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Gavin P. Horn [a], Sue Blevins [a], Bo Fernhall [b] & Denise L. Smith [a c]

[a] University of Illinois Fire Service Institute, 11 Gerty Drive, Champaign, IL, 61820, USA

[b] University of Illinois at Chicago, 808 South Wood Street, Chicago, IL, 60612, USA

[c] Skidmore College, 815 North Broadway, Saratoga Springs, NY, 12866, USA

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Core temperature and heart rate response to repeated bouts of firefighting activities

Gavin P. Horn[a]*, Sue Blevins[a], Bo Fernhall[b] and Denise L. Smith[a,c]

[a]*University of Illinois Fire Service Institute, 11 Gerty Drive, Champaign, IL 61820, USA;* [b]*University of Illinois at Chicago, 808 South Wood Street, Chicago, IL 60612, USA;* [c]*Skidmore College, 815 North Broadway, Saratoga Springs, NY 12866, USA*

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During live-fire firefighting operations and training evolutions, firefighters often consume multiple cylinders of air and continue to wear their personal protective equipment even after fire suppression activities have ceased. However, most studies have only reported core temperature changes during short-term firefighting activities and have shown a very modest increase in core temperature. Therefore, the purpose of this study is to evaluate core temperature and heart rate (HR) during repeated bouts of firefighting activity over ~3 h. The results of this study show that core temperatures increase by an average of 1.9°C – to a larger magnitude than previously reported – and continue to increase during subsequent work cycles (38.4 vs. 38.7) even after long breaks of more than 30 min. The rate of core temperature increase during work continues to increase later in the training exercise (from 0.036 to 0.048°C/min), increasing the risk for exertional heat stress particularly if long-duration firefighting activity is required at these later times.

Practitioner Summary: To date, core temperature and HR changes during firefighting have been reported for short-term studies, which may significantly underestimate the physiological burden of typical firefighting activities. Firefighter core temperatures are shown to increase to a larger magnitude than previously observed and the rate of rise in core temperature increases during subsequent firefighting activities.

Keywords: firefighting; core temperature; heart rate; heat stress

1. Introduction

It is well documented that firefighting leads to increased cardiovascular and thermal strain (Smith and Petruzzello 1998; Smith, Manning, and Petruzzello 2001; Soteriades et al. 2011; Horn et al. 2011). During a typical response, firefighters may perform intermittent bouts of heavy (resistance) exercise interspersed within longer duration (aerobic) exposure while in a hot ambient environment while wearing restrictive and highly insulated personal protective equipment (PPE). In many cases, these bouts of firefighting activity may be repeated several times after short breaks are allowed for recovery and rehabilitation (i.e. cooling, rehydration and change of air cylinder).

Firefighters in the USA typically utilise self-contained breathing apparatus (SCBA) rated for 30 min of air based on a consumption rate of 40 l/min. While fireground work is often conducted without use of SCBA prior to entering a burning structure, the exposure to live-fire conditions is limited by the consumption of air, which often occurs in less than 30 min because air consumption exceeds 40 l/min during heavy work (Williams-Bell et al. 2010). Thus, most research regarding the cardiovascular and thermal strain of firefighting has focused on a bout of firefighting activity that requires 20 min or less (Smith and Petruzzello 1998; Smith, Manning, and Petruzzello 2001; Horn et al. 2011). We have recently documented the timeline of recovery from a short-term bout of controlled firefighting activity lasting 18 min. Our data suggest that ~60 min is required for the firefighter's (HR) and core temperature to return to baseline levels (Horn et al. 2011). While significant study of repeated bouts of activity in firefighting PPE has been conducted in laboratory settings (e.g. Gallagher et al. 2012; Kim et al. 2013; Smith et al. 2013), the effect of repeated bouts of live-fire field firefighting activities on thermal and cardiovascular strain has not been studied.

Table 1 provides an overview of the few studies that have focused on measuring core temperature from live-fire training and research activities. Most studies have reported core temperature changes during short-term firefighting drills, and the modest increase found in firefighters' core temperature would not pose an immediate risk of heat illness. However, the values reported in published studies indicate considerable rate of rise for such short bouts of work, which for most firefighters required less than one cylinder of air. During actual firefighting operations and training evolutions, firefighters often conduct significant amounts of work prior to donning their face mask and consuming SCBA air as they enter an immediately dangerous to life and health environment, consume multiple cylinders of air and continue to wear their PPE even after fire suppression activities have ceased (such as during overhaul and clean-up activities). Thus, it is likely that

*Corresponding author. Email: ghorn@illinois.edu

Table 1. Summary of studies reporting core temperature rise during live-fire activities.

