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The Management of Heat Stress for the Firefighter: A Review of Work Conducted on Behalf of the Toronto Fire Service

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Abstract: This report provides a summary of research conducted through a grant provided by the Workplace Safety Insurance Board of Ontario. The research was divided into two phases; first, to define safe work limits for firefighters wearing their protective clothing and working in warm environments; and, the second, to examine strategies to reduce the thermal burden and extend the operational effectiveness of the firefighter. For the first phase, subjects wore their protective ensemble and carried their self-contained breathing apparatus (SCBA) and performed very light, light, moderate or heavy work at 25°C, 30°C or 35°C. Thermal and evaporative resistance coefficients were obtained from thermal manikin testing that allowed the human physiological responses to be compared with modeled data. Predicted continuous work times were then generated using a heat strain model that established limits for increases in body temperature to 38.0°C, 38.5°C and 39.0°C. Three experiments were conducted for the second phase of the project. The first study revealed that replacing the duty uniform pants that are worn under the bunker pants with shorts reduced the thermal strain for activities that lasted longer than 60 min. The second study examined the importance of fluid replacement. The data revealed that fluid replacement equivalent to at least 65% of the sweat lost increased exposure time by 15% compared with no fluid replacement. The last experiment compared active and passive cooling. Both the use of a mister or forearm and hand submersion in cool water significantly increased exposure time compared with passive cooling that involved only removing most of the protective clothing. Forearm and hand submersion proved to be most effective and produced dramatic increases in exposure time that approximated 65% compared with the passive cooling procedure. When the condition of no fluid replacement and passive cooling was compared with fluid replacement and forearm and hand submersion, exposure times were effectively doubled with the latter condition. The heat stress wheel that was generated can be used by Commanders to determine safe work limits for their firefighters during activities that involve wearing their protective clothing and carrying their SCBA.

Key words: Uncompensable heat stress, Heat injury, Modelling, Fluid replacement, Active cooling, Hand immersion

Introduction

In many occupational (e.g., firefighters, hazardous waste disposal, military) settings, protective clothing is required to shield the individual from environmental hazards or from injury. In these high-risk settings, any increase in psychological strain or impairment in mental functioning due to the clothing may also place the individual at an increased risk of an accident[1, 2]. Protective clothing ensembles restrict evaporative heat loss through decreased water vapor permeability, thus the evaporative heat loss required to maintain a thermal steady state (E_{req}) can exceed

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the maximal evaporative capacity of the environment (E_{max}) and create a condition of uncompensable heat-stress[3]. In these situations, trapped metabolic heat produced by working muscles, as well as heat gained from the local environment produce an increased thermoregulatory strain[4, 5]. As well, increased skin perfusion in response to the thermal strain during work creates an additional demand on the cardiovascular system.

Traditionally, it has been perceived that a firefighter's primary responsibility is to fight fires; however, in actuality, only a small percentage of time is spent on this task[6, 7]. Other aspects of a fire call include overhaul, ventilation, search and rescue and salvage[7–10]. Additional types of calls can include emergency responses, which incorporate the risk of exposure to unknown agents and/or poor air quality, such as hazardous material spills, suspected terrorist activity and industrial incidents. Although these environments do not involve direct live fire exposure, they do produce the necessity to protect firefighters against hazardous agents by wearing firefighting protective clothing (FPC) and self contained breathing apparatus (SCBA) regardless of the ambient temperature. In addition to wearing FPC and SCBA during such tasks, a firefighter is expected to be active (i.e., walking running, lifting and/or pushing objects), creating an increase in metabolic heat production and potential heat storage[7, 11, 12].

For the firefighter, internal heat production can vary from more prolonged light work involved with pump operations or light sweeping during cleanup activities, to shorter bursts of high intensity work such as carrying equipment up stairs, carrying a collapsed victim or advancing a charged hose line. The ambient conditions can also vary from the extremes of a high radiant heat load with live fire exposure to the normal ambient temperatures that often reach temperatures well above 30°C during the summer months. In 1987, changes in legislation led to the development of new protective clothing standards by the NFPA[10]. With these changes, came a new era of firefighter protective ensembles, which offered an increased protection from both hazardous materials and extreme environmental heat for short periods of time. However, the new clothing exacerbated the challenge of thermoregulation because of limited water vapor permeability across the clothing layers, which decreased the rate of heat exchange[13, 14]. Therefore, although this new clothing offered greater protection from external hazards it placed the firefighter at greater risk of succumbing to hyperthermia and heat illness.

Heart attack is the number one cause of death for in-line firefighters[15, 16]. An increase in body temperature places an additional strain on the heart to pump greater volumes of blood to the skin to promote heat loss to the environment. Any strategy or intervention that reduces the heat stress of wearing protective clothing should reduce the strain on the heart and hopefully reduce the incidence of heart attack for the firefighter.

The following is an overview of research that was conducted at Defence Research and Development—Toronto on behalf of the Toronto Fire Service (TFS) with funding provided through a grant from the Workplace Safety Insurance Board of Ontario. The aims of this research project were twofold; first, to establish safe work limits for a range of ambient conditions representative of the warm summer conditions in the Toronto area; and second, to propose strategies that would reduce the heat stress of wearing the protective ensemble and increase the safety of the firefighter. For a greater in-depth presentation of the different components of this research, the reader is referred to a number of recent publications[17–20]. All of the work described below initially involved approval from Defence R&D Canada's human research ethics committee and all subjects provided informed consent prior to participation.

