

# Risk factors associated with live fire training: Buildup of heat stress and fatigue, recovery and role of micro-breaks

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## Abstract.

**BACKGROUND:** Forty five percent of on-duty firefighter deaths every year are cardiovascular (CV) related. Heat stress and fatigue buildup are two common occupational risk factors for firefighters. These risk factors may increase the firefighters' chances of having cardiac events or even death.

**OBJECTIVE:** Buildup of heat stress and fatigue in firefighters and their recovery from these stresses during live-fire training exercises was investigated.

**METHODS:** Twenty full time firefighters, from two different fire-stations, performed live-fire training exercise constituting three real life firefighting scenarios and rest periods incorporated in between the scenarios. Core body temperature (CBT) and heart rate (HR) were measured in real time, using an FDA approved radio pill and a polar heart rate belt. Baseline and post-scenario measurements of perceptions of physical exertion, thermal stress and respiratory distress were also collected.

**RESULTS:** Heart rate and CBT increased significantly with the progression of the training. The HR and CBT levels at the end of each rest period were significantly higher than the baseline values. The actual rest periods provided after each scenario were shorter than the time needed for adequate recovery. Most of the firefighters crossed the industrial limit of hyperthermia and maximum recommended level of HR elevation from baseline. Firefighters from one of the stations took micro-breaks during scenarios and were found to spend less percent time over the limit of hyperthermia. These firefighters also needed less time to recover to baseline levels of HR and CBT.

**CONCLUSIONS:** There was significant heat stress and fatigue buildup as a result of the live-fire training exercise. Longer rest periods should be provided between scenarios to ensure recovery. Also, taking micro-breaks during a live fire training scenario might help in preventing heat stress and fatigue buildup.

Keywords: Live fire training, heat stress, fatigue, recovery, micro-breaks, hyperthermia, firefighters

## 1. Introduction

On average 100 on-duty firefighter deaths occur every year in the United States. Forty-five percent of these deaths are cardiovascular (CV) related and are a major cause of morbidity [1,2]. Each year, tens of thousands of firefighters are injured while fighting fires, rescuing people, responding to incidents, and

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training for their job [3]. From 2001–2010, 13 firefighters lost their lives during live-fire training [4]. Studies in firefighters have found increased risk of sudden cardiac events on the fire ground, responding to and returning from an emergency, and during physically demanding training [5]. Preventive measures should be applied aggressively to minimize injuries and deaths among firefighters [2].

Occupational and non-occupational factors may increase firefighters' risk of a CV related event [5]. Given the nature of their job, two common occupational stresses the firefighters are exposed to are: hot environment and physically demanding work. Firefighters work at near maximal heart rates (HR) in hot environment while wearing heavy personal protective equipment (PPE). Exposure to these stresses leads to buildup of heat strain which is the body's response to heat stress. Heat strain is associated with increases in HR and oxygen demand and theoretically increases the risk of ischemia and a sudden cardiac event. Heat strain if left unchecked, may result in increased accidents and heat-related disorders [6–8, 19]. Heat stress is the net load to which a worker may be exposed from the combined contributions of metabolic heat, environmental factors, and clothing requirement which may result in heat storage (HS) in the body [28]. A measure of heat stress is the building of HS above zero and an increase in core body temperature (CBT) above 38°C [9]. Along with performing physically demanding work in a hot environment, the weight associated with PPE also increases the risk of heat stress and affects the exchange of heat between the body and environment [10]. It has been established that PPE places an extra load on the firefighters, which increases the HS in the body [3,11,12]. The hot environment and PPE increase CBT and HS due to the exertion required of the job [13].

In a laboratory based study, Petruzzello et al. 2009 [14] concluded that even short duration activities in a hot environment can result in moderate to high levels of heat strain. While laboratory based studies are carried out in a controlled environment, there is a need to investigate the heat stress effects during live firefighting where conditions change continuously. Therefore, the main objectives of the proposed study were to investigate 1) the effects of heat stress from high intensity firefighting activities performed during live-fire training during shorter and longer durations, 2) the impact of heat stress on fatigue and hyperthermia buildup 3) the role of micro-breaks during the training exercise in alleviating fatigue and hyperthermia buildups, 4) firefighters' perception of heat stress and fatigue as the training progressed, 5) recovery from the stress during the rest periods incorporated in the training and 6) whether or not individual firefighters exceeded the recommended limits for hyperthermia and physical fatigue.

## 2. Methods

The University of Cincinnati's Institutional Review Board approved the study and each participant gave written informed consent before the study.

