Journal of Occupational and Environmental Hygiene, 1: 199–212
ISSN: 1545-9624 print / 1545-9632 online
DOI: 10.1080/15459620490432114

Physical Work Limits for Toronto Firefighters in Warm Environments

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This study examined the relationship between time to reach critical end points (tolerance time [TT] and metabolic rate for three different environmental temperatures (25°C, 30°C, and 35°C, 50% relative humidity), while wearing firefighting protective clothing (FPC) and self-contained breathing apparatus (SCBA). Thirty-seven Toronto firefighters (33 male and 4 female) were divided into four work groups defined as Heavy (H, n = 9), Moderate (M, n = 9), Light (L, n = 10), and Very Light (VL, n = 9). At 25°C, 30°C, and 35°C, TT (min) decreased from 56 to 47 to 41 for H, 92 to 65 to 54 for M, 134 to 77 to 67 for L, and 196 to 121 to 87 for VL. Significant differences in TT were observed across all group comparisons, excluding M versus L at 30°C and 35°C, and H versus M at 35°C. Comparing 25°C to 30°C, M, L, and VL had significant decreases in TT, whereas only VL had a significant decrease when 30°C was compared to 35°C. For 25°C to 30°C, the relative change in TT was significantly greater for L (37%) and VL (41%) compared with H (16%) and M (26%). For 30°C to 35°C, the relative change among the groups was similar and approximately 17%. During passive recovery at 35°C, rectal temperature (T_{re}) continued to increase 0.5°C above $T_{re\,final}$, whereas heart rate declined significantly. These findings show the differential impact of environmental conditions at various metabolic rates on TT while wearing FPC and SCBA. Furthermore, these findings reveal passive recovery may not be sufficient to reduce T_{re} below pre-recovery levels when working at higher metabolic rates in hot environments.

Keywords metabolic rate, protective clothing, rectal temperature, uncompensable heat stress, work tolerance

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INTRODUCTION

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.[1–3] Other aspects of a fire call include overhaul, ventilation, search and rescue, and salvage.[3] 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 neccessity 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.[2,4,5]

In 1987 changes in legislation led to the National Fire Protection Agency's (NFPA) development of new protective clothing standards.[6] 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. Because the new clothing is typically heavy, thick, multilayered, and bulky, it exacerbates the challenge of thermoregulation because of limited water vapor permeability across the clothing layers, which decreases the rate of heat exchange.[7–9]

Typical bunker gear configurations with SCBA weigh approximately 23 kg.[10–12] The increased bulk and mass can alter both gait mechanics and the efficiency of movement, increasing the metabolic cost of work by up to 50%.[10] Furthermore, when protective clothing ensembles restrict evaporative heat loss through decreased water vapor permeability, the evaporative heat loss required to maintain a thermal steady state can exceed the maximal evaporative capacity of the environment, creating a condition of uncompensable heat stress.[9] In these situations, trapped metabolic heat produced by working muscles, as well as heat gained from the local environment, produce an increased thermoregulatory strain.[11,13] Also, increased skin perfusion in response to the thermal strain during work creates an additional demand on the cardiovascular system.

It is common to record near maximal heart rates in firefighters for prolonged periods of time.[6,10,14–16] Unfortunately, in respect to firefighting many inline deaths from heart attack have been documented each year. The most recent statistics in the

United States reported that 46% (52 of 112) of firefighter deaths in 1999 were due to heart attack.[17] Although the majority of these deaths were firefighters over 50 years of age, 20 were due to heart attack for firefighters under 50. The number of deaths due to heart attack fluctuates slightly from year to year; however, heart attacks consistently represent the most frequent cause of inline deaths for firefighters.[3,18] In light of the inherent physiological strain associated with performing firefighter duties in protective clothing, the gear is a necessary tool for firefighter safety on the modern firefighting scene. Considering the advantages and disadvantages of protective clothing ensembles, there appears to be a trade-off between personal protection and the negative impact of additional metabolic and thermal loads.

The relationship between tolerance time (TT) and metabolic rate is well defined by a hyperbolic function when military protective clothing is worn in hot environments.[19,20] These relationships can be used to suggest safe work and rest schedules that can extend operations beyond those performed in a continuous fashion.[21] Similar information has not been generated for the firefighter, although work time data are available for specific rates of heat production and environmental temperatures.[16] Given that the cardiovascular and thermal strain is substantiated for firefighters,[10,13,15,22,23] there is a need to establish safe work guidelines that can be applied for different environmental temperatures over a range of metabolic rates that encompass firefighting duties and can create an uncompensable heat stress situation. In addition, following firefighting activity, it has been found that rectal temperature (T_{re})[6,10,15] and mean skin temperature ($\bar{T}_{sk}$)[10] continue to rise 5 to 10 min into recovery, increasing the risk of heat injury after work in FPC. These findings pose the following questions: are designated rest periods long enough for T_{re} to return to prerecovery levels; and, at what environmental conditions does a rest period become ineffective?

Therefore, the purpose of the present study was to (1) find out how long personnel can continue to work before reaching unsafe physiological limits while wearing their protective clothing and SCBA at 25°C, 30°C, and 35°C, and 50% relative humidity (RH); (2) determine how rapidly the individual cools during a 30-min recovery period following this work to exhaustion; and (3) examine the relationship between TT and metabolic work rate.

METHODS

Subjects

Following approval by DRDC Toronto's Human Ethics Review Committee, 37 subjects (33 men and 4 women) were selected from a pool of 70 active Toronto firefighters. Prior to participation the subjects were medically screened, and a full explanation of procedures, discomforts, and risks were given before obtaining written informed consent. Medical screening consisted of a baseline 12-lead electrocardiogram, a medical history questionnaire, a pulmonary function assessment, and a doctor's examination. Testing was performed in the climatic chamber at DRDC Toronto between October and May to limit heat acclimation through casual exposure to hot environments.

Determination of $\dot{V}O_{2peak}$

Peak oxygen consumption ($\dot{V}O_{2peak}$) was measured at a comfortable room temperature (22°C) using open-circuit spirometry on a motorized treadmill using an incremental protocol.[19,20] $\dot{V}O_{2peak}$ was defined as the highest observed 30-sec value for oxygen consumption ($\dot{V}O_2$) together with a respiratory exchange ratio ≥ 1.15. Relative values for $\dot{V}O_{2peak}$ in mL/kg/min were expressed in terms of total body mass for individual subjects. Heart rate (HR) was monitored during the treadmill protocol using a transmitter/telemetry unit (Polar Vantage XL, Kempele, Finland). The highest value recorded at the end of the exercise test was defined as peak HR (HR_{peak}). A physical activity profile was obtained by a verbal questionnaire to determine the presence or absence of regular involvement in aerobic activities.

Body surface area was calculated using the Dubois equation.[24] Body density was determined from underwater weighing using body plethysmography to determine residual lung volume.[25,26] Body fatness was calculated using the Siri equation.[27]

Definition of Groups

Firefighters were divided into one of four groups (8–9 men and 1 woman in each group) that performed treadmill exercise defined as Heavy (H, 4.8 km/h, and 5% elevation, $n = 9$), Moderate (M, 4.5 km/h, and 2.5% elevation, $n = 9$), Light (L, 4.5 km/h, and 0% elevation; $n = 10$), and Very Light (VL, 2.5 km/h, and 0% elevation; $n = 9$) in accordance with guidelines established for military work efforts.[28] Subjects were allocated such that the average age, aerobic fitness, and body fatness were similar across the groups (Table I).

