normal breakfast before arriving for training. Subjects were provided an indigestible pill to monitor core temperature (HQ Inc, Palmetto FL) and instructed to take the capsule at home approximately eight hours prior to arrival at the fire academy.

In the field trial subjects participated in a live burn training evolution designed by training instructors for the Allegheny County Fire Academy that included entering a training structure and extinguishing fires set in that structure. The live burn training evolution as set by the fire academy instructors did last approximately 20 minutes, this is a typical work time at a fire scene and was followed by one of three rehabilitation scenarios. The training were conducted in July and there were multiple sessions throughout the day. Both outside temperature and humidity was measured and recorded throughout the day. Subjects only participated in one session per day, but were allowed to participate in both days of training. Each session required teams of four firefighters to advance a 4.4 cm charged hose line to the second floor of a concrete structure to extinguish and ventilate simulated bedroom fires. Instructors reignited the extinguished rooms to allow continuous extinguishment and ventilation until 20 minutes elapsed.

Participants were required to wear a standard fire uniform consisting of pants and long sleeve shirt; fire personal protective ensemble of turnout pants, coat, nomex hood, gloves, work boots, helmet, and self contained breathing apparatus (SCBA). Fire academy instructors inspected participants' gear at the academy just prior to use in the training session. After arriving at the training site, the subjects did void and had urine specific gravity checked to confirm euhydration (USG < 1.020 g/ml), using a refractometer (SUR-NE, Atago Co, Ltd, Japan) Subjects were not eligible to participate in the live fire evolution unless USG < 1.020 g/ml. A dehydrated subject with a USG > 1.020 g/ml was provided water and retested for hydration prior to participation. When euhydrated, subjects were weighed nude (Health o Meter Professional Scale), and fitted with a heart rate monitor (Polar Electro Inc, Lake Success NY).

After the training session subjects were randomly assigned to one of three cooling scenarios, passive: in a climate controlled environment with moderate temperature and humidity or active: forearm water submersion using rehab chair (Kore Kooler™, Morning Pride, Dayton OH) or a liquid perfused cooling vest (Cool Shirt® Personal Cooling System, Shafer Enterprises, Inc., Stockbridge GA). The rehab chair and cooling vest protocol took place in a shaded pavilion at the training ground; the climate- controlled van was at the same site. Temperature and humidity were measured throughout the day during the training. Tap water was used to fill the rehab chair arm wells and ice water was used in the cooling vest. All subjects consumed 500 ml of tepid water during the 30-minute rehab period. All subjects removed their helmet and coat, unfasten their bunker pants and be seated during all cooling scenarios.

Heart rate (beats per minute), blood pressure (mmHg), core temperature, (°C) and ratings of perceived exertion (OMNI), comfort, sweating, and thermal sensation, (Figures 3,4,5) were recorded every 5 minutes during rehab. The rehab session began immediately on finishing the training session, subjects were directed to their cooling area, removed their bunker gear as described and were seated. Subjects were shown standard copies of an OMNI walk/run RPE scale, a sweating, thermal sensation, and comfort scale and asked to provide numerical rating of each of these. The subjective ratings were taken in the same order each time and subjects were shown the figures for each rating session. Instruction on the scales were provided at the first measurement period.

Heart rate was measured using a Polar monitor (Polar Electro Inc, Lake Success NY) Oral temperature (Welch-Allyn SureTemp Plus 690) were recorded at the beginning and end of the 30 minute rehab period. Nude weight was measured to assess water loss using a Health o Meter Professional. Core temperature was measured immediately prior to and after the fire evolution and every 5 minutes during rehabilitation.

3.4 DATA ANALYSIS

Power calculation for subject recruitment assumes there are no confounding between group factors since the subjects complete all trials and should not be systematically different from each other. There are two within group factors: one for the interventions (three levels) and one for the time with three key measurements for each intervention (pre work, pre rehab, post rehab). All assumptions are clinically relevant and based on the results of Selkirk and McLellan (2004)

"Physical Work Limits for Toronto Firefighters in Warm Environments" JOEH 1:199-212. With 12 subjects per group for core temperature we assume 1ºC mean difference with a standard deviation of 0.5ºC between averages of each of the three time points. We also assume a 0.5ºC difference between the averages of each intervention and the overall average of the three interventions. The power to detect a difference in core temperature is >90% with alpha of 0.05

This was a randomized experimental design. Subjects were allowed to participate on one or both of the two training days; subjects who participated on both days underwent two different cooling methods. Data were collected during the protocol and entered into Excel spread sheets. Data were analyzed using PASWSatistics 19 for Mac (SPSS Inc, Chicago IL).

All subject demographic and anthropometric variables are presented as mean ± SD. Core temperature and heart rate measured pre/post fire suppression were compared by two-way ANOVA conditioned on time and cooling device. Heart rate, core temperature and perceptual scales of comfort, RPE, sweating and thermal sensation were measured on each individual after fire suppression at time 0 of recovery then every five minutes after to 30 minutes. A repeated measures marginal model (ANOVA) assuming a normal distribution with first-order autoregressive covariance structures was used to analyze both heart rate and core temperature. Variables of interest are group (three devices), time, and $time^2$ to examine how the slope of the curve changes over time. We tested for group differences in the slopes and curvature over time ($\alpha=0.05$ for each interaction). If the interaction is not significant, the term was dropped from the model and tested with the next highest ordered term. Perceptual data was examined using two way repeated measures ANOVA (cooling device x time). Tukey's test was used to examine data post hoc.

Oral and core temperatures obtained at the beginning and end of the rehab period were examined with a Pearson Correlation Coefficient and Bland-Altman Test of Agreement. All statistical tests are two sided and conducted at $\alpha=0.05$.

4.0 RESULTS

This investigation compared the effects of two active cooling devices consisting of a Coolshirt vest or forearm immersion in water to passive cooling in a climate-controlled environment with moderate temperature and humidity after simulated firefighting activities. Subjects participated in a live fire training exercise at the Allegheny County Fire Academy under the supervision of instructors followed by a 30-minute rehabilitation protocol in which subjects were randomly assigned to one of the three protocols. Heart rate, core temperature, and perceptual measures (perceived exertion, thermal sensation, thermal comfort, and sweating sensation) were obtained during the rehabilitation period. All subjects completed maximal exercise tests at least one week prior to participating in the fire training exercise. Anthropometric measurements were recorded prior to the maximal exercise tests.

4.1 SUBJECT CHARACTERISTICS

Twenty- five subjects participated (23 male, 2 female) with eight subjects (7 male, 1 female) participating on both training days. These subjects were assigned to different cooling modalities each day (Kilpatrick, Robertson, Powers, Mears, & Ferrer, 2009). The subject characteristics (mean ± SD) are presented in Table 1.