Methods and Results

Phase 1–Establishing safe work limits

The first phase of the research project involved recruiting 40 volunteers from the TFS. Over 70 volunteers were screened initially such that the physical characteristics and aerobic fitness levels of our selected participants were sufficiently diverse to ensure that our findings would be applicable to all firefighters. Subjects were assigned to one of four groups (with 10 subjects (9 male and 1 female since 10% of the TFS were female) in each group) that performed very light, light, moderate or heavy treadmill exercise while wearing their protective clothing and carrying their SCBA. Details about the make and characteristics of the clothing can be found elsewhere[17, 21]. All subjects performed a familiarization trial and three experimental trials that involved randomly assigned exposures to 25°C, 30°C and 35°C at 50% relative humidity. Heat stress trials continued until rectal temperature (T_{re}) increased to 39.0°C, heart rate reached 95% of the individual's maximum value, dizziness or nausea precluded further exercise, the subject terminated the exposure due to exhaustion or the investigator terminated the trial because of safety concerns for the subject. Each heat stress exposure involved repeated 20-min bouts of work followed by a 10-min simulated SCBA air cylinder change that incorporated a brief period of no activity where the subject could remove their face shield and respirator and drink some water. Once the heat stress exposure had ended, subjects remained seated in the environmental conditions for a further 30-min recovery period with their helmet, face shield, respirator, SCBA, jacket, flash hood and gloves removed. The overpants were not removed but the Velcro was opened across the groin area.

At the same time as the laboratory trials were being conducted, thermal manikin testing was being performed with the TFS protective clothing ensemble. The purpose of this thermal manikin testing was to generate thermal resistance and water vapour permeability coefficients that could be used in a mathematical heat strain model to predict core temperature increases in different environmental conditions. Model predictions were then compared to the human data collected during the laboratory trials.

Table 1 provides the mean exposure times at the three environmental conditions for the four groups. Cleary, as the amount of internal heat production increased from very light to heavy work exposures times were reduced. Of note, however, is the impact of the environmental temperature on the magnitude of this reduction. Exposure times varied approximately 2-fold among the four work rates at 35°C whereas exposure times varied almost 3.5-fold at 25°C. At the cooler temperatures, there is a greater potential for heat loss to the environment and a greater potential for the sweat that is produced on the skin surface to move through the clothing layers and be evaporated. This is especially true at the lower rates of heat production.

Figure 1 shows that group differences in the delta T_{re} response were evident generally after 10–20 min of exposure. In addition, group differences became evident earlier as the environmental temperature increased. Within group comparisons revealed that approximately 30 min of exposure was necessary before significant differences were found between the 25°C and 30°C exposures or between the 30°C and 35°C exposures.

The thermal manikin evaluations allowed the use of a heat strain model to predict T_{re} responses under the conditions studied during this phase of testing. An example of the comparison between the predicted and observed T_{re} response is shown in Fig. 2. All of the predicted responses were within 1 SD of the observed mean T_{re} data. In addition, the predicted value always erred on the side of conservatism and indicated that a given T_{re} value would occur sooner than the observed response. Thus, the heat strain model was used to generate predictions for environmental conditions that were not examined in the present study. Safe exposure limits were generated for core temperature increases to 38.5°C.

Table 1. Mean values (± standard error) for exposure times in minutes at the ambient temperatures of 25°C, 30°C and 35°C with 50% relative humidity for the four groups performing very light, light, moderate or heavy work

Group	25°C	30°C	35°C
Heavy	56.4 (4.4)	47.4 (3.3)	40.7 (2.3)
Moderate	91.9 (8.5)	65.4 (3.7)	54.0 (3.5)
Light	134.0 (9.3)	77.1 (3.1)	67.3 (3.0)
Very Light	196.1 (12.9)	121.2 (8.4)	86.8 (5.1)

Subsequently, a heat stress wheel that incorporated these exposure limits was produced and disseminated to all fire services in Ontario. This heat stress wheel is depicted in Fig. 3.

At ambient temperatures above 30°C it was clear that the 30-min recovery period did little to promote cooling for the firefighter. As shown in Fig. 4 for the 35°C condition, although heart rates fell following the exercise period, T_{re} continued to increase to levels that were above 39°C. Although part of this rise could be due to the site chosen for the measurement of core temperature, it must be remembered that metabolic heat production was still elevated from the prior exercise periods and that the environmental conditions were not conductive for extensive heat loss. Based on these findings, it was apparent that alternative strategies, other than passive rest, during the rehabilitation periods were necessary in warm environments to help promote cooling.

Phase 2–Strategies to Reduce Heat Stress

A. Pants versus shorts

One option to reduce the heat stress associated with wearing a protective clothing ensemble is to remove some of the clothing layers that comprise the ensemble. The clothing layers that are removed, however, cannot affect the protection and safety of the ensemble provided to the firefighter. Recent evidence from the New York City Fire Department has shown that the replacement of the duty uniform long pants and shirt worn under the bunker clothing with shorts and a T-short did not increase the incidence of burn injury[22]. In addition, their analyses revealed that medical leave for heat exhaustion also decreased when shorts and T-shirt were worn under the bunker clothing[22].