Clothing Ensembles

During work, subjects wore their own NFPA standard protective firefighting turnout gear (Garment Model BPR5442TK, Morning Pride, Dayton, Ohio), gloves (Shelby Firewall, Memphis, TN), Nomex® flash hood (Majestic Fire Apparel, Lehighton, PA), helmet (Firedome PX Series, Bullard, Ky.), and SCBA (MSA, Pittsburgh, Pa.). Standard issue cotton station pants and Toronto fire t-shirts were worn beneath the turnout gear, along with underwear, shorts, socks, and running shoes. The Canadian Forces nuclear, biological, and chemical (NBC) impermeable protective overboot was worn in place of the standard rubber boot to simulate the impermeable characteristics of the rubber boot. The total weight of the ensemble approximated 22 kg. During all trials subjects breathed room air as opposed to SCBA; however, full SCBA was carried to simulate the weight of the bottle. The total thermal resistance of the firefighter protective clothing ensemble, determined with a heated articulating copper manikin at a wind

TABLE I. Anthropometric Measurements of Age, Height, Mass, Surface Area, Peak Heart Rate, Peak Aerobic Power, and Body Fatness for Heavy (H), Moderate (M), Light (L), and Very Light (VL) Groups and Overall Sample Mean

Group	Age (y)	Height (cm)	Mass (kg)	A_D[A] (m^2)	HR_{peak}[B] (b/min)	$\dot{V}O_{2peak}$[C] (mL/kg/min)	BF[D] (%)
H (n = 9)	40.2	181.6	85.6	2.06	184.2	51.8	17.3
	(0.8)	(2.2)	(3.4)	(0.05)	(2.8)	(1.9)	(2.0)
M (n = 9)	39.0	177.1	83.1	2.00	189.8	51.7	16.1
	(1.5)	(3.5)	(4.0)	(0.07)	(3.6)	(2.0)	(1.6)
L (n = 10)	40.0	178.9	83.6	2.02	189.3	51.3	16.9
	(1.3)	(3.0)	(3.3)	(0.05)	(2.4)	(2.1)	(1.3)
VL (n = 9)	39.2	180.3	88.2	2.08	186.0	50.5	17.2
	(1.0)	(1.3)	(3.1)	(0.04)	(3.4)	(2.0)	(0.6)
Overall	39.6	179.4	85.1	2.04	187.4	51.3	16.9
	(0.6)	(1.3)	(1.7)	(0.03)	(1.5)	(1.0)	(0.7)

Notes: Values are means (±SE). There were no significant differences observed between the groups.
[A] A_D = surface area.
[B] HR_{peak} = peak heart rate.
[C] $\dot{V}O_{2peak}$ = peak aerobic power.
[D] BF = body fatness.

speed of 0.85 m/sec, was 0.240 m^2/°C/W (1.55 clo). The Woodcock vapor permeability coefficient, determined with a completely wetted manikin, was 0.27.[29]

Experimental Design

All subjects performed a familiarization exposure in the most severe environmental condition (35°C, 50% RH, wind speed <0.1 m/sec), at their designated work rate until attaining one or more of the specific end-point criteria (see below). The first experimental trial was at least 10 days after the familiarization trial to limit the acute effects of acclimation. Each subject then performed randomly assigned experimental sessions at their corresponding work rates at ambient temperatures of 25°C, 30°C, and 35°C and 50% RH, while wearing the full firefighting protective ensemble. Subjects were asked to refrain from hard exercise (i.e., running, swimming, cycling, and weight lifting), alcohol, nonsteroidal anti-inflammatories, and sleep medication 24 hours before each session and also to refrain from consumption of caffeine or nicotine 12 hours before each session. Donation of blood was prohibited within 30 days of any part of the experiment. The protocol timeline was broken into a work and recovery phase as is shown in Figure 1.

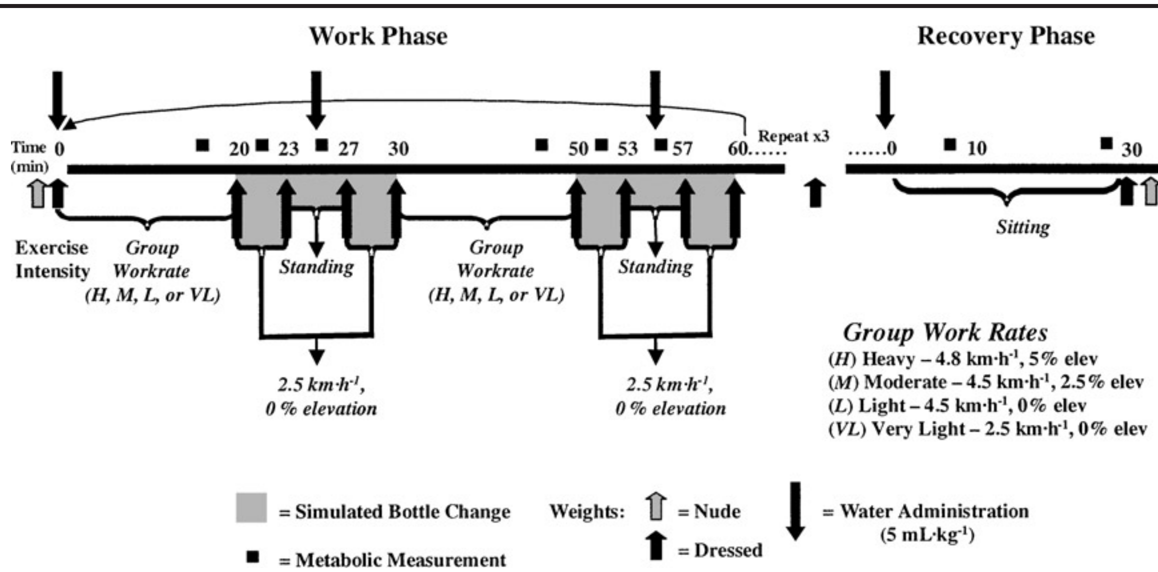

FIGURE 1. Protocol timeline for heat stress trials at 25°C, 30°C, and 35°C and 50% RH, with subjects wearing full firefighting protective clothing and self-contained breathing apparatus

Work Phase

Each work cycle was divided into a work portion and a simulated SCBA bottle change. The work portion consisted of walking at the assigned work rate for 20 min while wearing the protective ensemble and SCBA. At 20 min the simulated SCBA bottle change portion began. Subjects walked at 2.5 km/h, from min 20 to 23 to simulate walking to a bottle change station. After 23 min subjects straddled the treadmill while removing helmet, flash hood, SCBA facepiece, and gloves. At 26 min subjects were asked to don their SCBA, flash hood, helmet, and gloves and to resume walking at 2.5 km/h, from min 27 to 30, thus simulating the return to the work area. At 30 min subjects began another 20-min work portion, repeating the cycle until one or more of the specific end-point criteria was reached.

Recovery Phase

Recovery time zero was defined as the time at which the subject reached one of the specific end-point criteria. After recording a dressed weight, helmet, flash hood, gloves, jacket, tanks, and SCBA facepiece were removed and the subject was seated for the remainder of the 30-min recovery period exposed to the same environmental conditions. Although bunker pants were not taken off, the subjects were allowed to undo the Velcro on the front of the pants.

Specific End-Point Criteria

End-point criteria for the work phase included 4 hours of continuous work, T_{re} reaching 39.0°C, HR reaching or exceeding 95% of maximum for 3 min, dizziness or nausea precluding further exercise, subject exhaustion or discomfort due to the encapsulation of the clothing ensemble and respirator, or the investigator terminating the trial. End-point criteria for the recovery phase were similar to the work phase except that the T_{re} ceiling was raised to 40°C. Tolerance time was defined for all trials as the elapsed time from the beginning of the first work phase to the attainment of one or more of the end-point criteria that resulted in the termination of the work phase and the start of the 30-min recovery phase.

Dressing and Weighing Procedures

To control for the effects of circadian rhythm on T_{re}, all trials began at 7:30 a.m.[30] On arrival, subjects inserted a rectal probe and were weighed nude on an electronic scale, sensitive to the nearest 0.05 kg (Serta Systems Inc., Super-Count, Acton, Mass.). Skin thermistors and HR monitors were applied, and then subjects were dressed in station pants and t-shirts followed by bunker pants, jacket, flash hood, running shoes, and NBC overboot. Following water administration subjects donned SCBA tanks and their respirator facepiece, pulled over their flash hoods, and put on helmet and gloves to obtain full encapsulation. Subjects were then led into the climatic chamber where a final dressed weight was obtained, and skin and rectal thermistor monitoring cables were connected to a computerized data acquisition system (Hewlett-Packard 3497A control unit, 236-9000 computer, and 2934A printer, Pittsburgh, Pa.). Subjects straddled the treadmill walking surface and specific treadmill speed and grade were set prior to the first 20-min work portion.

Upon completion of the recovery phase, a final dressed weight was obtained to encompass all gear and subjects were removed from the climatic chamber. The subjects' nude weight was recorded within 5 min after subjects undressed and towelled dry.

Fluid Replacement

Prior to entering the climatic chamber, at min 25 of each 30-min work + SCBA bottle change cycle, and at the beginning of the recovery period, subjects were given 5 mL/kg of cool water (~15°C) to drink. If T_{re} exceeded 38.5°C or if the subject felt that he or she could not continue for at least another 15 min, water was not administered for the remainder of the work phase. This procedure was implemented to prevent an unabsorbed bolus of water from remaining in the gut after trial termination and effecting subsequent sweat rate calculations.