### 2.1. Subjects

Twenty full-time firefighters between the ages of 21 and 50 years with no known medical conditions were recruited from 2 different fire stations (referred to as Stn I and Stn II in Table 1). The live firefighting duration was significantly longer for the Stn I compared to the Stn II (Table 2). The demographics of the firefighters are given in Table 1. Participating firefighters were medically cleared for the study by the local fire department's occupational medical director. Female subjects were excluded if a urine pregnancy test was positive. The only female participant completed a pregnancy test and answered a series of questions regarding her menstruation cycle (since menstruation is an established cause for CBT increase from luteinizing hormone and follicle-stimulating hormone surge).

Table 1  
Demographics

Fire station	Number of firefighters	Age (yrs.)		Gender (M/F)	BMI (Kg/m <sup>2</sup> )	
		Mean (SE)	Range		Mean (SE)	Range
Stn I	8	34.25 (2.13)	24–41	7/1	26.54 (0.89)	21.0–30.0
Stn II	12	37.50 (1.26)	26–43	12/0	30.13 (1.34)	23.8–37.1

Table 2  
Break-up of the training exercise (durations in minutes)

Fire station	Avg Sc1 duration	Avg Rest 1 duration	Avg Sc2 duration	Avg Rest 2 duration	Avg Sc3 duration
Stn I	22.3	26.5	20.8	34.6	23.5
Stn II	8.3	25.4	6.8	24.0	7.3

## 2.2. Procedure

For this study, physiological and psychophysical outcomes were measured during live-fire training. The day before their training, each firefighter had finished a 24-hour shift (work schedule: 24 hour work +72 hour off for Stn I and 24 hour work +48 hour off for Stn II). The live-fire training exercises were part of their annual training routine. The training was carried out at “burn houses” specially designed for the training where class A combustible materials were burned to maintain high temperature during the exercise. The burn house temperatures were maintained at around 483°C and 260°C at Stn I and II, respectively.

### 2.2.1. Live-fire training exercise

The training exercise was divided into three scenarios (referred to as Sc1, Sc2 and Sc3). The scenarios represented real life firefighting activities, (e.g., fighting first and second floor fires). Each scenario was divided into three specific tasks (or evolutions). The evolutions were hose advancement, search and rescue, and backup. Firefighters from Stn I took *micro-breaks* (2–5 minutes) after each evolution, whereas firefighters from Stn II did not exit the burn house before the end of a scenario. The firefighters had rest periods between consecutive scenarios. During the rest periods, firefighters took their gear off and drank cold fluids. Table 2 shows the break-up of the training exercise.

### 2.2.2. Instruments and equipment

CBT was measured using FDA approved CorTemp<sup>®</sup> (HQ, Inc., Palmetto, FL) radio pill. The radio pill has been used by other researchers to monitor core temperature of firefighters [15]. The radio pill was administered to the firefighters 4–5 hours before the training exercise at their respective fire stations. Heart rate was measured using a POLAR (HQ, Inc., Palmetto, FL) HR belt. The HR belt was strapped to the chest of each participating firefighter once they arrived at the training facility. The CBT and HR data were transmitted to a receiver unit (HQ, Inc., Palmetto, FL) kept either in the coat pocket of each firefighter’s jacket or strapped to their suspender. Real time CBT and HR readings were recorded to the receiver unit every 20 seconds (0.05 Hz).

## 2.3. Data collection

Figure 1 shows a schematic overview of the data collection during the training exercises. Baseline measurements were taken when the radio pills were administered at the fire stations. Baseline data

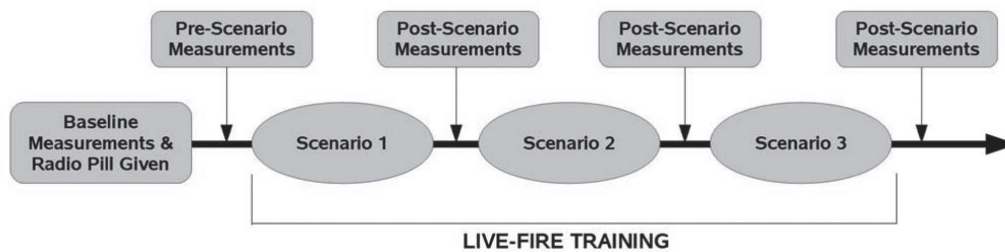


Fig. 1. Schematic of live-fire training exercise.

included vital signs (i.e., pulse, oxygen saturation, blood pressure tympanic temperature) and perceived ratings of physical exertion (BORG) [17], thermal stress [16,18] and respiratory distress [16]. Vital signs and psychophysical data (using the perception scales) were also collected before Sc1 and then after the end of each scenario. CBT and HR were recorded continuously throughout the training period, including the rest periods. The vital signs are not reported in this manuscript.