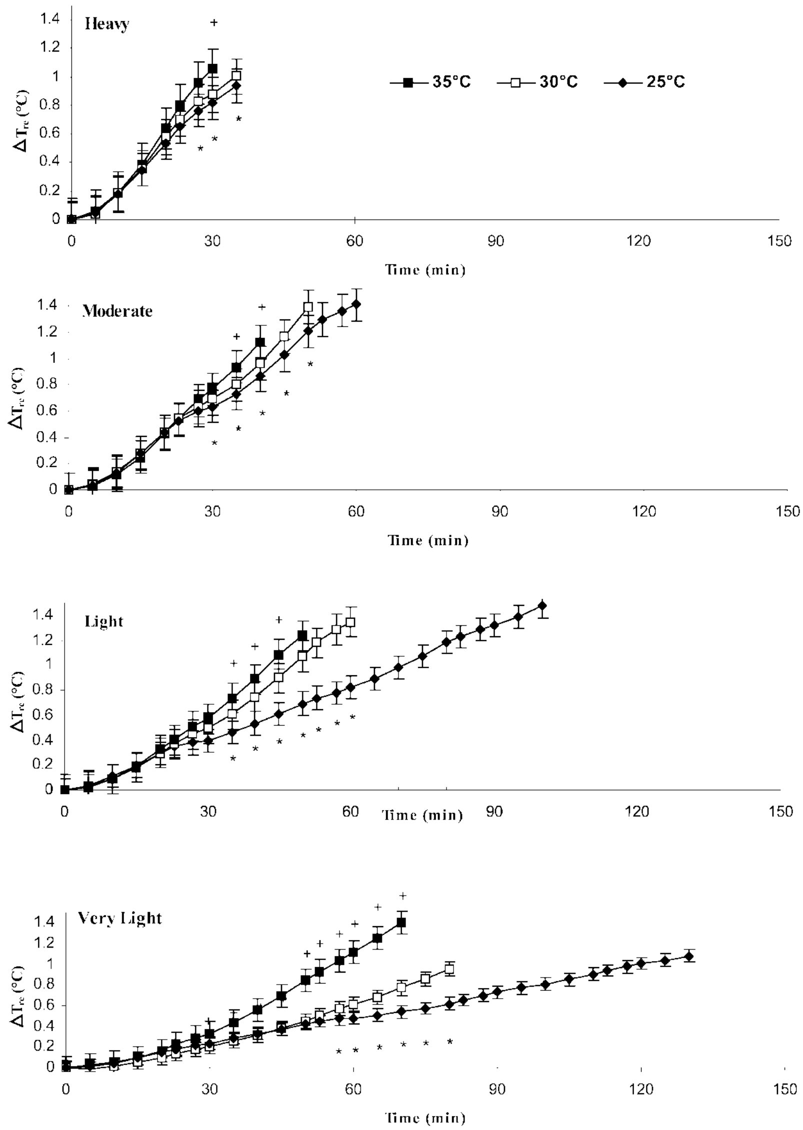

Fig. 1. The change in rectal temperature from rest at 25°C, 30°C and 35°C with 50% relative humidity for heavy, moderate, light and very light exercise while wearing firefighting protective clothing.

The asterisk indicates a significant difference between the 25°C and 30°C conditions whereas the cross indicates a significant difference between 30°C and 35°C. The figure was adapted from Selkirk and McLellan[17].

Our focus was to provide physiological evidence that replacing the duty uniform long pants with shorts improved exposure time during heat stress. To accomplish this, 24 of the subjects tested in phase 1 performed an additional trial while wearing shorts under their bunker pants and exercising at 35°C. Our data revealed that T_{re} was significantly reduced once exposure times exceeded 1 h (Fig. 5). During the 30-min recovery period, T_{re} also was significantly reduced during the last 15 min. In addition, as Table 2 shows, exposure times were significantly increased 10–15% for the lighter activities that involved wearing the protective clothing for longer periods of time that exceeded 60 min.

B. Impact of hydration

Fluid replacement during work in the heat is critical for 2 reasons; first, to maintain sweat rates to promote evaporative cooling[23]; and, second, to maintain blood volume such that the heart can continue to send warm blood to the skin to assist with the transfer of body heat to the environment[24]. In addition, fluid replacement following work in the heat is

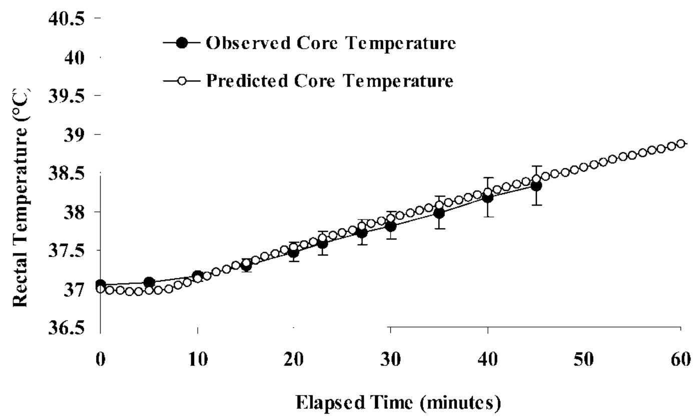

Fig. 2. An example of the relationship between the mean observed rectal temperature response (± 1 SD) during moderate exercise at 35°C and 50% relative humidity while wearing firefighting protective clothing and the core temperature predicted from the heat strain model.