Physiological Measurements

Temperature Measurements

Mean values over 1-min periods for T_{re} and a 7-point weighted $\bar{T}_{sk}$[31] were calculated, recorded, and printed by the computerized data-acquisition system. T_{re} was measured using a flexible vinyl-covered rectal thermistor (YSI Precisions 4400 Series, Yellow Springs Instrument Co. Inc., Yellow Springs, Ohio) inserted approximately 15 cm beyond the anal sphincter. $\bar{T}_{sk}$ was obtained from seven temperature thermistors (Mallinckrodt, Medical Inc., St. Louis, Mo.) taped on the forehead, abdomen, deltoid, hand, upper anterior thigh, shin, and foot.

Heart Rate Measurements

Heart rate was monitored using a transmitter (Polar Vantage XL), attached with an elasticized belt fitted around the chest and taped in place. The receiver was taped to the outside of the clothing, allowing for a continuous HR display. HR was recorded manually every 5 min during both the work and recovery phases of the heat stress trial.

Gas-Exchange Measurements

Details of the open-circuit spirometry used to determine expired minute ventilation, $\dot{V}O_2$, and carbon dioxide production have been presented previously.[20] Measurements were made during min 17–20 and 20–23 of each 30-min work + bottle change cycle and during min 7–10 and 27–30 of the recovery phase. Values were averaged from a 2-min sampling period for each subject following a 1-min washout period. The current SCBA facepiece outtake valve was modified to incorporate the attachment of an adaptor that allowed expired gases to be collected.

Sweat Measurements

During the trials, all nude and dressed masses were corrected for respiratory[32] and metabolic mass losses,[33] as well as for fluid intake. The rate of sweat production (SR) incorporated both the work and recovery phases.

Blood Sampling and Measurements

A 5-mL blood sample was obtained by venipuncture prior to the dressing procedures to determine osmolality using the Advanced Micro-Osmometer (Model 3300, Advanced Instruments, Norwood, Mass.).

Statistical Analyses

A one factor between (group) and one factor within (environmental temperature) analysis of variance (ANOVA) was used to compare the dependent measures of osmolality, TT, SR, and $\dot{V}O_2$. An ANOVA with one between factor (group) and two repeated factors (environmental temperature and time of exposure) were performed on the various dependent measures sampled over time (ie., ΔT_{re}, $\bar{T}_{sk}$, and HR) for the work and recovery phases. To correct for violations in the assumption of sphericity with the repeated factors, the Huynh-Feldt correction was applied to the F-ratio. When a significant F-ratio was obtained, post-hoc analyses utilized a Newman-Keuls procedure to isolate differences among the treatment means. In addition, the relationship between TT and the average metabolic rate over the duration of the heat exposure was fit with a hyperbolic function.[19,20,34] All ANOVAs were performed using statistical software (SuperAnova V. 1.11 (1991), Abacus Concepts, Inc.). For all statistical analyses, an alpha level of 0.05 was used.

RESULTS

Subjects

Anthropometric measures, HR_{peak} and $\dot{V}O_{2peak}$, are listed in Table I. There were no significant differences among groups for any of these measurements. Although group averages suggest moderate fitness levels, it is important to note that $\dot{V}O_{2peak}$ ranged between 40 and 60 mL/kg/min and subjects' activity levels ranged from sedentary to highly trained in each group.

Pre-Osmolality and Fluid Replacement

There were no significant differences in osmolality within or between the groups with values ranging from 287–293 mOsm/kgH_2O, well within the accepted range for a normal hydrated state.[35] During the heat stress trials subjects consumed 93% of the fluids they were administered. The average rate of consumption was 0.788 ± 0.05 L/h during the heat stress trials and there were no significant differences observed within or between groups.

Work Phase

Gas Exchange

After 20 min of work, there were no significant differences in $\dot{V}O_2$ observed within each group across the three ambient temperatures (25°C, 30°C, and 35°C) and there were no further changes in time during the heat stress. A significant main effect of $\dot{V}O_2$ was observed between all group comparisons. After 20 min of work $\dot{V}O_2$ was 2.09 ± 0.06, 1.62 ± 0.06, 1.29 ± 0.06, and 0.99 ± 0.06 L/min for H, M, L, and VL, respectively. These values approximated 47, 38, 30, and 21% $\dot{V}O_{2peak}$ for H, M, L, and VL, respectively.

Heart Rate

Figure 2 presents the HR response for the four groups during exposure to the three environmental conditions. Between-group comparisons (H vs. M, L, and VL; M vs. L, and VL; L vs. VL) showed that there were significant differences in HR for all group comparisons following the first 5 min of work for all three temperature conditions (25°C, 30°C, 35°C). Within-group comparisons for the 25°C and 30°C conditions revealed that HR was significantly higher in H and M at 30°C after 25 min of work, L after 15 min, and VL after 20 min of exposure. Comparisons between 30°C and 35°C revealed that exercise HR values were significantly higher in VL at 35°C after 20 min and after 40 min for M. There were no significant differences observed for H or L.

Rectal Temperature

The values for initial rectal temperature ($T_{re\,initial}$), final rectal temperature ($T_{re\,final}$), and the rate of T_{re} increase ($\frac{T_{re\,final} - T_{re\,initial}}{TT}$) are given in Table II.

$T_{re\,initial}$. We did not expect any differences for $T_{re\,initial}$ either within or between groups since group allocation was matched for fitness and the presentation of the experimental sessions was randomized. $T_{re\,initial}$ varied by less than 0.2°C between the groups and within the sessions. However, VL was significantly higher compared with H at 25°C, and in addition, M was significantly higher compared to the other groups at 35°C. There were also significant within-group differences. For example, $T_{re\,initial}$ at 30°C was significantly greater than 25°C and 35°C for H. In addition, at 25°C, $T_{re\,initial}$ for M was significantly lower than 30°C and 35°C, and L at 30°C was significantly greater compared to L at 35°C.

$T_{re\,final}$. H was significantly lower than M for all exposures and lower than L and VL at 35°C. Furthermore, $T_{re\,final}$ for VL was significantly lower than M and L at 25°C. When comparing the groups' $T_{re\,final}$ response across the three different temperatures, VL at 25°C had a significantly lower $T_{re\,final}$ compared with 30°C and 35°C.

Rate of T_{re} increase. All within- and between-group comparisons were significantly different for the rate of T_{re} increase during the heat stress trials.

T_{re} response over time. To normalize the differences in $T_{re\,initial}$ data are shown as ΔT_{re} ($\Delta T_{re} = T_{re} - T_{re\,initial}$) in Figure 3. Group differences in the ΔT_{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 neccessary before significant differences were found between the 25°C and 30°C exposures or between the 30°C and 35°C exposures.