## 2.4. Outcome variables

### 2.4.1. Measured/Recorded

Measured physiological responses used to quantify the effects of heat stress in this study were heart rate (HR) and core body temperature (CBT). Psychophysical responses included perceptions of physical exertion (PE), thermal stress (TS), and respiratory distress (RD).

### 2.4.2. Calculated

We calculated a) heat storage (HS),  $HS \text{ (watts per hour)} = \text{body weight (kg)} \times \text{change in CBT } (^\circ\text{C}) \times \text{specific heat capacity of body tissue (0.97 watts per hour/kg } ^\circ\text{C)}$  [13] b) time taken for each firefighter to recover to baseline HR after exercise to assess their physical fitness and the adequacy of rest durations built into the live-fire training and c) percent of total time spent inside hot environment over the threshold for hyperthermia.

In addition, we compared objectively measured physiological responses (HR and CBT) and the corresponding psychophysical responses associated with high intensity firefighting activities.

## 2.5. Data analysis

Continuous time-stamped CBT and HR data were downloaded from the receiver. Mean and peak CBT and HR were calculated for each scenario, beginning of rest period and end of rest period. Elevation in CBT, HR and HS as compared to the corresponding baseline values were calculated (End of Sc3 minus baseline). Each firefighter's CBT, HR and HS values were compared to established recommended limits to investigate if they crossed the threshold of hyperthermia [23] and overexertion associated fatigue [29].

If individual firefighters' HR did not recover to baseline level, then time needed for complete recovery after each scenario was calculated. For this calculation, we regressed the continuously monitored HR during recovery period with time and then extrapolated the regression line to find the time needed for HR to drop to baseline value. Since the durations of scenarios and rest periods were different for the two stations, we calculated percent normalized time spent over  $38^\circ\text{C}$  as follows:  $100 \times (\text{time spent over } 38^\circ\text{C}) / (\text{total time spent inside the hot environment})$ .

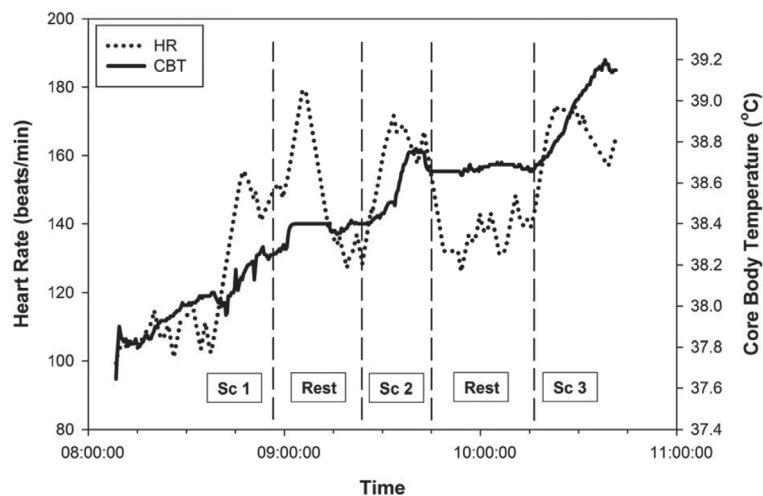


Fig. 2. Sample plot of continuously monitored HR and CBT.

## 2.6. Statistical analysis

Student's t-test was used to compare end of Sc3 values of physiological and psychophysical variables to baseline measurements. ANOVA was used to compare the two stations with respect to age, body mass index (BMI), and percent normalized time spent over hyperthermia limit. We investigated the association between physiological and corresponding psychophysical variables using Pearson's correlation coefficient and linear regression. Pearson's coefficient was used to investigate the relationship between CBT and HR. Statistical significance was tested at alpha level of 5%.

## 3. Results

### 3.1. Buildup of heat stress and fatigue

Figure 2 shows an example of HR and CBT responses for one firefighter (monitored in real-time) as he progressed through the live-fire training. The upward trend of HR and CBT responses at the End of Rest (EOR) for this firefighter as well as for all the firefighters suggest buildup of HS and fatigue. Despite having rest periods and regular cold fluid intakes between scenarios, mean CBT and HR values for all firefighters significantly increased (Fig. 3a) with respect to their baseline levels as the training progressed through three scenarios ( $p < 0.001$ ). Figure 3a shows percent changes in CBT and HR from the baseline values. Mean CBT and HR at the end of rest periods (Fig. 3b) were significantly higher than the baseline values ( $p < 0.001$ ). The average HS, of all the firefighters (from two stations), associated with tasks performed during Sc1, Sc2 and Sc3 were: 67, 73 and 83 watts/hr-m<sup>2</sup>, respectively. The mean HS ( $\pm$  SEM) by the end of Sc 3 for the Stn I and II firefighters were 70.24 ( $\pm$  14.00) watt/hr-m<sup>2</sup> and 60.79 ( $\pm$  4.79) watt/hr-m<sup>2</sup>, respectively. Psychophysical responses (PE, TS and RD) increased after each scenario and were significantly higher than the baseline values (all p-values  $< 0.001$ ) (Fig. 3c).