Author (year)	N	ΔT	$\Delta T/\Delta t$	HR_{ave}	Drill/environment (heat/fire)/time
Burgess et al. (2012)	44	0.6	0.050	152.1	12 min of simulated activities (dummy drag, carrying hose on stairs and crawling through maze)
Colburn et al. (2011)	25	0.7	0.035	175 (max)	20 min fire suppression evolution in a training structure including hose advance, fire suppression and ventilation
Horn et al. (2011)	12	0.70	0.037	168	18 min of simulated activity (stairs, forcible entry, search and hose advance) on 2-min work–rest cycle
Smith et al. (2011)	11	0.72	0.040	162	18 min of simulated activity (stairs, forcible entry, search and hose advance) on 2-min work–rest cycle
Smith et al. (2005)	11	0.4	0.072	169.1 (max)	Bout #1. Protocol included three bouts of firefighting activities lasting 5 min 30 sec to 6 min 20 sec with a short rest between bouts 1 and 2 and a 10-min rest between bouts 2 and 3
	11	1.0	0.100	180.9 (max)	Bout #2
	11	1.4	0.086	186.5 (max)	Bout #3. Total time only includes time working in structure, not 10-min rest between Bouts #2 and #3.
Eglin et al. (2004)	12	~1.0	~0.030	N/A	'Hot Fire' exercise
	2	0.27	0.010	N/A	'Fire Behaviour' exercise
	4	0.70	0.096	N/A	'Fire Attack' exercise
Smith et al. (2001)	7	1.4	0.088		8-min hose advance, 8-min chopping
Romet and Frim (1987)	5	1.3	0.032	153	Lead hand
	7	0.7	0.022	130	Secondary help
	7	0.4	0.016	123	Exterior firefighting
	4	0.3	0.009	112	Crew captain

firefighters experience a greater rise in body temperature during many activities than has been previously reported. Therefore, the purpose of this study is to characterise the effect of repeated bouts of firefighting activities on core temperature and HR responses.

2. Methods

2.1. Human subjects

Nine firefighters (six male and three female) who were cleared to serve as a firefighter by their current fire departments participated in this study. Table 2 provides the descriptive data for participants. Participants were between 20 and 45 years

Table 2. Descriptive statistics for the recruited firefighter subjects ($n = 9$).

	Mean (SD)	Range
Age (yr)	32.8 (9.8)	20–45
Height (m)	1.78 (0.06)	1.72–1.88
Weight (kg)	88.5 (19.8)	68.9–112.9
BMI (kg/m^2)	27.7 (6.2)	21.9–37.7
Resting HR (bpm)	68.7 (9.9)	51–78
Resting T_{co} (°C)	36.89 (0.27)	36.59–37.29

of age and ranged from normal body mass index (BMI) (21.9) to obese (37.7). Due to the low number of subjects included in this study, separate analyses were not conducted for male and female participants. This group of firefighters was a subsample of a larger study population ($N = 85$), chosen because each of these nine firefighters conducted relatively similar work–rest cycles throughout the 3-h training activities. Participants were fully informed of the purposes of the study and provided informed written consent indicating that they understood and voluntarily accepted the risks and benefits of participation. This study was approved by the University of Illinois Institutional Review Board.

Prior to testing, firefighters were provided with a standardised meal (energy bar, protein drink and banana), which was consumed ~1 h prior to pre-firefighting data collection. During firefighting activities, participants were actively encouraged to consume fluids to maintain hydration and doff their gear during breaks in training to promote cooling.

2.2. Experimental protocol

Firefighters performed ~3 h of intermittent live-fire training exercises in a concrete and steel training building fuelled by pallets and straw burners. Firefighting drills varied through the 3-h training period, but included four evolutions typically lasting 15–30 min, each separated by 20–40 min of rest (recovery) in which the firefighters hydrated and cooled, reviewed/critiqued the evolution with instructors and refilled their air cylinders. The training evolutions included coordinated fireground operations which firefighters in the engine company established a water supply for the pumper, advanced hose and extinguished the fire, while firefighters in the truck company conducted forcible entry, search and rescue and ventilation tasks. The firefighting drill scenarios included fires involving a simulated basement, restaurant, single-family dwelling and multi-story firefighting operations. Participants wore full firefighting PPE and SCBA provided by their home department during all firefighting activities. Data were collected during the summer and fall months in which ambient temperature ranged from 15°C to 25°C.