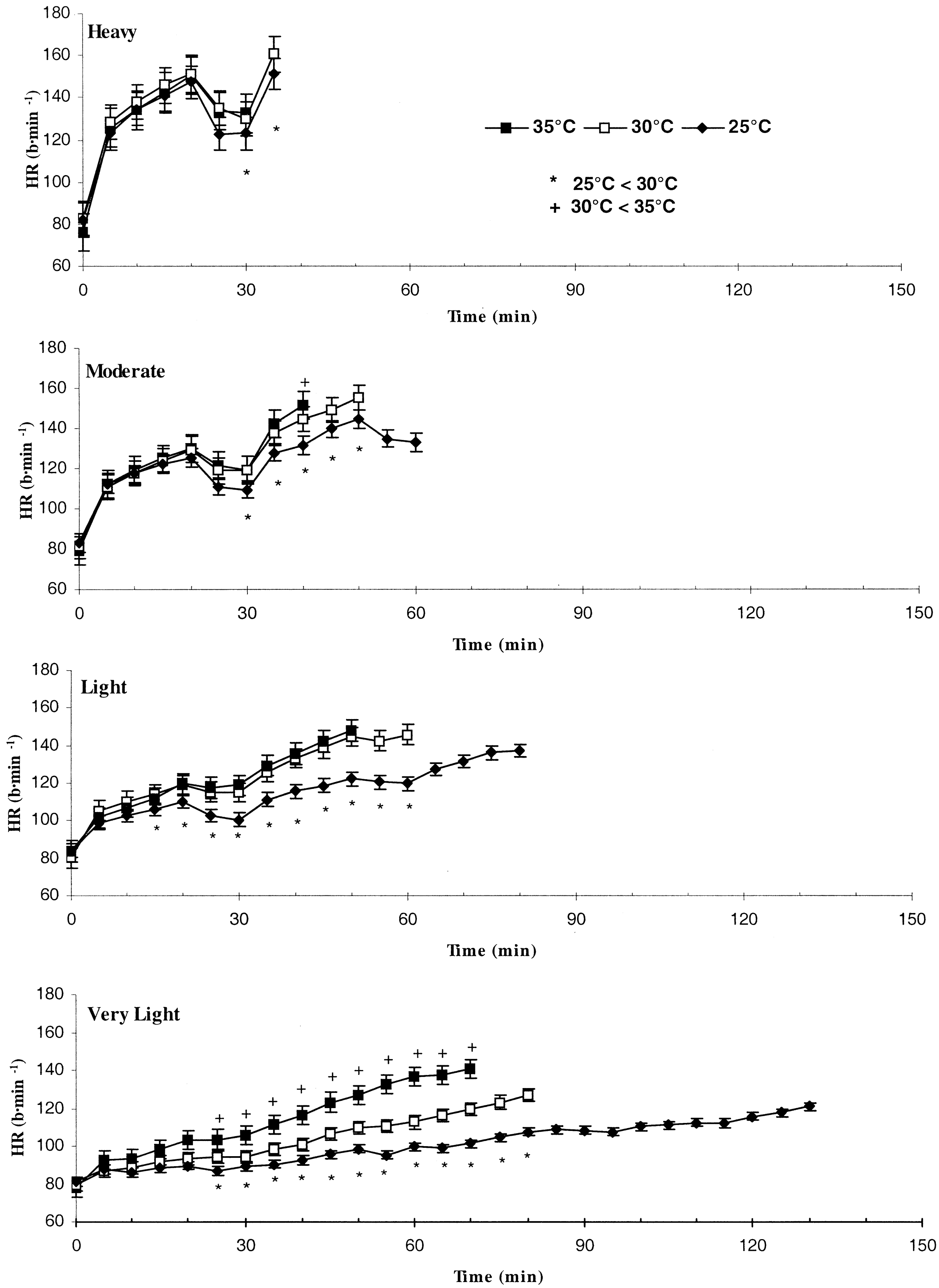

FIGURE 2. HR response during the work phase of the heat stress trial for H, M, L, and VL groups at 25°C, 30°C, and 35°C and 50% RH, with subjects wearing full firefighting protective clothing and self-contained breathing apparatus. Values are means (±SE).

TABLE II. Initial, Final, and Rate of Rectal Temperature Increase During the Work Phase of the Heat Stress Trials at 25°C, 30°C, and 35°C and 50% RH While Wearing Full Firefighting Protective Clothing and Self-Contained Breathing Apparatus for the Heavy (H), Moderate (M), Light (L), and Very Light Work Groups

	$T_{re\ initial}$ (°C)			$T_{re\ final}$ (°C)			Rate T_{re} ↑ (°C·h^{-1})		
Group	25°C	30°C	35°C	25°C	30°C	35°C	25°C	30°C	35°C
H (n = 9)	36.94	37.06^A	36.94	38.65^B	38.69^B	38.53^B	1.78	2.04	2.31
	(0.10)	(0.07)	(0.11)	(0.15)	(0.12)	(0.15)	(0.08)	(0.10)	(0.17)
M (n = 9)	36.92^C	37.05	37.04^D	39.00	39.00	38.88	1.41	1.81	2.03
	(0.11)	(0.09)	(0.10)	(0.00)	(0.002)	(0.10)	(0.09)	(0.08)	(0.07)
L (n = 10)	36.95	37.02^E	36.88	38.91	38.93	38.83^F	0.92	1.50	1.75
	(0.09)	(0.12)	(0.11)	(0.05)	(0.05)	(0.10)	(0.07)	(0.11)	(0.10)
VL (n = 9)	37.02^G	37.01	36.94	38.51^{H,I}	38.77	38.84^G	0.48	0.86	1.32
	(0.10)	(0.12)	(0.11)	(0.16)	(0.10)	(0.10)	(0.07)	(0.05)	(0.10)

Notes: Values are means (±SE). For the rate of T_{re} ↑ all comparisons, both within and between were signficantly different.
[A] Within significance: H-30°C > H-25°C and H-35°C.
[B] Between significance: H < M.
[C] Within significance: M-25°C < M-30°C and M-35°C.
[D] Between significance: M > H, L, and VL.
[E] Within significance: L-30°C > L-35°C.
[F] Between significance: L > H.
[G] Between significance: VL > H.
[H] Between significance: VL < M and L.
[I] Within significance: VL-25°C < VL-30°C and VL-35°C.

Mean Skin Temperature

After 10 min of exercise between-group comparisons revealed significant increases in $\bar{T}_{sk}$ as work rate increased from VL to M at 25°C. As environmental temperature increased to 30°C and 35°C, similar differences were observed after 15 and 20 min, respectively. There were no significant differences observed between H and M as temperature increased from 25°C to 35°C. Within-group comparisons between 25°C and 30°C revealed a significant increase in $\bar{T}_{sk}$ for VL throughout the trial, for M and L after 5 min of work, and for H after 20 min. For 30°C and 35°C a significant increase in $\bar{T}_{sk}$ at 35°C was observed after 15 min for H, 20 min for M and for VL, and 27 min for L. All significant differences remained for the duration of the trial.

Tolerance Time

There were significant differences in the TT observed across all group comparisons, excluding M versus L at 30°C and 35°C, and H versus M at 35°C (Table III). M, L, and VL had significant decreases in TT when ambient temperature increased from 25°C to 30°C, whereas only VL had a significant decrease when comparing the change in ambient temperature from 30°C to 35°C. The decrease in TT from 25°C to 30°C expressed as a percentage was significantly greater for L (40.5 ± 3.9%) and VL (37.3 ± 3.8%), compared with H (15.6 ± 3.6%) and M (26.4 ± 3.7%). However, the percent change in TT from 30°C to 35°C was not different among the groups (17.3 ± 2.1%).

Reasons for trial termination of the sessions are illustrated in Table IV for the various groups. Of the 111 experimental sessions 63% were terminated because T_{re} reached 39.0°C during the work phase. A further 19% were terminated with

TABLE III. Tolerance Time Expressed in Minutes During the Heat Stress Trials Conducted at 25°C, 30°C, and 35°C and 50% RH with Subjects Wearing Full Firefighter Protective Ensemble and Self-Contained Breathing Apparatus for the Heavy (H), Moderate (M), Light (L), and Very Light Work Groups

Group	25°C	30°C	35°C
H (n = 9)	56.4^A	47.4^A	40.7^B
	(4.4)	(3.3)	(2.3)
M (n = 9)	91.9^C	65.4^D	54.0^D
	(8.5)	(3.7)	(3.5)
L (n = 10)	134.0^E	77.1^E	67.3^E
	(9.3)	(3.1)	(3.0)
VL (n = 9)	196.1	121.2	86.8
	(12.9)	(8.4)	(5.1)

Notes: Values are means (±SE). Significant differences between groups:
[A] H < M, L, VL.
[B] H < L, VL.
[C] M < L, VL.
[D] M < VL.
[E] L < VL.
Significant differences within groups: 25°C–30°C – M, L, VL significantly different; 30°C–35°C, only VL significant.