Table 1 Subject Characteristics (N=25)

	Males (*N* = 23)	**Females (*N* = 2)**
Age (years)	**32.3 ± 7.8**	**29.5 ± 5.0**
Height (cm)	**177.3 ± 5.8**	**164.0 ± 5.7**
Weight (kg)	**91.4 ± 15.3**	**57.7 ± 8.3**
VO_{2peak} (mg/kg/min)	**43.3 ± 8.7**	**41.2 ± 5.9**
Body Fat (%)	**17.2 ± 5.7**	**12.8 ± 6.8**
BMI kg/m^2	**28.9 ± 5.1**	**21.0 ± 4.1**

Values presented as mean ± SD

The subject characteristics are also described by cooling modality group in Table 2. There were no differences in the fitness characteristics between groups using an ANOVA model (p = .906 for body fat between groups, p= .314 for VO_{2max} , and p=.663 for age). Ambient temperature was monitored throughout the day during the simulation, the values for both the climate-controlled vehicle and outdoors underneath the pavilion can be found in Table 3. There was not a significant difference between the climate-controlled van and pavilion temperatures (p= .126).

Table 2 Subject characteristics by cooling modality group
Values presented as mean ± SD.

	Passive (*N* = 9)	**Forearm Immersion (*N* = 13)**	**Cooling Vest (*N* = 11)**
Age (years)	**31.2 ± 8.9**	**32.2 ± 7.2**	**30.6 ± 6.4**
Height (cm)	**174.4 ±5.7**	**175.2 ± 7.3**	**176.9 ± 6.5**
Weight (kg)	**89.3 ± 22.4**	**86.6 ± 15.6**	**95.7 ± 22.2**
VO_{2peak} (mg/kg/min)	**43.3 ± 8.9**	**43.3 ± 9.0**	**40.4 ± 8.1**
Body Fat (%)	**18.4 ± 7.2**	**14.9 ± 3.9**	**17.6 ± 6.8**

Table 3 Ambient temperature during rehabilitation

Van Temperature	Pavilion Temperature Day 1	Pavilion Temperature Day 2
22.1°±0.43/71.9°± 1.24	**24.4±1.75/75.9°± 3.49**	**21.14°±2.60/71.1°± 4.62**

Temperature in Celsius/Fahrenheit, values presented as means ± SD

4.2 PHYSIOLOGIC RESPONSE

Physiologic measures including heart rate, core temperature and body mass were recorded prior to and after participating in the fire suppression training activity. These results are presented in Table 4. Heart rate and core temperature both significantly increased following 20 minutes of fire suppression for all groups ($p < 0.001$).

Table 4 Physiologic measures before and immediately following 20 minutes of fire suppression

	Heart Rate (bpm)		Core Temperature (°C)		Body Mass Change (kg)	Body Mass Change %
	Pre	Post	Pre	Post		
Passive	121 ± 29	175 ± 13	37.5 ± 0.5	38.2 ± 0.7	-0.84 ± 0.34	0.62
Chair	108 ± 23	172 ± 20	37.4 ± 0.3	38.3 ± 0.4	-0.72 ± 0.41	0.25
Vest	116 ± 22	177 ± 12	37.6 ± 0.2	38.3 ± 0.3	-0.86 ± 0.36	0.38

Values presented as mean ± standard deviation. bpm = beats per minute

During the rehabilitation period significant time main effects were observed for both heart rate (F= 64.60, p=.00) and core temperature (F= 17.04, p=.00). Heart rate and core temperature decreased over time as expected. There was no significant time x device interaction for heart rate (p= .470) or core temperature (p= .496). The pre and post core temperatures and the rate of core temperature recovery over the 30-minute rehabilitation period are presented for each cooling modality in Table 5. All three cooling modalities resulted in a decrease in core temperature over time with the cooling rate of the chair forearm immersion device being higher than cooling vest or passive (p=.036). All groups lost body mass via fluid loss, almost 1 kg, and the percentage of weight loss was 0.40% overall (Table 4.). However, there was not a significant difference between groups in the change in body mass (p=.59). There was not a significant difference between groups in core temperature (p=0.496) or heart rate (p=0.470) at the beginning of rehabilitation. The change in core temperature as a function of cooling protocol over time is represented in Figure 1. The change in heart rate over time as a function of cooling protocol is represented in Figure 2. Heart rate decreased over time (linear slope $p < .001$) and heart rate recovery was not different between groups (difference in slopes test, p = 0.85).

Table 5 Core temperatures pre and post rehabilitation

	Pre-recovery Core Temperature	Post-recovery Core Temperature	Rate= Δcore/time
Passive	38.37 °C	37.59 °C	.03 °C/min
Chair	38.8 °C	37.43 °C	.05 °C/min•
Vest	38.64 °C	37.85 °C	.03 °C/min

•Significant difference (p= .036)