With the exception of very early during the heat stress exposure, all of the predicted values fall within 1 SD of the observed mean response for the group of firefighters. A more detailed explanation of the procedures are explained elsewhere[21)].

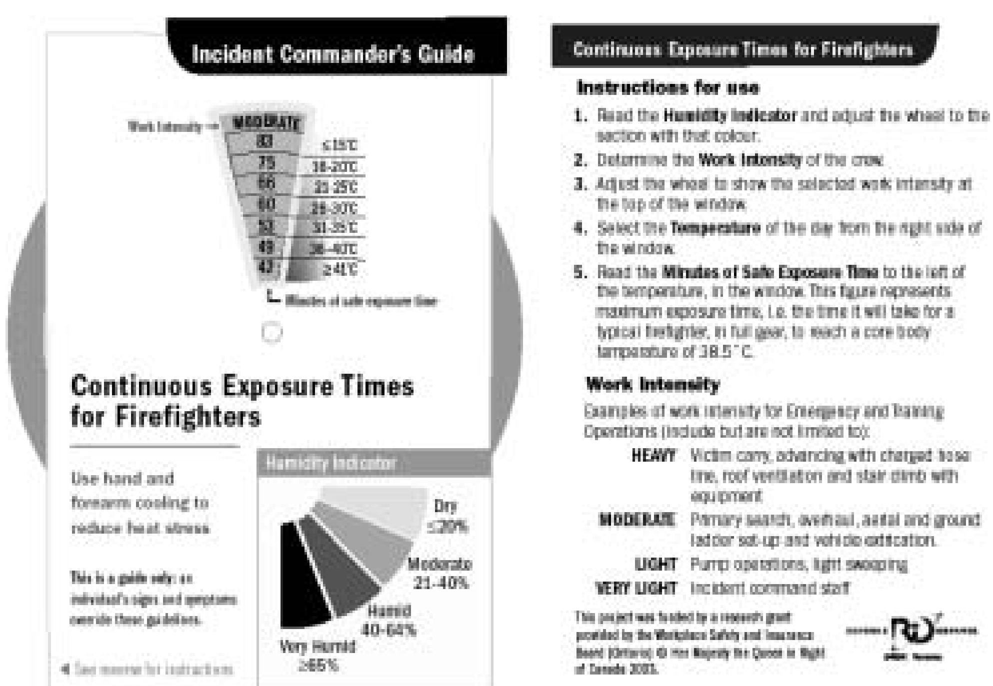

Fig. 3. A picture of the heat stress wheel disseminated through the Ontario Fire Marshall's office to all fire services throughout the province.

critical to restore body fluid levels to normal such that the individual does not begin a subsequent exposure in the heat in a dehydrated state.

Fifteen of our subjects from phase 1 returned to perform another familiarization trial and 4 experimental trials that involved wearing their protective ensemble and performing light exercise at 35°C. The experimental trials manipulated the amount of cool water that was provided throughout the

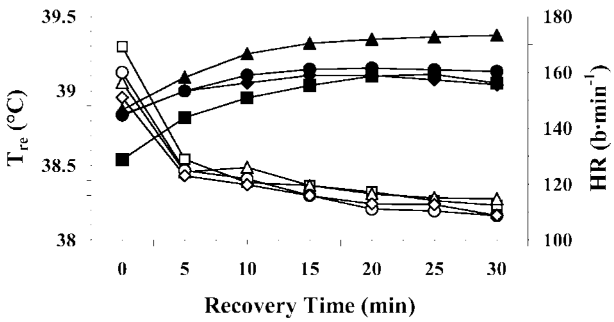

Fig. 4. Changes in rectal temperature (T_{re}) in the closed symbols and heart rate (HR) in the open symbols during 30 min of passive recovery at 35°C and 50% relative humidity following heavy (squares), moderate (triangles), light (circles) and very light (diamonds) exercise.

heat stress and included either no fluid, or 1/3, 2/3 and full fluid replacement determined from the sweat rates measured during the familiarization trial. Subjects performed two 20-min bouts of light exercise that were separated by a 10-min simulated SCBA cylinder change. Following this 50-min cycle, subjects removed most of their protective clothing (except for their boots and bunker pants) and then sat for a 20-min passive recovery period. If subjects were able to continue at this point, they then re-encapsulated in their protective ensemble and began the 50-min cycle of exercise all over again. The 50-min of exercise and 20-min of passive recovery continued until one of our end-point criteria were reached that was described previously. The exception was that T_{re} was allowed to increase to 39.5°C during the exercise phase of these experiments. Aliquots of fluid were provided immediately prior to beginning the heat-stress exposure, during the simulated SCBA cylinder change and at the beginning of the passive rest recovery.

Table 3 shows the effects of fluid replacement on exposure time. Remembering that some of the exposure time was spent resting, the table also shows the impact of fluid replacement on work time. Exposure times were increased approximately 20% when either two-thirds or full fluid replacement was provided and these improvements approached 25% when work time was calculated.