Eighteen out of 20 firefighters (7 from Stn I and 11 from Stn II) crossed the recommended upper limit for ergonomic criteria for maximum allowable HR elevations (from baseline) of +55 and +75 beats/min for task durations of 60 and 20 minutes, respectively [29].

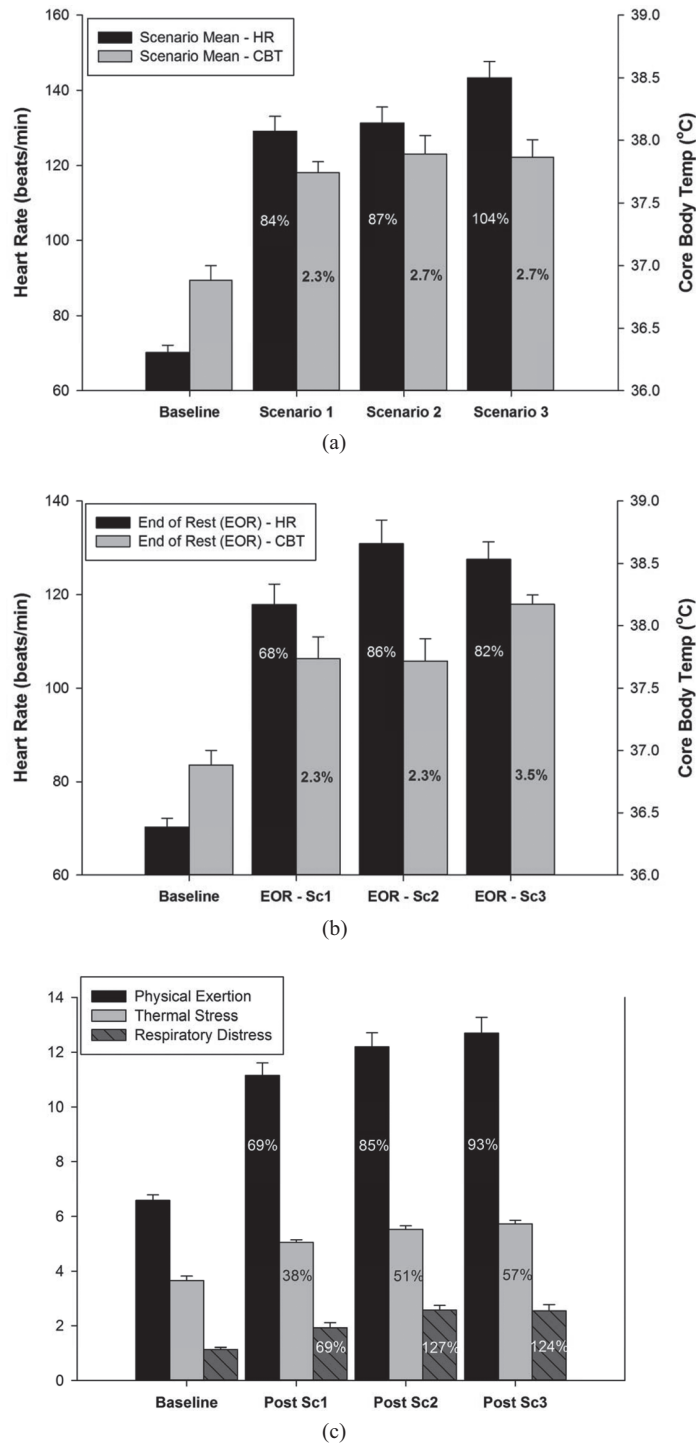


Fig. 3. a. Comparison of mean CBT and HR with baseline values. b: Comparison of End of Rest (after each scenario) CBT and HR with baseline. c: Psychophysical responses measured after each scenario compared to baseline.