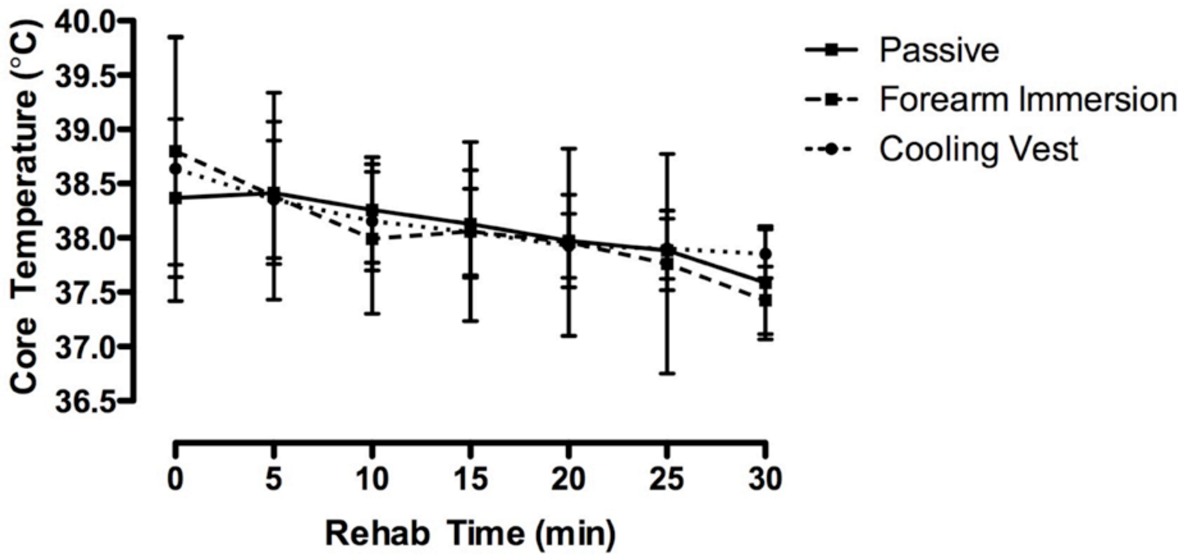

Figure 1 Core temperature changes during rehabilitation

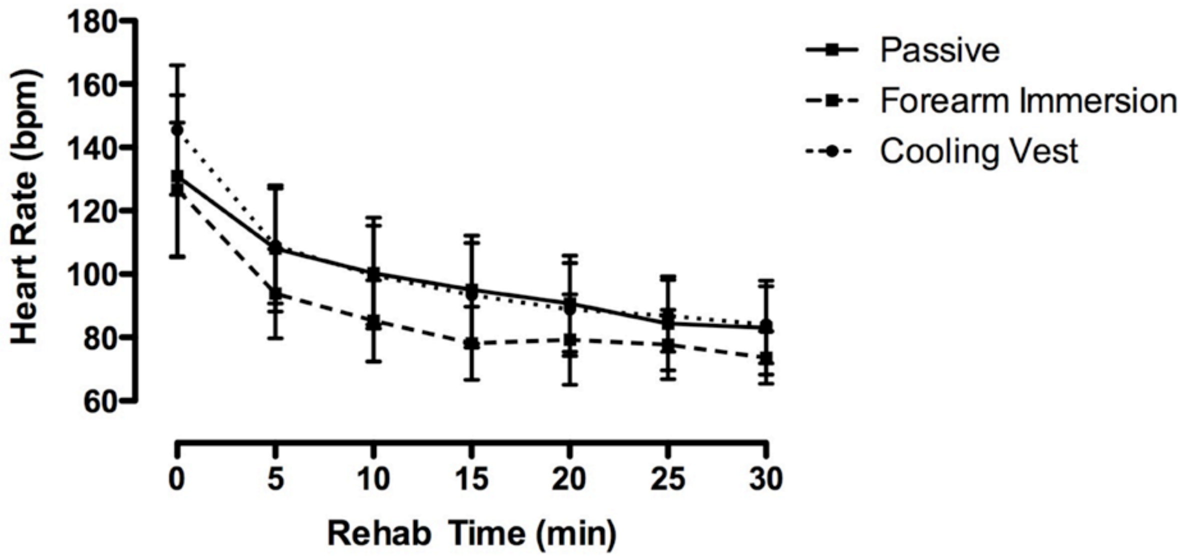

Figure 2 Heart rate changes during rehabilitation

4.3 PERCEPTUAL MEASURES

Perceptual measures (ratings of perceived exertion, thermal sensation, thermal comfort, and sweating sensation) were obtained during the 30-minute rehabilitation for all groups. All of the perceptual metrics were developed for use during activity. For the purposes of this study they were used during the rehabilitation period. The perceptual measures are presented in Table 6 as means ± SD at time 0 and after 30 minutes of rehabilitation.

Table 6 Comparison of perceptual measures at the beginning and end of three rehabilitation protocols

Perceptual Scale	RPE (OMNI)		Comfort sensation		Thermal sensation		Sweating sensation	
Time (min)	0	30	0	30	0	30	0	30
Passive	3.6±2.1	0.2±.4	2.1±.8	1.1±.3	3±1.1	1.0±0.0	5.9±1.9	1.0±0.0
Chair	3.1±2.8	0±0	2.1±.8	1±0.0	2.9±1.0	1.0±0.0	5.0±1.4	1.0±0.0
Vest	3.9±2.9	0±0	2.2±.8	1±0.0	3.4±1.0	1.0±0.0	5.9±2.2	1.0±0.0

Presented as means ± SD

A two way ANOVA based on time and rehabilitation method was performed for each perceptual variable (ratings of perceived exertion, thermal comfort, thermal sensation, and sweating). These measures were each compared between groups to determine if the cooling modality had a differential effect on the construct specific perception. The p values for each ANOVA are presented in Table 9 of the Appendix. There were no significant main effects or interaction of perceptional measures by cooling modality. There were significant main effects ($p=.000$) for each of the perceptual scales based on time. These data are presented in Table 10 of the Appendix.

A correlation coefficient of $r=0.665$, $p= .00$ was noted between the ratings of perceived exertion (OMNI) and HR taken during the recovery indicating a moderate to strong correlation between the two variables. Correlation coeffeicients for core temperature and each of the perceptual measures were also performed: for core temperature x OMNI $r=0.363$, $p=.00$, comfort sensation $r=0.345$, $p=.00$, thermal sensation $r=0.415$, $p=.00$, and sweating sensation $r=.421$, $p=.00$. These data indicate a moderate correlation between core temperature and perceptual measures during the recovery period.

Table 7 Differences between perceptual measures over time during rehabilitation

Rating scale	OMNI	Comfort sensation	Thermal sensation	Sweating sensation
F value	8.416	19.51	33.73	50.18
p value scale x time	.000	.000	.000	.000

5.0 DISCUSSION

This study compared two common active cooling modalities to passive cooling in moderate temperature and humidity following 20 minutes of fire suppression. This study is similar to previous studies of fire suppression in that we observed significant hyperthermia, tachycardia, and dehydration (S. Petruzzello, J. Gapin, E. Snook, & D. Smith, 2009; D. Smith, Manning, & al, 2001). However, this investigation failed to identify an advantage of active cooling in terms of heart rate or core temperature recovery when the firefighter was provided with 30 minutes of fireground rehabilitation. In addition, the cooling modalities did not differentially affect the perceptual measures during rehabilitation.

5.1 PHYSIOLOGIC RESPONSE

This study augments what is currently known about cooling firefighters during fireground rehabilitation. Three previous studies examining physiologic recovery in a hot environment have reported that it is difficult to mitigate heat stress without active cooling devices such as fans, vests, or forearm immersion (Bennett, et al., 1995; J. B. Carter, et al., 1999; Selkirk, et al., 2004). However, these studies included extreme hyperthermic conditions during the rehabilitation period. Bennett, et al 1995 reported a wet bulb temperature of 28.9°. Selkirk et al, 2004 employed an ambient temperature of 35° C with 50% relative humidity during the rehabilitation phase. The third investigators (Carter, et al, 1999) used rest in a 40° C room with 70% humidity. All of these conditions are warmer than either the outside (24.4±1.75° C) or inside (22.1±0.43°C) temperatures used in the present experiment. Across much of North America and Europe, extremely hot (≥35°C) temperatures are rare, making ambient temperatures in these areas generally more favorable for rehabilitation, decreasing the need for significant intervention during recovery beyond the passive rehabilitation described in this investigation.