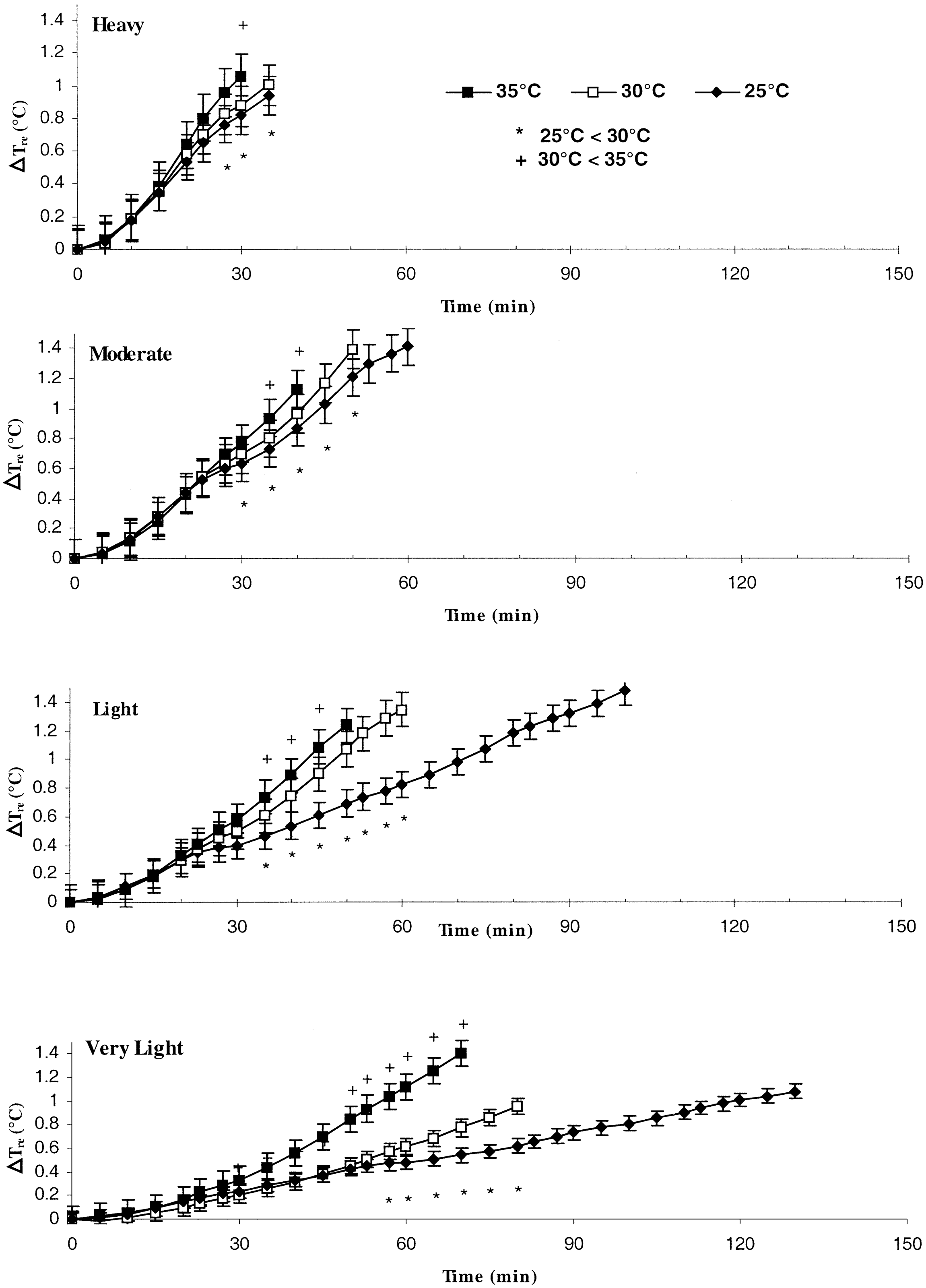

FIGURE 3. ΔT_{re} response during the work phase of the heat stress trial for H, M, L, and VL groups at 25°C, 30°C, and 35°C and 50% RH with subjects wearing full firefighting protective clothing and self-contained breathing apparatus. Values are means (±SE).

TABLE IV. Reasons for Termination of the Heat Stress Trials at 25°C, 30°C, and 35°C with 50% RH for the Heavy (H), Moderate (M), Light (L), and Very Light (VL) Work Groups

	H (n = 9)			M (n = 9)			L (n = 10)			VL (n = 9)		
Reason for Termination	**25°C**	**30°C**	**35°C**	**25°C**	**30°C**	**35°C**	**25°C**	**30°C**	**35°C**	**25°C**	**30°C**	**35°C**
T_{re}	5	4	3	9	8	6	6	8	7	3	5	6
Exh	1	1	1	—	1	2	3	1	1	3	4	3
HR	3	4	5	—	—	—	1	1	1	—	—	—
Dizziness/Nausea	—	—	—	—	—	1	—	—	1	—	—	—
Time	—	—	—	—	—	—	—	—	—	3	—	—

Note: Values represent the number of subjects during each trial that attained a rectal temperature (T_{re}) of 39.0°C, ended due to exhaustion (Exh), reached or exceeded a heart rate (HR) of 95% HR_{peak} for 3 min, ended due to dizziness or nausea, or attained the time limit of 4 hours of work.

subjects complaining of exhaustion, with half of these sessions occuring in the VL group. Eighty percent of all sessions terminated for HR occurred with heavy work. All subjects completed the 30 min of recovery during the recovery phase.

Recovery Phase

Gas Exchange

After 10 min of recovery $\dot{V}O_2$ was similar among all groups and temperatures (0.43 ± 0.02 L/min), and remained similar for the duration of the recovery period (0.36 ± 0.01 L/min).

Heart Rate

Heart rate responses during the 30 min of recovery are depicted in Figure 4. Between-group comparisons revealed that HR was significantly lower for VL compared to the other groups throughout recovery at 25°C and 30°C. At 35°C, however, although HR was different at time 0 among the groups there were no other differences for the remainder of the recovery period. Within-group comparisons revealed significantly lower HR for all groups after 10 min of recovery at 25°C compared with 30°C. In contrast, only group VL displayed lower HR during recovery at 30°C compared with 35°C.

Rectal Temperature

ΔT_{re} during the recovery phase is depicted in Figure 4. Between-group comparisons revealed that ΔT_{re} for H and M were signficantly greater than L and VL after approximately 15 min of recovery. Significant differences in the ΔT_{re} response were also observed for all groups following 10 min of recovery for the comparisons between 25°C and 30°C, and between 30°C and 35°C.

Sweat Rate

There was a significant main effect of temperature on sweat rates. Sweat rates at 25°C (0.39 ± 0.02 $kg/m^2/h$) were significantly lower compared to 30°C (0.49 ± 0.03 $kg/m^2/h$) and 35°C (0.51 ± 0.03 $kg/m^2/h$).

Curve Fitting

The relationship between the average $\dot{V}O_2$ and TT throughout the work phase fit with a hyperbolic function for each of the three environmental conditions is shown in Figure 5. Convergence of the curves can be seen at higher work rates, whereas there is a divergence in TT at lower metabolic rates. The mathematical functions describing these relationships are also presented in Figure 5.

DISCUSSION

The purpose of the present study was to further define the physiological strain associated with wearing FPC and SCBA at various ambient temperatures. 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 nonfire environment wearing their protective ensemble and using their SCBA.(3) As such, we realized the importance in documenting the heat stress associated with wearing FPC 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 Toronto Fire Service, a large sample size was recruited in order to encompass a full spectrum of active Toronto Fire Services personnel. We also attempted to control or match for many factors that might influence the thermoregulatory and cardiovascular responses during heat stress. For example, the percentage of female firefighters in the Toronto Fire Service is less than 10%, justifying the placement of one female in each group. Elevation in $T_{re\ initial}$ in female subjects has been found during the mid-luteal phase compared to the early follicular phase,(36) and thus would affect TT. In light of these findings, female subjects were tested at the same time during each 28-day firefighter shift cycle. The subjects in the present study were matched for age since aging can be associated with a decrease in cardiovascular function, manifested as a decrease in HR_{peak}, and a lowering of $\dot{V}O_{2peak}$. Variations in clothing fit were minimized by having subjects wear their own properly fitted bunker gear.(37) In addition, subjects were matched for aerobic fitness and body fatness—two important factors