2.3. Measurements

Standing height was measured with a stadiometer and recorded to the nearest 0.5 cm. Body weight was obtained using a digital scale and recorded to the nearest 0.1 kg. BMI was calculated as weight/height^2 (kg/m^2).

HR was measured throughout the firefighting exercises with a HR watch (S625X, Polar Electro Oy, Oulu, Finland). Data were collected every 5 s and were subsequently averaged over 60-s intervals. Participants ingested a gastrointestinal temperature transmitter pill 6–12 h prior to the drills, and core temperature was recorded throughout the training (MiniMitter Vital Sense, Phillips Respironics, Bend, OR, USA). Core temperature data were recorded every 60 s. HR and core temperature data were synchronised with a master clock in order to provide a consistent timeline between the two instruments. Typical data from a single participant are shown in Figure 1. Each work cycle (firefighting drill) was analysed individually to quantify the following:

(1) Duration – The duration of each work cycle is determined based on the analysis of HR data. The start of the cycle coincides with a sustained increase in HR from resting values and is assumed to conclude once the HR declines over a sustained period of time.

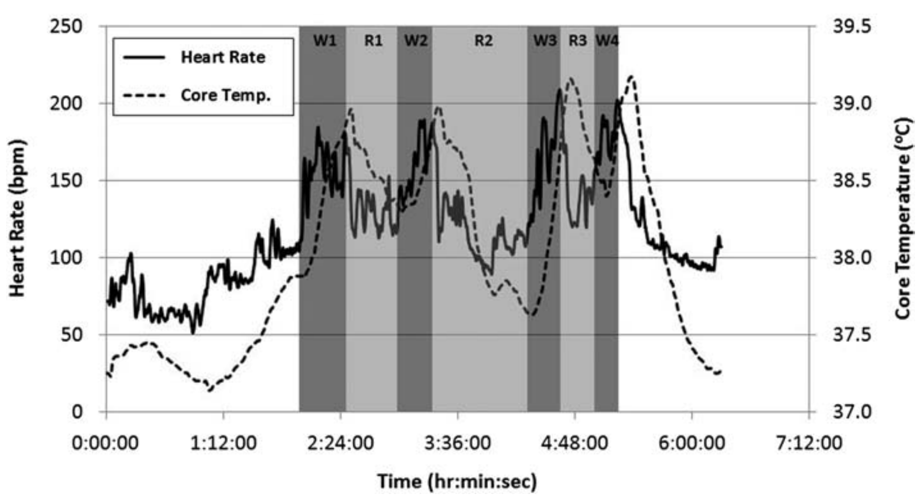

Figure 1. Typical trace of firefighter HR and core temperature during the live firefighting training exercise. The timeline during firefighting activities is partitioned between work (W#, dark shading) and rest (R#, light shading) cycles.

(2) Peak HR (HR_{peak}) – Calculated as the highest value attained during each individual work cycle.
(3) Average HR (HR_{ave}) – HR values reported every 5 s are averaged over the entire duration of each work cycle.
(4) Maximum core temperature ($T_{co,max}$) – Calculated as the maximum value attained during each individual work cycle.
(5) Time rate of change in core temperature ($\Delta T_{co}/\Delta t$) – Change in core temperature divided by the work cycle duration.
(6) Time delay between end of peak HR and peak core temperature (Δt_{peaks}) – Difference in time between when HR declines at the end of the work cycle and the maximum core temperature value reported prior to the next work cycle.

Each rest cycle was analysed individually to quantify the following:

(1) Duration – The start of the rest cycle coincides with the end of the previous work cycle and ends when a sustained increase in HR is detected. During these rest cycles, short-term increases in HR due to walking or completing rehab activities are considered normal.
(2) Minimum HR (HR_{min}) – Calculated as the minimum value attained during each individual rest cycle.
(3) Average HR (HR_{ave}) – HR values reported every 5 s are averaged over the entire duration of each rest cycle.
(4) Minimum core temperature ($T_{co,min}$) – Calculated as the minimum value attained during each individual rest cycle.
(5) Time rate of change in core temperature ($\Delta T_{co}/\Delta t$) – Change in core temperature divided by the cycle duration.