The data from the present investigation agree with a previous laboratory study, conducted at the University of Pittsburgh, involving active and passive cooling after 50 minutes of treadmill walking in a heated room. This investigation also failed to identify an advantage of active cooling during a 20-minute rehabilitation period (Hostler, Reis, Bednez, Kerin, & Suyama). Similarly, a comparison of hand cooling in cold tap water failed to promote differences in core temperature and heart rate recovery when compared to the control condition of seated rehabilitation in a cooler 15°C room after removing the helmet, coat and hood (J. M. Carter, Rayson, Wilkinson, Richmond, & Blacker, 2007). Collectively, these studies indicate that passive cooling following fire suppression allows for physiologic recovery without the need for additional measures if the majority of thermal protective clothing is removed and firefighters are allowed to rest in a moderate temperature and humidity environment. Furthermore, the data in the present study shows that a climate-controlled environment can be created in an air-conditioned vehicle in a field setting producing an advantageous environment if the outside temperature and/or humidity are suboptimal.

The data obtained in the present study differ from many other cooling studies as there was not a significant advantage shown using active cooling devices. Most other studies were conducted in a laboratory environment where temperature and humidity were both elevated during rehabilitation. (Bennett, et al., 1995; Selkirk, et al., 2004) The elevated ambient temperature in these cases would inhibit passive cooling as evaporative, radiative, and conductive cooling would be less effective. In the present study the ambient temperature was temperate, 21° to 24° C with humidity ranging from 39 to 49% for the subjects in the outdoor cooling protocol. The passive cooling subjects rested in a climate-controlled environment with a temperature around 21°C which provided a favorable environment for passive cooling. These temperatures are considered to be moderate and produce a temperature gradient for heat loss in humans.

5.2 COOLING MODALITIES

In addition to the ambient temperature and humidity, the insulation properties of TPC affect cooling rates during fire rehabilitation so the amount of TPC removed affects total cooling potential. Turnout gear creates a microclimate of high temperature and humidity for the wearer because of its vapor barrier and insulation. (Rossi, 2003) TPC prevents normal cooling via evaporation, radiation, conduction and convection. In the present study removal of the turnout coat, helmet and unfastening of turnout pants facilitated cooling. Prior studies have utilized different cooling protocols that did not always include removal of TPC. This would decrease cooling rates and demonstrates the need to remove TPC to achieve optimal cooling during rehabilitation.

The cooling modalities of a Coolshirt and forearm immersion (Kore Kooler™) were chosen as they are marketed towards firefighter rehabilitation and are commercially available. There is no special training required to use either the vest or forearm immersion and both are portable. These factors make them practical to use at a fire scene. However, the vest does require ice and electricity to function, which may limit its use on a fireground. The forearm immersion only requires water to operate making it more versatile and easily used in the field. These devices were purchased with funds from the FEMA grant supporting this study.

Similar devices have been studied previously in laboratory investigations; especially forearm immersion for cooling after work. Giesbrecht, et al., 2007 used hand or hand and forearm immersion in two different water temperatures to cool subjects after bouts of work in a hot room (40°C 40% relative humidity) while wearing TPC. The rest periods with forearm immersion in that study took place in a 21°C room making it similar to the rehabilitation conditions in the present study. In this study there was an advantage to use of forearm immersion in reduction of core temperature. Another study by Hostler, Reis, et al., 2010 examined multiple cooling devices in a laboratory setting, including a cooling vest and forearm immersion, allowing for comparison of device effectiveness in the field vs. controlled conditions. This laboratory investigation did not find an advantage to active cooling methods over passive in a moderate environment. In the present field investigation, our results were similar to those found by Hostler et al. as there was not an advantage found with active cooling methods. In the present study, heart rate and core temperature were shown to decrease across time without significant differences by cooling modality after 30 minutes of rehabilitation.

Barr, Gregson, Sutton, & Reilly, 2009 compared multimodal cooling (forearm immersion combined with a cooling vest) to passive cooling in a 21°C room after 20 minutes of treadmill walking. In their laboratory-housed study, the rehabilitation period was limited to 15 minutes and appears to include the time required for doffing and donning TPC for a second bout of treadmill walking. The cooling rate for the active cooling arms in Barr et al 2009 is comparable to the passive cooling reported in the present study (0.03 ± 0.01°C/min vs. 0.02 ± 0.01°C/min). The passive cooling rate of -0.01 ± 0.01°C/min reported in Barr et al (2009) is likely influenced by the short period of continued heat accumulation following cessation of exercise in protective clothing that has been reported in other studies (Hostler, Bednez, et al., 2009; Hostler, et al.; D. Smith, et al., 2001). A greater core temperature reduction may have been noted in the passive cooling group in that study if the rehabilitation period had been lengthened beyond 15 minutes. The rehabilitation period in the present study was twice that in length allowing for a greater recovery in core temperature.

Laboratory studies allow for the greatest amount of control of ambient conditions. Temperature and humidity can be controlled for investigations using hot, cold, or temperate conditions for work or recovery. Investigations of recovery from heavy work in TPC have typically taken place in the laboratory. (Selkirk, et al., 2006) Studies that take place in the field do not have the advantage of environmental control, but are more realistic for firefighter work and recovery as this activity takes place in uncontrollable temperature and humidity conditions. The laboratory studies can quantify the amount of work performed by the subjects using ergometers or controlled activity. In a training activity at a fireground there is less control over the amount of work a subject performs as subjects work in groups during fire suppression and time spent working may be limited by air supply. There are few studies that have taken place during fire training or during actual working hours for firefighters. These investigations have demonstrated the physical and perceptual demands on firefighters (D. L. Smith, et al., 2001) but have not investigated rehabilitation.