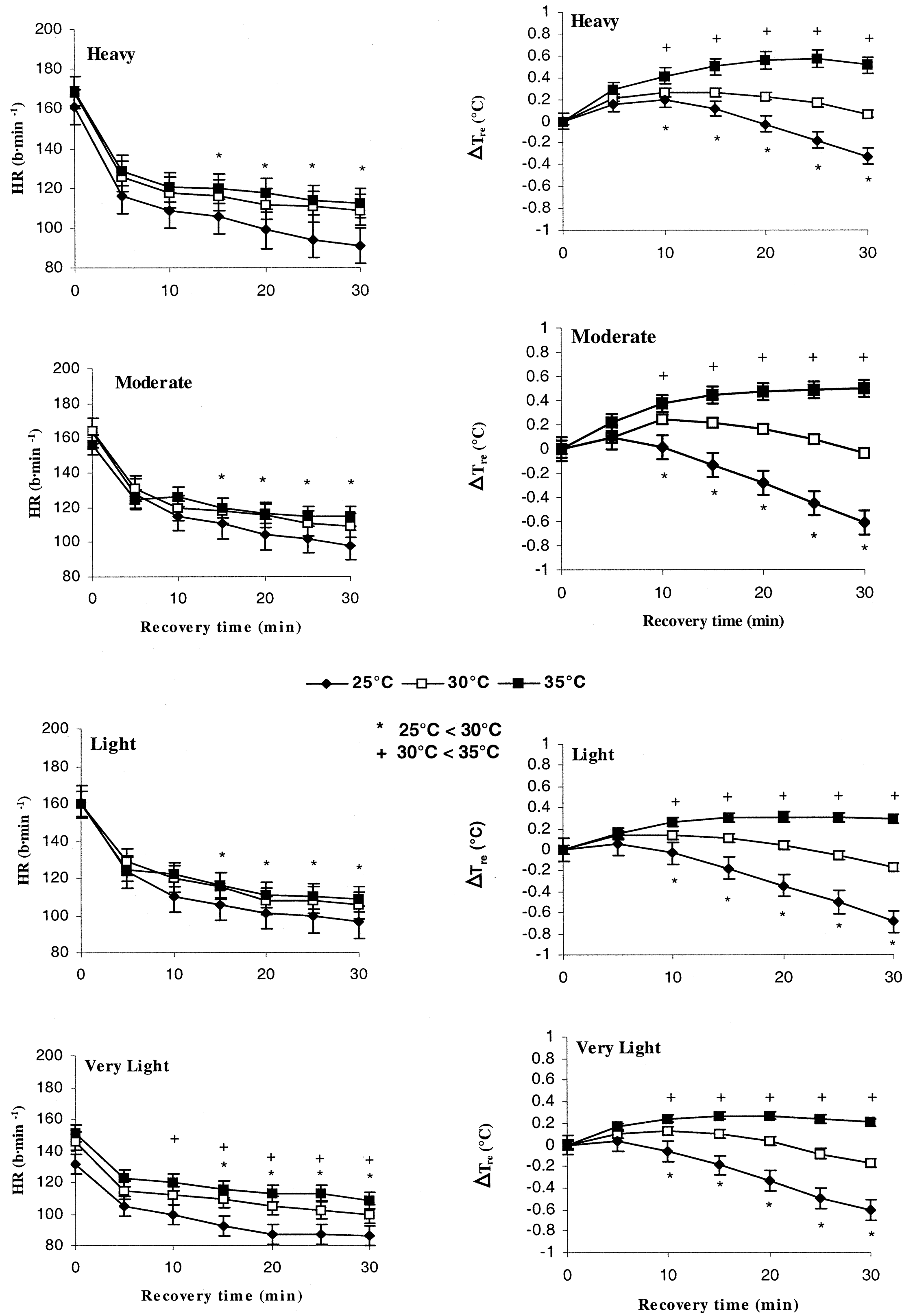

FIGURE 4. HR and ΔT_{re} response during the 30-min recovery phase of the heat stress trials for H, M, L, and VL groups at 25°C, 30°C, and 35°C and 50% RH, with subjects sitting wearing boots, bunker pants, and t-shirts. Values are means (±SE).

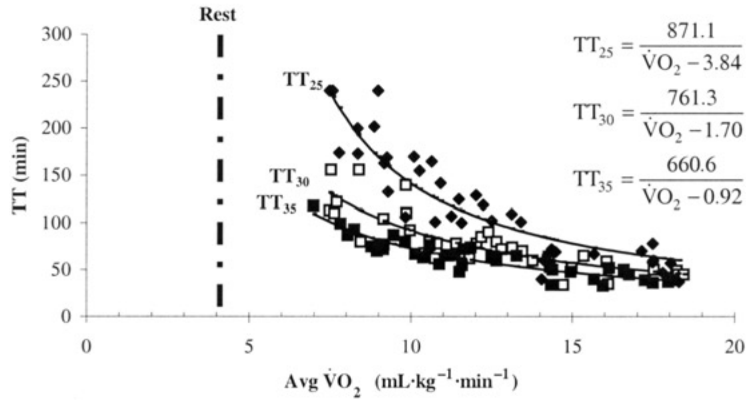

FIGURE 5. Curvilinear relationships between TT and Avg $\dot{V}O_2$ for all subjects at 25°C (◆), 30°C (⊠), and 35°C (⟹) and 50% RH while wearing full firefighting protective clothing and self-contained breathing apparatus. Mathematical hyperbolic functions describing the relationship are also shown for the three ambient conditions. An average resting metabolic rate equivalent to 4.0 mL/kg/min is also presented.

contributing to tolerance of uncompensable heat stress.[38,39] It has been documented that gender is not an issue when dealing with tolerance to uncompensable heat stress where subjects are matched for $\dot{V}O_{2peak}$ and body fatness.[38] Special attention was given to ensure that females in the present study had comparable anthropometric values both between and within each group. Furthermore, considering that TT for the participating females were comparable to group averages and that firefighter recruitment standards within the Toronto Fire Services are independent of gender, active firefighters should have comparable fitness levels, and thus similar responses to those seen in the present work regardless of gender.

Hypohydration is associated with increased cardiovascular and thermoregulatory strain during exercise[40,41] and can lead to a decreased tolerance to uncompensable heat stress regardless of fitness levels.[42] Fluid replacement decreases physiological strain during exercise in the heat[43] and has also been shown to produce a decreased cardiovascular strain while exercising in protective clothing.[44] In the present study, pre-osmolality values were well within the range for normal hydration.[35] In addition, subjects were given 5 mL/kg of water every 30 min during the exposure, equating to approximately 0.6–1.0 L/h. Sweat rates averaged 0.94 L/h across the three temperatures, and thus the percentage of body mass lost due to dehydration was less than 0.5%.

It has been well documented that certain firefighting activities incorporate a large amount of heavy upper body work for short durations.[22,23] 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,[45] 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. Physiologically, cardiovascular strain from leg exercise would be lower compared to arm exercise at the assigned work rates due to the size of the recruited muscle mass. Therefore, in the present study continuous arm exercise was not used to simulate firefighting duties since the smaller muscle mass and local muscle fatigue would limit heat exposure times. As a result, treadmill walking was selected in order to recruit a large muscle mass and to produce TT ranging between 30 and 90 min in the highest ambient environmental temperature of 35°C, 50% RH.

Tolerance time in the present study was dependent on both the work rate and the environmental conditions present. For example, comparisons between H and VL showed that TT increased two- and four-fold at 35°C and 25°C, respectively. In contrast, within the H group there were no significant differences observed in TT as temperatures increased from 25°C to 30°C to 35°C. Final core temperatures were significantly lower for H (∼38.6°C) in the present study compared to the other groups, as 3, 4, and 5 subjects ended because of high HR at 25°C, 30°C, and 35°C, respectively. The lower $T_{re\ final}$ and higher HR observed demonstrate the cardiovascular limitations on TT at these higher metabolic rates lasting between 15–30 min.

Similar findings were made by Smith et al.,[6] and White and Hodus,[46] using work rates of 2.5 L/min and 2.0 L/min, respectively. During these work rates, T_{re} at exhaustion was less than 38.5°C after 30 min of moderate work[46] and less than 38.0°C after 15 min of heavy work.[6] Thus, it appears that firefighters performing heavy work may succumb to physical exhaustion before heat stress becomes a critical issue. However, the firefighter that has difficulty due to cardiovascular limitations may likely have a lower fitness level as well, and thus may tolerate a much lower rectal temperature.[38]

Following firefighting activity, it has been found that T_{re}[6,10,15] and $\bar{T}_{sk}$[10] continue to rise 5 to 10 min into recovery, increasing the risk of heat injury after work in FPC. The present study shows that HR should not be used as an index of the heat strain being experienced by the firefighter during recovery. Clearly, as evident when looking at Figure 4, the fall in HR during recovery would not predict or indicate the continued rise in T_{re} during exposure to 35°C. Similarly, the comparable HR following 30 min of recovery at 30°C and 35°C for groups H, M, and L, for example, do not reflect T_{re} differences (approximately 0.5°C) between these environmental conditions. Our data would not recommend that firefighters be permitted to don their protective clothing and SCBA and begin a subsequent exercise phase at 35°C following this passive recovery period. It would appear that other cooling strategies such as fans[5] or hand and forearm submersion in cool water[47,48] may be necessary to reduce the heat strain and allow subsequent work schedules to be completed.