Subjects reported gastric discomfort when they were asked to consume large volumes of fluid and most were unable to consume the equivalent of the full-fluid replacement aliquots. In addition to reducing core temperatures and heart rates, fluid replacement also conferred another advantage to the subjects. Fluid replacement allowed subjects to attain higher core temperatures during the work periods that involved weight-bearing activity. When fluid was not provided, most subjects ended their trials during a rest period and complained of being dizzy when they attempted to stand up and re-encapsulate. In contrast, almost all of the subjects ended their exposure during a work period when two-thirds or full fluid replacement was provided.

C. Active versus passive cooling

The results from the first phase of the research project revealed that alternative cooling strategies were necessary to help reduce core temperature during periods of rest recovery when the firefighter was able to remove most of their protective clothing. The same subjects involved with the study for hydration performed three experimental heat-stress exposures that involved passive cooling or active cooling with either a mister or forearm and hand submersion in cool water. The experimental design was similar to that described above for the study on hydration. The different cooling strategies were applied during the 20-min rest recovery periods. During all trials, subjects received a volume of fluid that was equivalent to the amount of sweat lost during the familiarization trial.

As previously described, the passive rest recovery, or passive cooling, involved removing most of the protective clothing and sitting for 20 min while exposed to the ambient conditions of 35°C and 50% relative humidity. The mister (Versa Mist®) delivered a fan-propelled fine mist vapor at a rate of 2,000 cubic feet per min. Subjects were seated approximately 5 feet in front of the mister where the wind speed at the point of contact for the subjects was 1.94 m·s^{-1} (7 km·h^{-1}). The hand and forearm submersion was accomplished using an insulated tank that was temperature controlled (17.4 ± 0.2°C) prior to submersion in order to simulate hose-line water temperature. During submersion, subjects leaned over the tank with hands and arms submerged to the elbow joint for 20 min.

Both cooling methods significantly reduced T_{re} during the heat-stress exposure and extended exposure and work times (Fig. 6). As shown in Table 4 below, these positive effects were most dramatic when forearm and hand submersion was used to cool the subjects during the rest periods. Compared with passive cooling, forearm and hand submersion extended exposure times 65% and total work time by 60%. In addition, more subjects ended their trial that involved the forearm and hand cooling because they were physically exhausted from having to carry their SCBA for such a long time rather than because they had attained dangerously high core temperatures. It is also noteworthy that 70% of the total heat lost to the water bath occurred during the first 10 min of submersion.

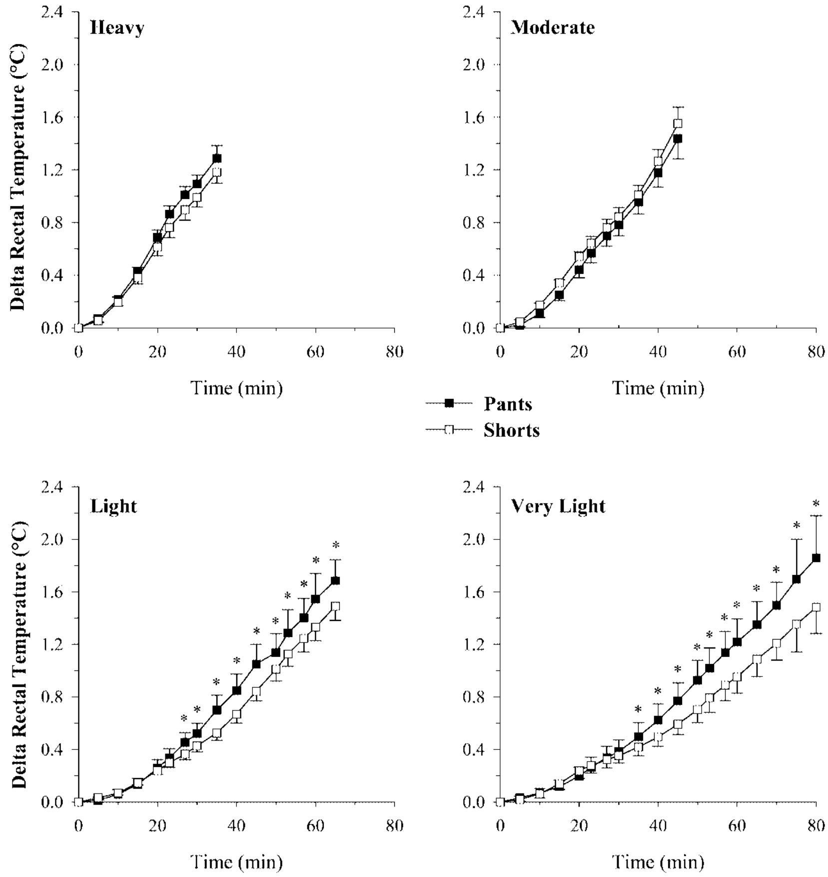

Fig. 5. Delta rectal temperature responses for firefighters while wearing either pants or shorts under the bunker pants during very light, light, moderate or heavy exercise at 35°C.

The asterisk indicates a significant difference when pants or shorts are worn. The figure was adapted from McLellan and Selkirk[18].