Hydration status has been shown to influence recovery of heart rate and core temperature following exertion with dehydration attenuating heart rate and core temperature recovery. (Crandall, Gonzalez-Alonso) Hydration was controlled during the rehabilitation period in the present protocol. Each subject drank 500 ml of tepid water to replace a portion of the fluid lost during the work protocol. The average fluid lost by all subjects was 0.80±0.37 Kg during the live fire training protocol. The fluid lost was not completely replaced by 500 ml of water for most subjects but previous studies have shown that subjects may not tolerate the consumption of fluid levels necessary to achieve total volume replacement in a short period of time. (Selkirk, et al., 2006) Due to the influence of hydration on heart rate recovery and core temperature a standard amount of fluid was consumed by all subjects during the rehabilitation period. Other studies have shown the amount of work that can be completed when wearing TPC is greater in rehydrated than dehydrated individuals indicating a physiologic benefit to hydration. (Selkirk, et al., 2006) Investigations have concentrated on the amount of work that can be performed after rehydration during rehabilitation periods. (Hostler, Bednez, et al., 2010) (Selkirk, et al., 2006) Hydrated individuals can complete more work than dehydrated, and the type of fluid used does not affect work if the individual is fully rehydrated. These studies have examined fluid replacement strategies over relatively short periods of time. Currently less is known about hydration and recovery during the hours after work in TPC.

5.3 PERCEPTUAL MEASURES

There is currently a limited amount of information on the use perceptual scales during fireground rehabilitation. Perceptual measures are normally used to gauge effort during activity but not during rehabilitation. There are multiple studies establishing the validity of the OMNI RPE scale during various aerobic and resistance training modalities. Also, numerous studies have examined session RPE, the post-exercise rating of global exertion experienced during an entire exercise session. Foster et al. (2001) was the first to use session RPE as an index of over-training. One recent study by Kilpatrick et. al. (2009) asked for subjects to provide RPE estimates for the exercise session after the session had ended and found that the ratings were most related to the RPE experienced at the end of the exercise session. However, this study did not ask the subjects to provide RPE estimates of their level of exertion associated with recovery. There are data regarding the perception of exertion during recovery from structured aerobic activity under laboratory conditions. In these studies, the decrease of RPE reported by subjects during the recovery period reflected the decrease in metabolic acidosis (Robertson, et al., 1992; Swank & Robertson, 2002). Both found that, as expected, heart rate and respiratory rate decreased along with RPE but that the decrease in HR was not reflected by the RPE-overall, the rating corresponding to the whole body. The present study did not take measurements of metabolic acidosis but saw a rapid decrease in RPE during the rehabilitation period.

The present study recorded subjects' ratings on four perceptual scales and found that perceptual responses during rehabilitation were significantly different across time. Perceptions of effort, thermal sensation, thermal comfort, and sweating were higher when first ending the 20-minute training period when compared to the end of the recovery. These results were expected as the participants had ended active work in heat and were resting seated in a favorable environment. The physiologic measures of core temperature and heart rate decreased during the rehabilitation period. As perceived exertion may provide perceptual analogues of physiologic changes it would be unusual for RPE to increase or remain constant during rehabilitation from fire suppression. There were no significant differences in perceptual responses during rehabilitation based on the cooling protocol. This was consistent for all of the perceptual constructs. This indicates that the active cooling modalities did not result in an accelerated recovery in the perceptual responses when compared to the passive conditions during rehabilitation. This is similar to the physiologic results in that heart rate and core temperature decreased significantly across time, but there were not significant differences across cooling modality. This also indicates that the subjects did not feel that the active cooling modalities caused noxious stimuli during rehabilitation based on the thermal comfort scale. Correlation coefficients were obtained for core temperature and each of the perceptual measures including RPE and thermal sensation. These produced moderate correlations (core temperature x OMNI $r=0.363$, comfort sensation $r=0.345$, thermal sensation $r=0.415$, and sweating sensation $r=0.421$,) indicating that core temperature may not be the most influential mediator of perceptual measurements.

An interesting finding was the moderate positive correlation found between OMNI RPE responses and heart rate during recovery (r=.655) which indicates a moderate to strong positive relationship between the decrease in these variables during the rehabilitation period. Although a positive value was noted presently between heart rate and RPE, heart rate is generally not considered to be an influential mediator of RPE during or after exertion. Decreases in pulmonary ventilation and respiratory rate along with metabolic acidosis are more closely related to the reduction in RPE during recovery from exercise than heart rate. (Robertson, et al., 1992)

Perceived exertion and thermal perception have been examined in relation to exertion at different ambient temperatures during work. Maw et. al. examined aerobic work in 40°, 24°, and 8°C while subjects exercised for 30 minutes on a cycle ergometer at a constant work load.(Maw, Boutcher, & Taylor, 1993) Thermal perception scores were linked to skin temperature, and were higher with elevated skin temperature. Exercise was better tolerated in cool conditions reflected by lower RPE scores. Subjects reported higher thermal sensation and they felt the work was harder while exercising in the hot condition (40° C). While core temperature increased in all conditions, skin temperature and heart rate were significantly higher in the hot condition, and the investigators reported that perceived exertion was most influenced by skin temperature rather than core temperature. The authors speculate that vasodilatation affected thoracic sensations which may have contributed to the higher levels of exertion. Temperature stimulation to different areas of the body using both hot and cold stimuli has also been examined. Cooling stimulation to body segments improves comfort in an overly warm environment and warming stimuli is perceived as comfortable in a cold environment. (H. Zhang, Huizenga, Arens, & Wang, 2004) These observations may be of benefit by increasing comfort of firefighters after work in heat by applying cold local stimuli during rehabilitation. Correlations between RPE and core temperature (r= 0.742 to 0.856) have been reported, demonstrating that RPE may be used to monitor thermal stress when working in a hot environment. (Gallagher, et al.) Thermal sensations and RPE measures are also strongly correlated (r= 0.822 to 0.936); taken together they can provide non-invasive information on core temperature in an active individual. However, individuals with higher aerobic fitness have an enhanced tolerance to work in the heat (Cheung, 2007) which could influence ratings of perceptual measures during work and recovery. The present investigation found moderate correlations between core temperature and RPE (r=0.363, p=.00,) and thermal sensation (r=0.415). This may represent differences between perceptions during treadmill walking versus recovery from a live fire exercise.

It is important to note that even after 30 minutes of structured rehabilitation that included cooling and rehydration, most subjects remained mildly hyperthermic (core T=37.63± 0.21) with seated heart rates exceeding 80 bpm. We speculate that it may not be possible to return a firefighter to baseline or near-baseline core temperature after significant exertion in TPC within 30 minutes using reasonable rehabilitation measures. It may be possible to increase the rate of cooling in personnel using more intensive measures such as complete submersion in an ice bath or infusion of cold saline. However, these methods would not be practical in the field and may be poorly tolerated by individuals. To achieve increased safety for firefighters during prolonged fireground operations recovery may need to be facilitated by increasing the number of personnel available for operations to allow for longer or more frequent rehabilitation periods.