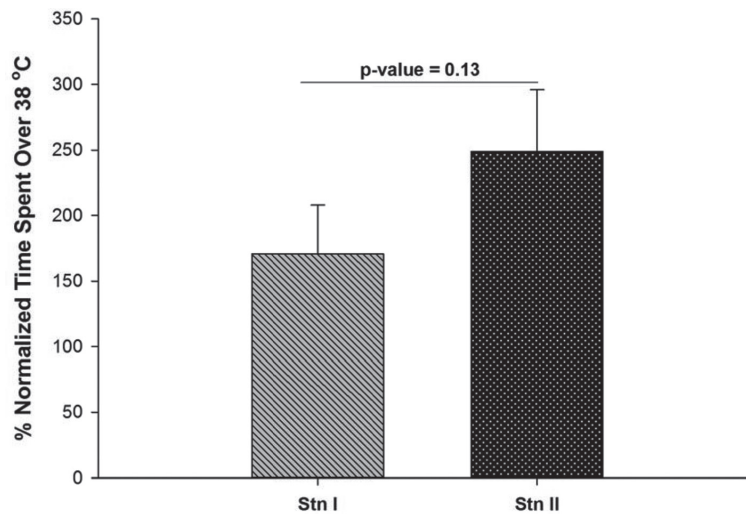


Fig. 4. Time spent over hyperthermia limit as percent of total time spent inside hot environment.

To compare the heat strain with corresponding cardiac strain, we calculated rate of changes in HR with respect to CBT using the time series data obtained during real-time monitoring. For all firefighters from two stations, the average slope of HR vs. CBT regression line was 13.42 beats/min per °C [equation:  $HR = CBT * 13.42 \text{ beats/min per } ^\circ\text{C} - 385 \text{ beats/min}$ ]. Using the regression equation, the cardiac strain corresponding to the hyperthermia limit [23] (38°C) was calculated to be 124.4 beats/min. The average slopes of HR vs. CBT for Stn I during Sc1, Sc2 and Sc3 were -1.68, 11.58 and 30.28 beats/min per °C, respectively. For Stn II the average slopes of HR vs. CBT for Sc1, Sc2 and Sc3 were -5.14, 40.37 and 57.37 beats/min per °C, respectively. The HR vs. CBT slopes for the firefighters from the two stations were not significantly different from each other (t-test p-values ranged between 0.20–0.47).

### 3.2. Effect of total time spent inside hot environment

All eight firefighters from Stn I and 10 out of 12 firefighters from Stn II crossed the recommended limit for industrial hyperthermia (CBT > 38°C) [23]. On average, firefighters from Stn I and II spent 64 min and 51 min, respectively above the CBT limit. Percent normalized time spent over 38°C (with respect to total time spent inside the hot environment) were (mean ± SEM) 171 ± 37% and 249 ± 47% for Stn I and II, respectively but they were not statistically different between the stations ( $p = 0.13$ ) (Fig. 4).

### 3.3. Recovery from heat stress and fatigue inducing physical exertion

Throughout the training and at the end of recovery periods, CBT and corresponding HR levels of all firefighters stayed above their baseline values. On the average the mean drops in HR of all firefighters during the first 2 minutes after the end of the training (i.e., after Sc3) were 5 beats/min and 18 beats/min for Stn I and II, respectively. One out of 8 firefighters from Stn I and 3 out of 12 from Stn II had a drop of 42 beats/min or greater in HR during the first two minutes of recovery period [3]. None of the firefighters had a recovery HR ≤ 110 beats/min after 1 min of recovery time [30].

The average times needed to recover to baseline HR after Sc1, Sc2 and Sc3 for Stn I firefighters were 38, 35 and 51 minutes, respectively. For Stn II firefighters, the times needed to recover to baseline HR

after Sc1, Sc2 and Sc3 were 35, 41 and 63 minutes, respectively. We compared the stations with respect to the firefighters' HR recovery time needed to reach their baseline after each scenario and they were not significantly different (range of p-values for Sc1, Sc2 and Sc3 was 0.25–0.36).

### 3.4. Firefighters' perception of physiological responses to working in hot environment

Heart rate was positively correlated with PE, TS and RD [Pearson  $r^2$ : 0.79 ( $p < 0.001$ ), 0.82 ( $p < 0.001$ ) and 0.62 ( $p < 0.001$ ), respectively]. Core body temperature was also positively correlated with PE, TS and RD [Pearson  $r^2$ : 0.52 ( $p < 0.001$ ), 0.51 ( $p < 0.001$ ) and 0.35 ( $p = 0.002$ ), respectively]. We also performed linear regression for each combination of physiological and psychophysical variables. The slopes of regression lines for HR vs. PE, TS and RD were 0.033 ( $p = 0.002$ ), 0.012 ( $p < 0.001$ ) and 0.010 ( $p = 0.002$ ), respectively. The regression slopes for CBT vs. PE, TS and RD were 0.983 ( $p < 0.001$ ), 0.306 ( $p < 0.001$ ) and 0.225 ( $p = 0.009$ ), respectively.