Table 2. Mean values (± standard error) for exposure times in minutes at 35°C with 50% relative humidity for the four groups performing very light, light, moderate or heavy work while wearing either duty uniform long pants or shorts under the bunker pants. The asterisk indicates a significant difference between long pants and shorts

Group	Long Pants	Shorts
Heavy	40.8 (2.4)	43.5 (2.2)
Moderate	53.5 (3.7)	54.2 (3.4)
Light	65.8 (3.9)	73.3* (3.4)
Very Light	83.5 (4.7)	97.0* (5.1)

Table 3. Mean values (± standard error) for exposure times and work times at 35°C with 50% relative humidity while subjects performed light work while wearing their firefighting protective ensemble and received either no fluid or one-third, two-thirds or full fluid replacement. The asterisk indicates a significant difference to the no fluid trial

	Fluid Replacement			
	No Fluid	One-Third	Two-Thirds	Full
Exposure Time (min)	95.3 (3.8)	104.2* (5.8)	112.9* (5.2)	111.8* (3.5)
Work Time (min)	65.3 (3.8)	74.2 (5.8)	82.9* (5.2)	82.6* (3.5)

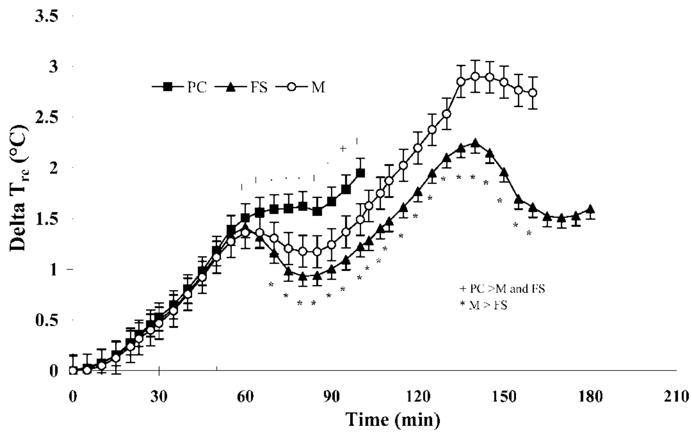

Fig. 6. Delta rectal temperature responses for firefighters while wearing protective clothing during light exercise at 35°C and receiving either passive cooling (PC), forearm and hand submersion (FS) or cooling with a mister (M) during 20-min rehabilitation periods that followed 50-min work bouts. The figure was adapted from Selkirk *et al.*[19].

Table 4. Mean values (± standard error) for exposure times and work times at 35°C with 50% relative humidity while subjects performed light work while wearing their firefighting protective ensemble and received either passive cooling or active cooling with either a mister or forearm and hand submersion during rest periods

	Cooling Method		
	Passive	Mister	Forearm and Hand Submersion
Exposure Time (min)	108.0 (3.59)	139.1* (8.28)	178.7* (13.00)
Work Time (min)	78.0 (3.59)	95.1* (4.96)	124.7* (7.94)

Discussion

The purpose of the present research was twofold; first, to further define the physiological strain associated with wearing FPC and SCBA at various ambient temperatures, and second, to recommend various intervention strategies that could be used to reduce and manage the heat strain experienced by the firefighter, thereby reducing their risk for heat injury. Although, we could not simulate the radiant heat of direct fire exposure in our climatic chambers we recognized that many firefighting activities do not involve direct exposure to a fire (e.g. overhaul, toxic spills). Indeed, it has been documented that a significant proportion of the firefighter's time is spent in a non-fire environment wearing their protective ensemble and using their SCBA[8]. As such, we realized the importance to document the heat-stress associated with wearing a firefighting protective ensemble during ambient conditions that are representative of the warm summer months in temperate climate regions such as Toronto.

To ensure that our findings would be applicable to all members of the TFS, a large sample size was recruited in order to encompass a full spectrum of active TFS personnel. We also attempted to control or match for many factors that might influence the thermoregulatory and cardiovascular responses during heat-stress such as fitness[25], age[26] and gender[27].

It has been well documented that certain firefighting activities incorporate a large amount of heavy upper body work for short durations[28, 29]. However it is important to realize that firefighters self-pace and work in pairs using work and rest schedules in order to continue these activities until their SCBA alarms sound. Since heat storage is a function of the absolute rate of heat production[30], it was inconsequential for the purpose of our study whether the firefighters' metabolic heat was generated using arm, leg, or a combination of arm and leg exercise.

Phase 1

The findings from phase 1 of our research showed that tolerance time while wearing the FPC and SCBA was dependent on both the work rate and the environmental conditions. The relationships observed between tolerance time and metabolic rate[17] were similar to those described for military personnel wearing biological and chemical protective clothing[13, 31]. In addition, the validation of the heat strain model with our laboratory findings was consistent with previous validation studies using military protective ensembles[32]. Thus, the internal validity of the prediction model from the current and past[32] work generated an increased confidence in applying the model to other environmental conditions that were not specifically examined in the current project. The heat stress wheel that was produced (Fig. 3) from this phase of the study has been approved for use by the Ontario Fire Marshall's office.