5.4 STUDY LIMITATIONS

There are a number of limitations to this study and the interpretation of the data. While our subjects performed fire suppression and ventilation, this was a training fire in a controlled setting. Physiologic responses in the uncertain and rapidly changing environment of an actual fire may differ from the observed responses during a controlled training and rehabilitation session. In the present study the amount of work performed by individual subjects was not controlled, but all completed similar fire suppression training scenarios while supervised by a fire academy instructor. The protocol used in the present investigation produced near maximal heart rates based on the subjects' age, a rapid and substantial rise in core body temperature, and nearly one liter of mass lost to sweating in an operationally relevant time interval. The current subject pool was diverse representing both the career and volunteer fire service and displayed a wide range of fitness and morphometrics but the subjects may not be representative of firefighters in other areas of North America and Europe. Studies using only career firefighters from large departments have subjects with more similar fitness levels and training in live fire evolutions. (Selkirk, et al., 2006)

5.5 FUTURE AREAS OF RESEARCH

This investigation demonstrated the need for continued research on work and rehabilitation in hyperthermic environments. Thirty minutes of rehabilitation was insufficient to return firefighters to baseline physiologic measures, although their perceptual measures returned to pre-fire suppression levels. It may be beneficial to investigate devices and work practices such as precooling an individual before work to blunt physiologic heat stress during fire suppression activities. As hydration levels can affect aerobic work capacity, a field investigation that examines the effectiveness of various rehydration strategies on rehabilitation would provide useful information. In addition to the amount of fluid consumed, the effect of the fluid temperature and composition on core temperature and perception of heat stress could help direct recommendations for rehabilitation

Session RPE, where the subject reports their perception of effort associated with the entire work session, may be helpful since obtaining RPE during fire fighting is logistically difficult. The relation between session RPE and the perceptual and physiological responses should be examined. There are also scales specific for use during recovery from activity that may be more sensitive to the effects of rehabilitation. Use of perceptual rating tools that have directions with job-specific wording may also provide a more accurate picture of physiological stress and strain during and immediately after firefighting.

Other peripheral measures such as skin temperature and respiratory rate should be investigated to determine the relationships of these variables to perceptual constructs during rehabilitation. Furthermore, obtaining perceptual metrics during rehabilitation after work in a hot environment may help determine when a firefighter is recovered enough to return to fire suppression activities. This concept should be investigated.

5.6 CONCLUSION

A single 20-minute bout of fire suppression results in near maximal heart rate, a rapid and substantial rise in core temperature, and mass lost from sweating of nearly one kilogram. We have shown that following 20 minutes of fire suppression, removing TPC in a moderate temperature (approximately 22°C) results in heart rate and core temperature recovery over 30 minutes that is equal to the recovery realized with forearm immersion or ice water-perfused cooling vests. Ratings of perceived exertion, thermal comfort, thermal sensation, and sweating sensation measured during rehabilitation also did not differ between active or passive cooling modality over 30 minutes.

This study compared the physiological and perceptual responses during fire rehabilitation in a climate-controlled ambient environment to two popular cooling devices. Data were collected on two typical early-summer days in Western Pennsylvania (24.4°C±1.75 and 21.14°C±2.60). Given that the currently investigated devices employ a common and limited set of conductive or convective cooling strategies, we believe that it is unlikely that dramatically different results would be obtained with another similar cooling device applied after fire suppression. Finally, these data suggest there is a limited role for active cooling of firefighters when moderate temperature and low humidity exists, or can be created. Passive cooling in a climate controlled environment is able to reduce hyperthermic core temperature without special intervention when insulating clothing is removed and the ambient environment has moderate temperatures and humidity. We cannot speak to the use of active cooling devices in conditions of recovery in hot, humid conditions (Selkirk, et al., 2004).

APPENDIX A

Appendix 1.

Definition and Scaling Instructions for the Measurement of Perceived Exertion

This scale contains numbers from 0 to 10 that will be used to rate the perception of physical exertion. The perception of physical exertion is defined as the intensity of the subjective effort, strain, discomfort and/or fatigue that you feel during an exercise task. We use this scale so that you may translate into numbers your feelings of exertion while exercising. These feelings should be general about the body as a whole.

The range of numbers on the scale should represent a range of feelings from "Extremely Easy" to "Extremely Hard". In order to help you select a number that corresponds to your subjective feelings consider the following. When the exercise feels between "Extremely Easy" and “Easy” respond with a number 1. An example of when you would rate a number 1 would be when you encounter the same feelings as you have when you are walking very slowly.

When the exercise feels between “Hard” and "Extremely Hard” respond with a number 9. For example, a rating of 9 would be appropriate when your feelings of exertion are the same as your memory of how you felt during the most physically exhaustive work you have ever done.

When rating, think of your feelings associated with the numbers 1 and 9 first. Then, think of the exertion associated with the exercise at the moment and make your judgment. If the exertion feels less than a 1 or greater than a 9, respond with a 0 or 10, respectively. You should only rate a number 0 when you are at rest such as sitting down or standing around.

In summary,

1. You will be asked to give a rating of perceived exertion every minute of the test.
2. Give each rating by selecting any number from 0 to 10 that corresponds to the perception of exertion for your total body.
3. Try to estimate the degree of exertion as accurately as possible.
4. Do not underestimate or overestimate the exertion, simply rate your feelings caused by the exercise at the moment.
5. There are no right or wrong answers.
6. Start with any number that is appropriate