## 4. Discussion

### 4.1. Buildup of heat stress and fatigue

Heat stress builds up inside the body when total heat gained (due to work related increase in metabolism and environmental temperature) exceeds the heat lost to the environment. Heat stress can result in heat exhaustion, increased risk of ischemia and accidents, heat stroke and even death [6–8]. Literature reports that moderate to heavy physical workload carried out in hot environment demands increased skin blood flow (for heat dissipation via sweating) and with decreased blood volume (due to hemoglobin concentration) results in increase in HR [31]. Therefore, collectively these physiological mechanisms trigger fatigue. Fatigue buildup may leave the firefighters unable to perform their duties safely and may also lead to undue cardiovascular events. In this study, elevations above baseline levels in CBT, HS and HR outcomes were used as objective indicators of buildup of heat stress and recovery HR level after each scenario provided a measure of fatigue, respectively. Perceptions of physical exertion (PE), thermal stress (TS), and respiratory distress (RD) were used to investigate the psychophysical responses to these buildups.

For the participating firefighters in this study, mean CBT, HS and HR increased during each scenario of the training exercise [see Fig. 3a and Section 3.1] which suggests that there was buildup of heat stress and associated increase in physiological demand from the live-fire training exercise. Ninety percent (7 from Stn I and 11 from Stn II) of the firefighters crossed the upper limit for HR elevation during physically demanding work [29] which suggests that the live-fire training was physically demanding and potentially fatiguing to the majority of the firefighters. The buildup of heat stress and physiological demand were also apparent from the increased CBT, HS and HR values at the end of each rest period as compared to the respective baselines [see Fig. 3b]. As the firefighting training progressed from Sc1 to Sc3 there was a progressive rise in positive slope of resting HR vs. time suggesting buildup of fatigue from working in hot environment [31]. Also, End of rest HR (indicative of resting HR after each scenario) increased as training progressed [see Fig. 3b] suggesting fatigue build up. Ninety percent (18 out of 20) of the firefighters crossed the recommended CBT threshold for industrial hyperthermia (38°C). The firefighters from Stn I and II spent 48% (61 out of 128 min) and 75% (54 out of 72 min) of the training duration (all scenarios and rest periods combined), respectively with their CBT over the hyperthermia limit. Four out of 8 firefighters from Stn I and 5 out of 12 from Stn II were above the recommended



threshold for HS per unit body surface area:  $60 \text{ watt/hr-m}^2$ , for acclimatized workers [21,22]. Buildup of heat stress and fatigue as a result of working in the hot environment is known to decrease the efficiency of muscles [29] which may increase the chances of the firefighters getting into accidents.

It has been established that increase in CBT is associated with increased HR. Furthermore, the increase in slope of HR vs. CBT is dependent on combination of metabolic demand and heat level [20]. In this study, the slope of HR vs. CBT increased with the progression of the training [see Section 3.1]. The CBT increased significantly with the training and hence increase in HR vs. CBT slope as training progressed, suggests that HR and CBT are not linearly related. Rather, at higher CBT levels, one can expect a higher increase in HR for a constant change in CBT as compared to lower levels of CBT. Since working in hot environment causes a decrease in stroke volume, to maintain sufficient cardiac output level, HR has to increase proportionately [26]. According to the results from all subjects, the cardiac strain [see Section 3.1] associated with the hyperthermia limit of  $38^\circ\text{C}$  was 124.4 beats/min. This value was in agreement with 124.8 beats/min reported by Kuhlemeier et al. [20], and 125 beats/min reported by Kamon and Belding [24]. Hence, if the firefighters' HR did not elevate above 124.4 beats/min, then they can be expected to stay below the threshold of hyperthermia. We found that the HR vs. CBT slope for the combined data for all firefighters was 13.42 beats/min per  $^\circ\text{C}$  while Kuhlemeier et al. reported a value of 35.4 beats/min per  $^\circ\text{C}$ . This difference between the slopes can be because the firefighters in our study are expected to be more acclimatized to heat as compared to the participants in the study performed by Kuhlemeier et al. [20].

The average rate of change of CBT with respect to time (for all subjects) increased over scenarios:  $0.0006^\circ\text{C/min}$  during Sc1 to  $0.0023^\circ\text{C/min}$  during Sc3 (marginally significant: t-test p value = 0.06). This may suggest that performing physically demanding tasks for longer duration in hot environment may cause CBT to rise faster. Time dependent change in HR also increased from Sc1 (0.028 beats/min) to Sc3 (0.033 beats/min) suggesting that fatigue built up faster with progression of training exercise. However these results were not statistically significant (t test p-value = 0.44).