When working with protective clothing in an occupational setting a major issue of contention is the length of time that an individual can work before succumbing to heat exhaustion. In fact, the main goal should be to set work limits in such a way that the individual approaches but never reaches this state. However, given the vast differences in physical characteristics among working populations this is not an easy task.

The equations representing the curvilinear relationships can be used to predict TT for various work and rest schedules. The value of the vertical asymptote for these equations signifies an infinite TT and delineates compensable and uncompensable heat stress. Thus, an infinite work time for TT_{25} would be predicted at an average metabolic rate of 3.84 mL/kg/min. Since this value is representative of a resting metabolic rate, implementing work and rest schedules while remaining fully encapsulated at 25°C should allow more total work to be accomplished.[21] However, the vertical asymptotes of 1.70 and 0.92 mL/kg/min for the equations representing 30°C and 35°C, respectively, are physiologically unattainable. Even under resting conditions at 30°C and 35°C the body would continue to store heat, thus implementing work and rest schedules while remaining fully encapsulated at these higher ambient temperatures would not allow more total work to be accomplished.

It is recognized that the length of a bottle will depend on a variety of factors such as physical characteristics (fitness, body composition, and mass) and work intensity. However, to allow comparisons between the different work rates, SCBA bottle lengths needed to be standardized in the present work. Our curves that predict TT could easily accommodate different bottle durations (15–45 min) since they are based on a time-weighted average for metabolic rate. Based on the assumption that an average air cycle lasts 30 min (20 min work + 10 min SCBA bottle change), our data predicts that a firefighter performing heavy work at 25°C would last two work cycles (SCBA bottles), or a TT of 56 min. However, working at 35°C, that same firefighter would only make it partially through the second bottle (40 min) before succumbing to exhaustion.

Comparatively, during light work at 25°C, on average the firefighters could continue for at least four bottles (120 min) before succumbing to exhaustion. At 35°C, however, that same firefighter should last only slightly more than two bottles or 67 min. Therefore, based on these examples, a conservative guideline to limit heat-related illness while performing light work would be four bottles or 120 min at 25°C, and two bottles or 60 min at 35°C before going to a recovery station. A similar guideline of two and one bottles could be set for the heavy group in regard to continuous work for 25°C and 35°C, respectively. Based on these two examples our prediction equations could be used to establish guidelines for each of the remaining conditions and work rates. Furthermore, for metabolic rates which are higher than group H in the present study it is likely that the firefighter would succumb to physical exhaustion during continuous work before significant elevations of T_{re} are achieved.

If body cooling can occur during periods of rest, then implementing work and rest schedules can increase the total work time while reducing the heat strain.[34] Group M had an average metabolic rate of 13 mL/kg/min throughout each of the heat stress exposures. Based on the prediction equation TT_{25}, continuous work at this average metabolic rate would produce a TT of 90 min. If an intermittent work and rest cycle involving 15 min work and 15 min of rest was implemented, the average metabolic work rate for M would be reduced to 8.5 mL/kg/min which assumes a resting $\dot{V}O_2$ of 4 mL/kg/min. Thus, this lower average metabolic work rate would increase TT to 190 min and the total work performed to 100 min. In contrast, at 35°C, continuous work for M would produce a TT of 55 min based on equation TT_{35}. Incorporating a similar intermittent work and rest cycle would increase total TT to 90 min while reducing total work time to 45 min. Thus, in the latter situation, at 35°C, an intermittent schedule would not be optimal for maximizing total work while remaining fully encapsulated.

What would be the effect of an intermittent work and rest cycle where protective clothing was removed during recovery? Consider an intermittent schedule with recovery periods similar to the present study. Firefighters working in group H had rectal temperatures of approximately 38.0°C for both the 25°C and 35°C conditions after 30 min of exposure (see Figure 3 and Table II). Thus, assuming a 30-min work and rest cycle, after 30 min of work the firefighters would then go to recovery for 30 min. T_{re} after the 30 min of recovery would theoretically be 37.7°C and 38.5°C for 25°C and 35°C, respectively (see Figure 4). Thus, if it is recommended that T_{re} not exceed a critical temperature of 39.0°C when performing work in FPC,[15] the firefighter working at 25°C would be able to return to work for at least one more work cycle (SCBA bottle). However, the firefighter working in the ambient temperature of 35°C would not be able to complete a second bottle of air before reaching a potentially dangerous heat stress situation. Thus, during the recovery period, even removing some parts of the protective clothing ensemble may not be sufficient to extend work times in warm environments.

Clearly, these findings have illustrated the importance of developing methods for keeping active firefighters' T_{re} below a critical level. There are many ways this can be accomplished. In cooler ambient conditions, implementing work and rest cycles could increase total work time while slowing the rise in T_{re}. Furthermore, if operational requirements permit commanders to rotate duties, this may be another effective method to reduce the average metabolic rate and thereby extend TT.

At higher environmental temperatures a work and rest schedule that incorporates some form of active cooling during the recovery period may be the only viable option available to extend work times. For instance, forearm submersion[47,48] or fan cooling[5] have been suggested as modalities for active cooling. However, the effectiveness of these modalities during subsequent work periods has not been conclusively addressed. The restriction of fluid or beginning work in a hypohydrated state has also been shown to have detrimental effects when exposed to uncompensable heat stress for longer than 60 min,[49] yet there are presently no known guidelines for firefighters. Further examination of such factors need to be elucidated in order to maximize firefighter performance and safety.

CONCLUSIONS

The present findings document the differential impact of environmental conditions at various metabolic rates on TT while wearing FPC and SCBA. Implementation of work and rest schedules at lower metabolic rates and environmental temperatures may be sufficient to extend work times. However, at higher ambient temperatures passive recovery may not be sufficient to reduce T_{re} below prerecovery levels. Furthermore, during passive recovery in hot environments HR may not be used as an indicator for the extent of heat strain being experienced by the firefighter. Thus, combining the relationship between TT and metabolic rate and potential active cooling modalities, safe work limits can be developed for firefighters working in various ambient conditions while wearing FPC and SCBA.

ACKNOWLEDGMENTS

The authors acknowledge the assistance and technical support of Jan Pope, Robert Limmer, John Hilton, and Peter Tikuisis. Also, special thanks to all of the volunteers from the Toronto Fire Services for their willingness to participate in this research supported by the Ontario Workplace Safety Insurance Board.

Funding for this study was provided by the Ontario Workplace Safety Insurance Board.