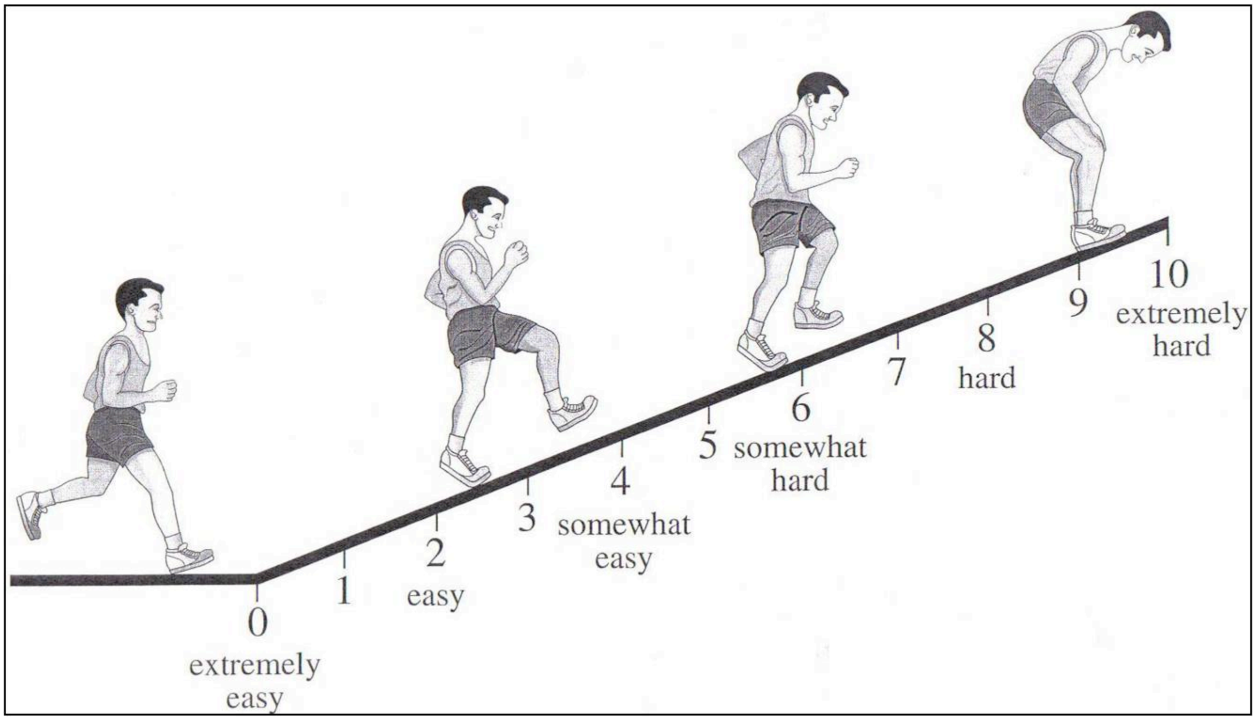

Figure 3 OMNI walk/run scale

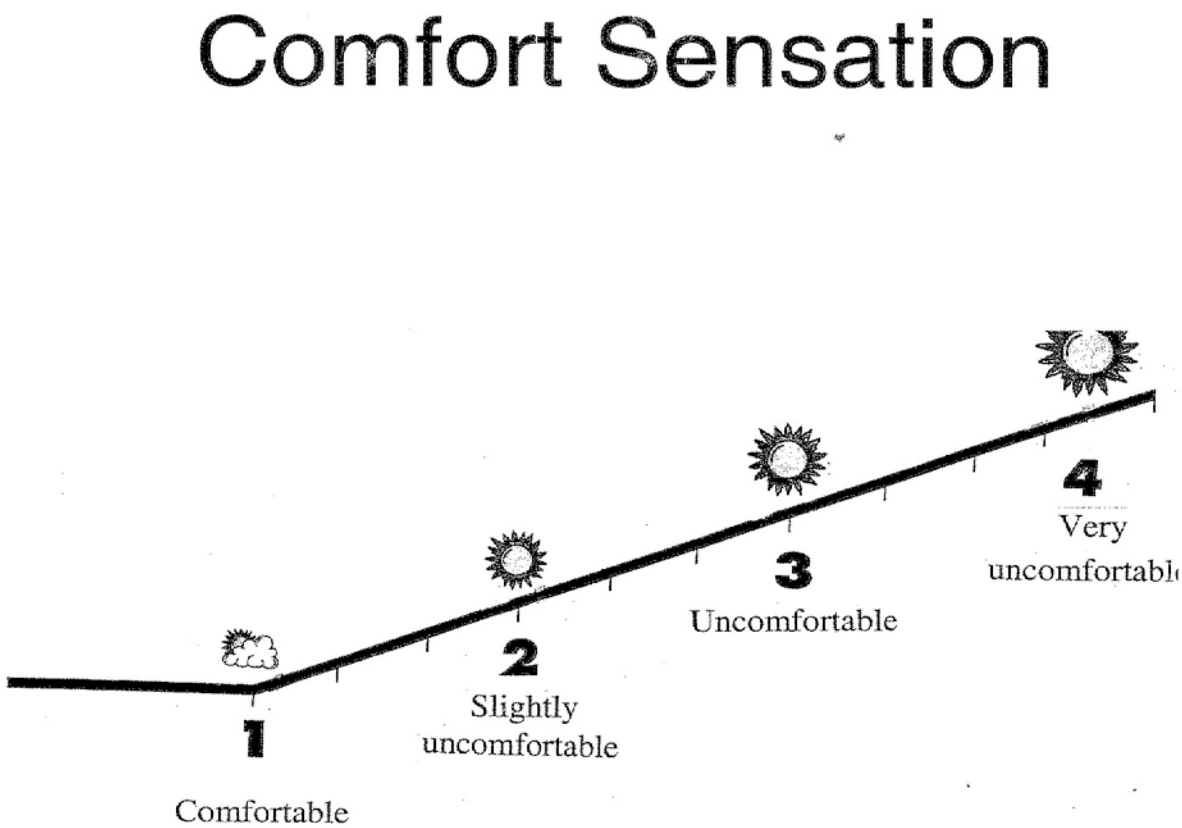

Figure 4 Comfort scale

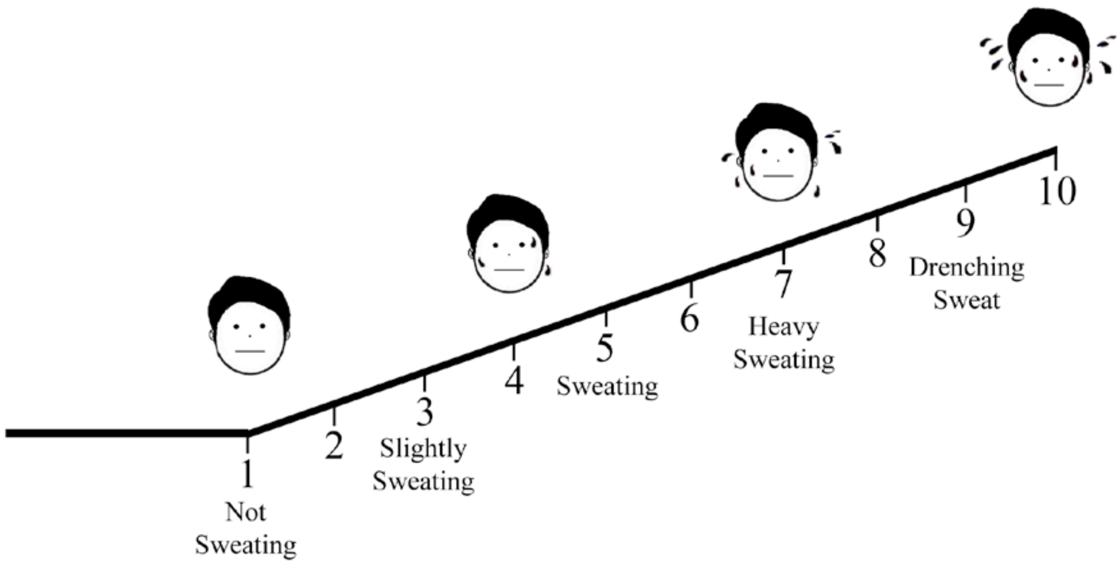

Figure 5 Clean sweating scale

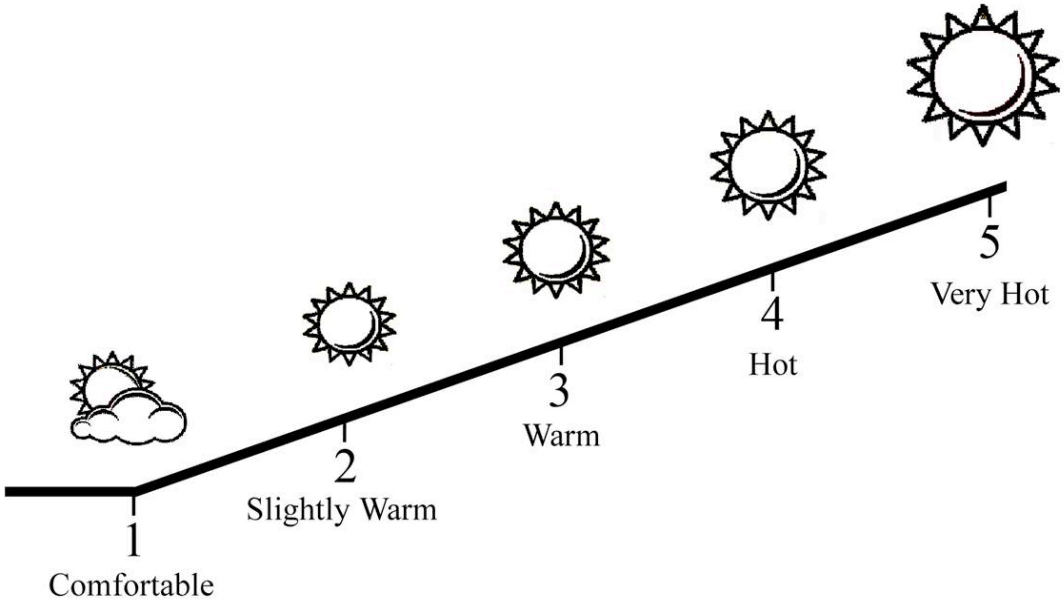

Figure 6 Thermal sensation scale

Table 8 Comparison of recent literature for firefighters and work

Investigator	Work load	Clothing	Subjects	Temperature Humidity	Rehabilitation	Results
Richmond, VL 2008	Search/rescue SDBA or EDBA and 2 hose length	TPC	16 firefighters	27° C 50% humidity	No methods	Increased core T to 39.1° C 72% HRR with EDBA 38.6°C and 67% HHR c SDBA
McLellan, TM	Heavy, mod, light, very light treadmill walk	Long pants vs shorts under TPC	24 firefighters	35° C, 50% humidity	Slow walk/stand after 20 min work, water, 30 min seated after work complete	Shorts prolonged work time in light and very light walk
Malley, KS	Constant workload at 50% MVO2 from max test	Modern turnout gear vs traditional(no gear pants) and shorts vs pants under modern	23 firefighters	Inside lab "stable temp and humidity"	Walk on treadmill	Modern uniform decrease ex time by 3 min vs traditional, modern c shorts not different from traditional, Tcore same in all
Selkirk, GA 2006	Walk 4.5 km/hr 50 min, rest 30 min until HR 95%, Tcore 39.5	TPC	12 firefighters	35° C, 50% humidity	High, mod, low, no fluid replacement (78,63,37% fluid loss)	Tol (work+rest) time increased with all fluid replace, work (no rest) increased c high and mod fluid
Rossi, R 2003	Live fire training and exercise in heated room	3 types of TPC: 2 breathable, 1PVC coated coat	17 Firefighters	50 to 190° C in fire building 50% humidity 31°-38° C in room	none	Core T increased 0.6° to 1°C after 15 min exercise in hot room, highest humidity in PVC coat
Bennett B.L. 1995	30 min rest and 30 min walk x 2 in warm room	TPC	12 male volunteers	28.9° wet bulb	No vest vs. 1 of 2 cooling vests under	The larger cooling vest reduced heat strain more than the small one, both extended tolerance times