The data collected in this study suggests that the firefighters had consistent heat stress and fatigue buildup during the live-fire training exercise despite having rest periods between scenarios. Since the activities performed during live-fire training were comparable to real-life firefighting, these results may be applicable to on-duty firefighting. Further research should be carried out to investigate if the firefighters experience heat stress and fatigue buildup, at the end of their shift, similar to that found in this study. In case of such build up, adequate recovery is required before the firefighters engage in next physically intensive exercise so that they can perform their duty safely while avoiding accidents.

#### 4.2. Recovery from heat stress and fatigue inducing physical exertion

Recovery HR is an indicator of physical fitness and has been found to be strongly associated with long term risk of mortality among adults with good cardiovascular health. Having a drop in HR of  $\leq 42$  beats/min after 2 minutes of recovery time following intense exercise is strongly associated with lack of fitness and affects long term well-being [25]. Therefore, inadequate drop in HR during the first couple of minutes of recovery time after physically demanding tasks could be used as an indicator of poor physical fitness. After strenuous exercise, it is essential that an individual recovers adequately before exercising again. In daily life where firefighters may go on multiple "fire-runs" during their shift, inadequate recovery from heat stress and physical exertion may lead to acute and chronic health effects.

Based upon above discussion, our data shows that despite the rest periods incorporated between consecutive scenarios, the firefighters did not recover with respect to CBT and HR (Figs 2 and 3: EOR CBT

and HR were greater than the baseline values). In our study, 80% of the firefighters (7 from Stn I and 9 from Stn II), after 2 minutes of completion of Sc3, had a drop in HR less than or equal to 42 beats/min suggesting inadequate recovery. Another indicator of a poor recovery from working in a hot environment is having 1 minute recovery HR greater than 110 beats/min [30]. In our study recovery HR of all the firefighters at 1 minute after the training was greater than 110 beats/min indicating that none of the firefighters had sufficient recovery from heat stress and fatigue.

Since recovery time from high intensity firefighting training was not adequate, we calculated the recovery time required to bring the HR of individual firefighters to baseline. The time needed for recovery to baseline HR was greater than the rest durations used after each scenario [see Section 3.3] suggesting that the firefighters did not have enough time to recover completely before going back inside the hot environment. According to the recovery time calculated from our data, an additional 9 to 11 minutes after Sc1 and about 17 minutes after Sc2 should be provided to ensure sufficient recovery. The time needed to recover, with respect to HR, increased with the progression of the training exercise i.e., the recovery time needed after Sc3 was higher than that after Sc1 [see Section 3.3]. Increased recovery time needed after each scenario may also corroborate buildup of fatigue and heat stress. Fatigue buildup and increased amount of lactic acid in the muscles render the muscles less efficient [29]. Going into the “burn house” to perform live-fire training exercises without having recovered completely and therefore with reduced efficiency, can increase the firefighters’ chances of accidents and cardiac events. Hence, the rest duration after each scenario should be increased to ensure that the firefighters have recovered adequately before participating in the next scenario. Also, during the rest periods, fire chiefs should ensure that the firefighters take appropriate rest and drink plenty of cold fluids. Buildup of heat stress and fatigue from physically intense exercise without adequate recovery increases the threat the firefighters face daily. This also makes it important for the firefighters to accurately perceive the stresses imposed on their body so that they can take steps necessary for avoiding mishaps while working in a hot environment.

#### 4.3. Firefighters’ perception of physiological responses to working in hot environment

It is important for firefighters to accurately perceive the stresses building in their body so that they can take active measures to avoid unfortunate accidents. A potential disconnect between actual physiological response to a stress and how firefighters perceive it can prove to be dangerous as the firefighters may not realize the need to take precautionary measures to alleviate the stress. We compared the perceptions of PE, TS and RD at the end of the training to the baseline values to evaluate if the firefighters could accurately perceive the buildup of stresses. Perceptions of PE, TS and RD were significantly higher at the end of the training exercise as compared to the respective baselines. The perception values also increased with the progression of the training exercise, but this change (from scenario to scenario) was not always statistically significant [see Fig. 3c]. Also, the perception variables were positively correlated to the physiological outcome variables. The correlations between HR and PE from our study were similar to the range reported in the literature (0.8–0.9) [27]. In order to examine the relative changes in objectively measured physiological responses (increase in HR and CBT) and the corresponding psychophysical responses (perceptions of PE, TS and RD) we obtained slopes of regression lines for each combination of physiological and psychophysical variables. The slopes of regression lines for each combination of physiological and psychophysical variables were positive (and each slope was statistically significant,  $p < 0.05$ ). This implies that the firefighters could accurately perceive the heat strain and fatigue building up in their body during this study.