Another important finding from the first phase of the study was the fact that passive recovery did little to cool the firefighter when they continued to be exposed to the warm ambient conditions. In the present study, and in others[9, 10, 33], it has been found that T_{re} continues to rise 5 to 10 min into recovery increasing the risk of heat injury after work in FPC. The present work also revealed that HR should not be used as an index of the heat strain being experienced by the firefighter during recovery. Clearly, as evident when comparing Fig. 4, the fall in HR during recovery would not predict or indicate the continued rise in T_{re} during exposure to 35°C. These findings, therefore, were instrumental in rationalizing the need to examine alternative strategies during phase 2 of our work that would assist in reducing and managing the heat strain of firefighters and allow subsequent work schedules to be completed.

Phase 2

Pants Versus Shorts

Recent studies by Malley *et al.*[34] and Prezant *et al.*[35] have provided support for the decision to replace the duty uniform with shorts and a T-shirt for the New York City Fire Department. In the former study, Malley *et al.*[34] had firefighters exercise on a treadmill at room temperature at workrates that led to exhaustion in 15–20 min. Although exercise time was significantly extended from 15 to 17 min when shorts were worn there was no effect on the core temperature increase over this short duration of activity. The findings from the present study would extend this null effect to include moderate and heavy workrates that lead to exhaustion in less than 60 min. However, as tolerance times are extended because of lower rates of heat production there is a greater opportunity for changes in the thermal resistance of the clothing ensemble to impact on the heat loss to the environment. As a result, thermal strain is reduced and tolerance times are extended, as they were for groups performing light exercise in the present work. Physiological manipulations such as heat acclimation[36, 37] endurance training[36, 38] and hydration[39] have all been shown to only exert an influence on exercise time in the heat while wearing protective clothing during lower metabolic rates where tolerance times are extended beyond 60 min.

If the benefits for replacing P with S are only evident during activities that last beyond 60 min is this relevant for firefighters? Firefighting activities can demand a very high percentage of VO_{2max}[28, 29] that can lead to exhaustion in less than 20 min. However, self-pacing and the implementation of work and rest schedules could easily extend the involvement of the firefighter well beyond 20 min. Commanders might also rotate personnel between heavier and lighter duties following exchange of air bottles every 20 min to maximize their availability. Further there are numerous situations where firefighters are required to wear their protective ensemble with or without their SCBA that does not involve fire suppression activity. In these situations such as emergency response, accident investigation and building clean-up following fire suppression the intensity of the work effort may be equal to or lower than those involved with the demands of fire suppression. In all of these situations where exposure time while wearing the firefighting protective ensemble would be extended beyond 60 min, the current findings would suggest that the replacement of P with S would reduce the thermal and cardiovascular strain and extend tolerance time approximately 10–15%. These are not huge improvements but they are comparable to the relative improvements noted following heat acclimation[37] or fluid replenishment[39] when protective clothing is worn while performing light exercise in a hot environment.

Of perhaps greater concern for those responsible for authorizing the replacement of P with S is whether the protection of the ensemble is in any way compromised such that the firefighter would be at greater risk to injury. The recent prospective analyses of New York City firefighters would suggest that the burn incidence and severity were not affected by replacing P with S[35]. Indeed, this prospective analysis also suggested that days lost for medical leave due to heat exhaustion were significantly reduced when S was worn[35]. Taken collectively, therefore, the findings from the present study and those from Malley *et al.*[34] and Prezant *et al.*[35] would support the recommendation to replace P with S. The TFS has now also supported this recommendation.

Fluid Replacement

Fluid restriction[39–41] and hypohydration[40] have been shown to have detrimental effects on tolerance time while wearing protective clothing. Dehydration of one to three percent of body mass is associated with decrements in both psychological[42, 43] and physiological[44–46] performance. A core temperature increase of 0.1°C–0.2°C has been reported for every percentage decrease in body mass[46–48] and an elevated internal temperature can increase mental and cognitive impairments, such as increasing decision time and decreasing working memory[46] as well as lead to unsafe behaviour in the workplace[49].

Stimuli to drink are not activated until a dehydration of approximately 2% of body weight occurs[44], thus while working in the heat, an individual's thirst response will not accurately predict body fluid needs[49]. Therefore, even when fluid is administered *ad libitum*, the drive to drink is inadequate to maintain an euhydrated state during heat-exposures[44, 50]. This phenomenon has been called voluntary dehydration, which represents a complex process that incorporates both psychological and physiological stimuli[51, 52]. Given the importance of maintaining euhydration while working in the heat and wearing protective clothing, forced hydration schedules must be examined in order to ensure proper fluid replacement.

The effectiveness of fluid replacement depends on a number of factors such as volume[23, 53] and temperature[41, 54] of the fluid ingested, the rate of gastric emptying from the stomach, the rate at which fluid is absorbed from the small intestine[55, 56] and type of exercise being performed[57]. In addition, as thermal strain and dehydration increase, there is a decrease in the rate of gastric empting due to decreased stomach secretion and contraction[58].