Giesbrecht G. 2007	3 sets of 20 min exercise bouts	TPC	6 male volunteers	40°C and 40% humidity	Rest or hand vs hand+forearm immersion in 10° or 20°C H_2O	Immersion in 10°C H2O produced lower core T than all other conditions
Blacker, S 2006	3 studies, effect of cool vests wearing suits during tunnel walk, worn during high and normal T, during fire training and hand immersion after fire training	TPC or gas tight suit	10 firefighters in each study	16.5° C for gas tight suit, 170°C for heated fire training 15-20° for unheated training	Cool vest during activity or hand submersion after activity in 10°C H2O in a 15°C room	Cool vest did not reduce core or skin T worn during activity, Hand immersion not different from passive
Wong, J 2004	Walk 50 min, rest 30 min cycles	TPC	15 male firefighters	35°C, 50% humidity	Passive in TPC, Mister, or forearm submersion in 17.4° C H2O	Tolerance time and work time were both extended with active cooling
Morrison, JB 1999	10 min stepping periods 10 min rest	TPC	12 firefighters	40°C, 70% humidity	Removal of coat in front of fan, or unfasten coat, no fan both in hot room	Rectal T increased 1.5°C with passive and .8°C with fan cooling
Davis,JK 2009	Walked and did arm curls 40 min in hot room, 40 min recovery	TPC	8 males	33.7°C wet bulb	Rest in 22°C, 35% humidity removal of TPC and use of hand cooling device vs passive	No significant difference until 35 min, then cooling device increased cooling

Table 9 Differences between perceptual ratings between cooling device used during the rehabilitation period

Ratings scale	OMNI	Comfort sensation	Thermal sensation	Sweating sensation
F value	.555	.286	.593	1.473
p value device x time	.867	.942	.780	.188

Table 10 Differences between perceptual ratings over time during rehabilitation

Rating scale	OMNI	Comfort sensation	Thermal sensation	Sweating sensation
F value	8.416	19.51	33.73	50.18
p value scale x time	.000	.000	.000	.000

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