Activities performed during live-fire training exercise exposes the firefighters to several stresses such as: physical exertion, thermal stress and respiratory distress. These stresses may not be operating independently. Also, it may not be possible for the firefighters to accurately differentiate between the perceptions of these stresses. For example, our data shows that HR was positively correlated with perception of TS along with PE. However, the psychophysical scales of PE, TS and RD are designed to capture an individual's perception to each of these stresses independent of each other. We believe that a *composite* perception scale which reflects global measures of PE, TS and RD should be designed without the assumption that these stresses are independent of each other. This may be helpful in two ways: accurately capture an individual's global perception of different physiological demands, and help individuals like firefighters to sharpen their skills of perceiving the stresses building up in their body.

#### 4.4. Effect of total time spent inside hot environment and role of micro-breaks

Total heat transferred between two bodies is given by, in general, rate of heat transfer x time allowed for the transfer. Hence, we hypothesized that total time spent inside the hot environment (*burn house*) would play an important role in our investigation of heat stress and fatigue buildup. Eighteen out of the 20 firefighters' CBT exceeded the recommended threshold for industrial hyperthermia [23] of 38°C. Interestingly, 15 firefighters had their CBT over the threshold for industrial hyperthermia for periods longer than they were in the hot environment. This also corroborates our finding of heat stress buildup and residual effects that persisted even after the firefighters left the "burn-house".

Values of greater than 100% for percent normalized time spent over the industrial hyperthermia limit for both stations showed that the firefighters' CBT stayed elevated above the limit even after they left the hot environment [see Fig. 4]. Although total time spent inside the hot environment was significantly higher for Stn I (39.5 min) than for Stn II (20.8 min), percent normalized time spent over the CBT limit was lower for Stn I than Stn II (171% and 249% for Stn I and II, respectively). This unexpected finding may be explained, partially, because firefighters from Stn I took *micro-breaks* for 2–5 minutes between tasks performed within each scenario while the firefighters from Stn II did not exit the hot building until all the tasks for a scenario were completed. To further investigate the role of *micro-breaks* we compared the stations with respect to percent time spent over hyperthermia limit without factoring in the *micro-breaks*. If we did not account for the micro-breaks taken by Stn I firefighters, the percent normalized time spent over the hyperthermia limit was not significantly different between the stations (50% and 70% for Stn I and II respectively;  $p$ -value = 0.15). We also found that the recovery time needed after Sc2 and Sc3 were lower for Stn I as compared to Stn II, although the results were not statistically significant [see Section 3.3]. These findings may suggest that taking short breaks during scenarios of live-fire training may help firefighters avoid prolonged CBT elevation over the hyperthermia limit for longer durations and aid recovery. Firefighters from Stn I also had lower HR vs. CBT slopes [see Section 3.1] implying that if other variables were kept constant for same amount of increase in CBT, Stn I firefighters would experience a smaller increase in cardiac strain. This may be partly because taking small micro-breaks reduced the HR temporarily during the scenarios resulting in smaller slope of HR vs. CBT regression line. Repeating this study with larger sample size and for different durations of micro-breaks may shed more light on the usefulness of micro-breaks during live-fire training.

## 5. Limitations

Although we collected HR and CBT data in a real-life firefighting environment, our study had a few limitations. Our sample was small which might have resulted in insufficient power for some of the

statistical analyses. Also, the firefighters were from two different fire stations and hence the differences between the training environment (e.g., burn-house temperature and training durations) might have also reduced some of the statistical power. Another limitation of our study was that we only recruited full-time firefighters so that we could obtain adequate medical history recorded during their annual physical examination.

## 6. Conclusions

Heat and fatigue buildup may occur in firefighters not only from actual firefighting but also from live-fire training exercises. Buildup of these stresses may lead to life-threatening accidents. In this study results show that during the live-fire training exercise, firefighters exceeded the limit of industrial hyperthermia (38°C) and their CBT stayed over the limit for longer than they were inside the hot environment. The firefighters also exceeded the recommended upper limit for HR elevation (from their baseline HR) associated with physical exertion. After each scenario of the training, the firefighters' HR and CBT did not recover adequately before re-entering the training facility for the following scenario. Based on our findings related to heat stress, fatigue buildup, and inadequate recovery it is recommended that length of the rest periods should be increased for complete recovery of HR and CBT to baseline state. Furthermore, the fire chief should ensure that during the recovery period, the firefighters truly rest and drink plenty of cold fluids. Inadequate recovery after training may also be avoided by improving physical fitness. Taking micro-breaks during each scenario of the training may also help prevent firefighters' CBT and HR from exceeding the recommended limits.

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