In the current study, there was a significant decrease in the T_{re} tolerated at the end of the final work period when no fluid was provided compared to the full fluid replacement trial (38.8°C vs. 39.1, respectively). These findings are consistent with those reported previously by McLellan and Cheung[41] who used a continuous exercise and heat-stress protocol. Thus when fluid is not provided, cardiovascular stability is compromised such that exhaustion occurs at an earlier T_{re} during weight-bearing activity. This observation is similar to the response observed between trained and untrained individuals[25], where the untrained individuals experienced a greater cardiovascular strain at a given T_{re} due to lower blood and stroke volumes[59]. In fact, fluid replacement during work in the heat has been deemed as important as hydration status prior to work[40]. In addition, failure to replace fluid loss can negate advantages obtained from acclimation[40] and/or aerobic fitness[47] placing a high fit or acclimated individual at higher risk of heat-related illness. From a health and safety perspective, fluid replacement allows higher core temperatures to be tolerated during weight-bearing activity. This is especially important for firefighters and other workers wearing protective clothing and exposed to high levels of heat stress.

Increased sweat rates without an increase in sweat evaporation, as observed when wearing encapsulating clothing, can lead to an increase in the rate of dehydration and thermal strain[40, 60]. Since dehydration by as little as 2% body weight can have a detrimental effect on heat strain and tolerance during uncompensable heat-stress while working in FPC and SCBA, limiting the extent of this dehydration should be a goal of the active firefighter. Given that fatigue and heat-related illness correspond to a critical limiting T_{re}[61], fluid ingestion may be a viable way of attenuating the development of physiological strain through the reduction of T_{re} and HR during a given work bout. As a result, proper amounts of fluid replacement could significantly decrease the risk of cardiovascular instability, syncope, myocardial infarction or even death during work in FPC and SCBA.

Active Versus Passive Cooling

In this study both the use of the mister and the hand and forearm submersion were effective in extending both work and total exposure time in the heat. However, the use of hand and forearm submersion was clearly the better cooling option under the conditions that were studied. Hand and forearm submersion in cool water produces a vasoconstriction of the AVA's through centrally mediated temperature receptors in order to maintain thermal equilibrium. However, when the body is in a hyperthermic state, it has been shown that vasodilation of AVA's is not compromised at water temperatures ranging from 10–30°C[62–64]. Optimal water bath temperatures have been found to be between 10–20°C, with the cooler water producing faster rates of body cooling at the onset, with a subsequent plateau observed after 20–30 min of submersion[62]. In the present study, heat transfer to the water bath was comparable to previous work using extremity submersion at 20°C[62, 65]. As well, a greater heat transfer to the water bath was observed during the first 10 min of the submersion compared to min 10–20, as has been previously reported[62, 65], due to the elevated heat transfer gradient at the beginning of the submersion.

In the past, the implementation of work and rest cycles has been found to help increase total work time, assuming that environmental conditions allow for cooling during rest periods[66]. At higher ambient conditions or when wearing protective clothing while remaining encapsulated, work and rest schedules may not allow for more total work to be accomplished. Furthermore, even removing restrictive clothing during rest, such as SCBA and upper body protective gear, may not be adequate to extend total work times at higher ambient conditions or metabolic rates. For example, during the phase 1 study, firefighters following a continuous work protocol similar to the present study produced tolerance times of 67 min. Given that the T_{re} cut-off was a conservative 39.0°C during phase 1, subjects' tolerance time would have increased by 17 min to 84 min if they had been allowed to continue until T_{re} values equaled 39.5°C (as they did in phase 2). In contrast, during phase 2 passive cooling (removing upper body protective gear), produced an average tolerance time of 108 min of which 78 min represented actual work time. In this comparison, passive rest did extend the tolerance time, but actually reduced the amount of total work performed (78 versus 84 min). However, by incorporating an active cooling strategy during the designated rest periods, WT was increased by 25% and 60% during M and FS, respectively, when compared to PC.

When dealing with protective clothing ensembles in an occupational health and safety setting, the goal is to set limits such that individuals never reach their critical limits. From this view point, it is preferred that a firefighter succumbs and stops work due to physical exhaustion as opposed to heat exhaustion, similar to which has been observed during work at higher metabolic work rates[10, 17, 67]. Not only did forearm submersion extend TT and WT's by 60% compared to passive cooling and 30% compared to the mister trials, there was a significant reduction in the thermal strain associated with the given workload at a specific period of time. The implications of this finding is that even if the cooling is not used to extend total work time, cooling will significantly reduce the heat strain associated with any given task. Ultimately, this would help to reduce the occurrence of heat-related injury and possibly myocardial infarction in active firefighters.

Summary

The research that was conducted on behalf of the Toronto Fire Service has developed guidelines that allow Incident Commanders to safely manage the heat stress of wearing firefighting protective clothing. Our approach was to first establish safe work limits that would prevent the body's core temperature from reaching dangerously high levels. However, equally important was our approach to show the importance of certain intervention strategies that should be used to assist the firefighter during the rehabilitation period. The importance of being proactive during this rehabilitation period cannot be emphasized enough. Our findings conclusively revealed that by providing adequate fluid replacement and forearm and hand immersion exposure time (and work productivity) increased 100%; and, this increase was accomplished safely without putting firefighters at an increased risk of succumbing to heat illness. Even if 20 min of active cooling seems impractical it must be remembered that 70% of the cooling was achieved in the first 10 min of immersion. Thus, applying this cooling technique for only 10 min would still be a very effective countermeasure strategy.

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