REFERENCES

1. **Lusa, S., V. Louhevaara, and K. Kinnunen:** Are the job demands on physical work capacity equal for young and aging fire-fighters. *J. Occup. Med. 36*:70–74 (1994).
2. **Baker, S.J., J. Grice, L. Roby, and C. Matthews:** Cardiorespiratory and thermoregulatory response of working in fire-fighter protective clothing in a temperate environment. *Ergonomics 43*:1350–1358 (2000).
3. **Austin, C.C., G. Dussault, and D.J. Ecobihon:** Municipal firefighter exposure groups, time spent at fires and use of self-contained-breathing-apparatus. *Am. J. Ind. Med. 40*:683–692 (2001).
4. **White, M.K., M. Vercruyssen, and T.K. Hodous:** Work tolerance and subjective responses to wearing protective clothing and respirators during physical work. *Ergonomics 32*:1111–1123 (1989).
5. **Carter, J.B., E.W. Banister, and J.B. Morrison:** Effectiveness of rest pauses and cooling in alleviation of heat stress during simulated fire-fighting activity. *Ergonomics 42*:299–313 (1999).
6. **Smith, D.L., S.J. Petruzzello, J.M. Kramer, S.E. Warner, B.G. Bone, and J.E. Misner:** Selected physiological and psychobiological responses to physical activity in different configuratons of firefighting gear. *Ergonomics 38*:2065–2077 (1995).
7. **McLellan, T.M., I. Jacobs, and J.B. Bain:** Influence of temperature and metabolic rate on work performance with Canadian forces NBC clothing. *Aviat. Space Environ. Med. 64*:587–594 (1993).
8. **Nunneley, S.A.:** Design and evaluation of clothing for protection from heat stress: An overview. In J.B. Morrison, ed., *Environmental Ergonomics: Sustaining Human Performance in Harsh Environments*, pp. 87–89. Philadelphia, Pa.: Taylor & Francis, 1988.
9. **Givoni, B., and R.M. Goldman:** Predicting rectal temperature response to work, environment, and clothing. *J. Appl. Physiol. 32*:812–822 (1972).
10. **Duncan, H.W., G.W. Gardner, and R.J. Barnard:** Physiological responses of men working in fire fighting equipment in the heat. *Ergonomics 22*:521–527 (1979).
11. **Smith, D.L., S.J. Petruzzello, J.M. Kramer, and J.E. Misner:** Physiological, psychophysical, and psychological responses of firefighters to firefighting training drills. *Aviat. Space Environ. Med. 67*:1063–1068 (1996).
12. **Smith, D.L., S.J. Petruzzello, J.M. Kramer, and J.E. Misner:** The effects of different thermal environments on the physiological and psychological responses of firefighters to a training drill. *Ergonomics 40*:500–510 (1997).
13. **Smith, D.L., T.S. Manning, and S.J. Petruzzello:** Effect of strenuous live-fire drills on cardiovascular and psychological responses of recruit firefighters. *Ergonomics 44*:244–254 (2001).
14. **Romet, T., and J. Frim:** Physiological responses of fire fighting activities. *Eur. J. Appl. Physiol. 56*:633–638 (1987).
15. **Faff, J., and T. Tutak:** Physiological responses to working with fire fighting equipment in the heat in relation to subjective fatigue. *Ergonomics 32*:629–638 (1989).
16. **Skoldstrom, B.:** Physiological responses to fire fighters to workload and thermal stress. *Ergonomics 30*:1589–1597 (1987).
17. **United States Fire Administration (USFA):** *Firefighter Fatalities in the United States in 1999* (Contract No. EME-1998-CO-0202-T0006). Emmitsburg, Md.: USFA, 2000.
18. **Washburn, A.E., P.R. Leblanc, and R.F. Fahey:** Fire fighter fatalities. *NFPA J. July/August*:50–62 (1998).
19. **McLellan, T.M.:** Work performance at 40°C with Canadian Forces biological and chemical protective clothing. *Aviat. Space Environ. Med. 64*:1094–1100 (1993).
20. **McLellan, T.M., J.I. Pope, J.B. Cain, and S. Cheung:** Effects of metabolic rate and ambient vapor pressure on heat strain in protective clothing. *Eur. J. Appl. Physiol. 74*:518–527 (1996).
21. **McLellan, T.M.:** *Tolerance Times for Continuous Work Tasks While Wearing NBC Protective Clothing in Warm and Hot Environments and the Strategy of Implementing Rest Schedules*, DCIEM No. 94-62. Toronto: Defence and Civil Institute of Environmental Medicine, 1994.
22. **Lemon, P.W., and R.T. Hermiston:** The human energy cost of fire fighting. *J. Occup. Med. 19*:558–562 (1977).
23. **Gledhill, N., and V.K. Jamnik:** Characterization of the physical demands of firefighting. *Can. J. Appl. Physiol. 17*:207–213 (1992).
24. **Gephart, F.C., and E.F. DuBois:** Clinical calorimetry, fourth paper. The determination of the basal metabolism of normal men and the effect of food. *Arch. Int. Med. 15*:833–845 (1915).
25. **Clausen, J.L.:** *Pulmonary Function Testing Guidelines and Controversies: Equipment, Methods and Normal Value*. Toronto: Grune and Stratton, Inc., 1982.
26. **Forsyth, R.D., M.J. Plyley, and R.J. Shephard:** Estimation of body fatness of Canadian forces. *Can. J. Appl. Sport Sci. 9*:5P (1984).
27. **Siri, W.E.:** The gross composition of the body. In *Advances in Biological and Medical Physics,* vol. 4, pp. 239–280. New York: Academic Press, 1956.
28. **Gonzalez, R.R., L.A. Stroschein, J.A. Gonzalez, and K.B. Pandolf:** *Copper Manikin and Heat Strain Model Evaluations of Chemical Protective Ensembles for the Technical Cooperation Program (TCCP)*, Tech.

Rep. 94-4. Natick, Mass.: U.S. Army Research Institute of Environmental Medicine, 1993.
29. **R.R. Gonzalez:** Manikin results for the thermal resistance and water vapour permeability of Toronto firefighting protective clothing. April, 2003. United States Army Research Institute of Environmental Medicine, Natick, MA. (Personal Communication.)
30. **McLellan, T.M., G.A. Gannon, J. Zamecnik, V. Gil, and G.M. Brown:** Low doses of melatonin and diurnal effects on thermoregulation and tolerance to uncompensable heat stress. *J. Appl. Physiol. 87*:308–316 (1999).
31. **Hardy, J.D., and E.F. Dubois:** The technique of measuring radiation and convection. *J. Nutr. 15*:461–475 (1938).
32. **Mitchell, J.W., E.R. Nadel, and D.W. Hill:** Respiratory weight loss during exercise. *J. Appl. Physiol. 32*:474–476 (1972).
33. **Snellen, J.W.:** Mean body temperature and the control of thermal sweating. *Acta. Physiol. Pharmacol. Neerl. 14*:99–174 (1966).
34. **McLellan, T.M., I. Jacobs, and J.B. Bain:** Continuous vs. intermittent work with Canadian Forces NBC clothing. *Aviat. Space Environ. Med. 64*:595–598 (1993).
35. **Kaplan, L.A., and A.J. Pesce:** *Clinical Chemistry Theory, Analysis and Correlation: Analyte Reference Chart*. St. Louis, Mo.: C.V. Mosby Company, 1984.
36. **Tenaglia, S.A., T.M. McLellan, and P.P. Klentrou:** Influence of menstrual cycle and oral contraceptives on tolerance to uncompensable heat stress. *Eur. J. Appl. Physiol. 80*:76–83 (1999).
37. **Holmer, I.:** Protective clothing and heat stress. *Ergonomics 38*:166–182 (1995).
38. **Selkirk, G.A., and T.M. McLellan:** Influence of aerobic fitness and body fatness on tolerance to uncompensable heat stress. *J. Appl. Physiol. 91*:2055–2063 (2001).
39. **McLellan, T.M.:** Sex-related differences in thermoregulatory responses while wearing protective clothing. *Eur. J. Appl. Physiol. 78*:28–37 (1998).
40. **Candas, V., J.P. Libert, G. Brandenberger, J.C. Sagot, C. Amoros, and J.M. Kahn:** Hydration during exercise: Effects on thermal and cardiovascular adjustments. *Eur. J. Appl. Physiol.* 55:113–122 (1986).
41. **Sawka, M.N., A.J. Young, W.A. Latzka, P.D. Neufer, M.D. Quigley, and K.B. Pandolf:** Human tolerance to heat strain during exercise: Influence of hydration. *J. Appl. Physiol. 73*:368–375 (1992).
42. **Cheung, S.S., and T.M. McLellan:** Heat acclimation, aerobic fitness, and hydration effects on tolerance during uncompensable heat stress. *J. Appl. Physiol. 84*:1731–1739 (1998).
43. **Candas, V., J.P. Libert, G. Brandenberger, J.C. Sagot, and J.M. Kahn:** Thermal and circulatory responses during prolonged exercise at different levels of hydration. *J. Physiol. 83*:11–18 (1988).
44. **Cheung, S.S., and T.M. McLellan:** Influence of hydration status and fluid replacement on heat tolerance while wearing NBC protective clothing. *Euro. J. Appl. Physiol. 77*:139–148 (1998).
45. **Sawka, M.N., R.R. Gonzalez, L.L. Droplet, and K.B. Pandolf.:** Heat exchange during upper- and lower-body exercise. *J. Appl. Physiol. 57*:1050–1054 (1984).
46. **White, M.K., and T.K. Hodous:** Physiological responses to the wearing of fire fighter's turnout gear with Neoprene and GORE-TEX Barrier Liners. *Am. Ind. Hyg. Assoc. J. 49*:523–530 (1988).
47. **House, J.R., C. Holmes, and A.J. Allsopp:** Prevention of heat strain by immersing the hands and forearms in water. *J. R. Nav. Med. Serv. 83*:26–30 (1997).
48. **Livingstone, S.D., R.W. Nolan, and S.W. Cattroll:** Heat loss caused by immersing the hands in water. *Aviat. Space Environ. Med. 60*:1166–1171 (1989).
49. **Cheung, S.S., T.M. McLellan, and S.A. Tenaglia:** The thermophysiology of uncompensable heat stress. *Sports Med. 29*:329–359 (2000).