Average values of these measures for each of the four work cycles and three rest cycles were also calculated along with the attained maximum core temperature and maximum HR (regardless of when the maximum occurred).

2.4. *Analytical methods*

Results are expressed as mean ± SD. The six variables reported for the four work cycles and five variables reported for the three rest cycles were analysed independently using repeated measures ANOVA to determine differences between each cycle (i.e. changes with time). Correlations between BMI, age, resting HR and the variables mentioned in the previous section were calculated for each of the individual work cycles ($n = 36$) and rest cycles ($n = 27$). Statistical significance was set at $p \leq 0.05$.

3. Results

Table 3 depicts the average values for each variable during each of the four work cycles. Significant time effects were detected for duration ($p = 0.042$), maximum HR ($p = 0.009$), average HR ($p = 0.001$), maximum core temperature achieved ($p = 0.028$) and time rate of change in core temperature ($p = 0.017$). The first work cycle was significantly longer than cycles 2 and 4. Group averages for peak HR, average HR and maximum core temperature increase in each successive work cycle, though not all inter-cycle differences, are statistically significant as seen in Table 3. The time rate of change in core temperature was significantly higher for work cycle 4 than for cycles 1 and 2. The time delay between the peaks in HR and core temperature shows a visual trend from work cycles 1–3, increasing from ~6 min to over 8 min, though these data show large person-to-person variation and are not statistically significant ($p = 0.396$).

Table 3. Mean HR and core temperature data from work cycles ($n = 9$).

	Work cycle			
	1	2	3	4
Duration (min)	31.0 (11.8)[a,b]	17.8 (5.8)[c]	21.3 (5.9)[b]	15.8 (4.2)[c,d]
HR_{peak} (bpm)	181.2 (14.7)[b]	182.6 (11.6)[b]	185.8 (12.7)	188.4 (15.6)[a,c]
HR_{ave} (bpm)	139.6 (14.7)[a,b,d]	150.5 (14.5)[b,c]	153.2 (12.4)[b,c]	160.0 (16.7)[a,c,d]
$T_{co,max}$ (°C)	38.43 (0.36)[a,c,d]	38.62 (0.32)[c]	38.67 (0.34)[c]	38.72 (0.42)[c]
$\Delta T_{co}/\Delta t$ (°C/min)	0.036 (0.019)[b]	0.032 (0.010)[b]	0.048 (0.031)	0.048 (0.019)[a,c]
Δt_{peaks} (min)	6.1 (2.0)	7.2 (3.1)	8.3 (5.9)	7.2 (2.3)

HR_{ave}, average heart rate; HR_{peak}, peak heart rate; $T_{co,max}$, maximum core temperature; $\Delta T_{co}/\Delta t$, time rate of change in core temperature; Δt_{peaks}, time delay between end of peak HR and peak core temperature.
[a] Different than cycle 2 ($p < 0.05$).
[b] Different than cycle 4 ($p < 0.05$).
[c] Different than cycle 1 ($p < 0.05$).
[d] Different than cycle 3 ($p < 0.05$).

The 36 individual work cycles (four work periods for nine individuals) were combined to find correlations between these activities and core temperature responses (Table 4). The duration of the work activity was negatively, and relatively weakly, correlated with peak HR ($r = -0.344$, $p = 0.040$), average HR ($r = -0.515$, $p = 0.001$) and increase in time rate of change in core temperature ($r = -0.346$, $p = 0.039$). The maximum core temperature achieved and rate of rise in core temperature during the work cycle are both strongly and positively correlated with the peak HR achieved ($r = 0.508$, $p = 0.002$; $r = 0.676$, $p < 0.001$, respectively) and average HR ($r = 0.643$, $p < 0.001$; $r = 0.513$, $p = 0.001$, respectively). Finally, the time difference between peaks is weakly correlated only with the rate of rise in core temperature during the work cycle ($r = -0.386$, $p = 0.020$).

Table 5 provides average HR and core temperature values during each of the three rest periods between the four work cycles. Significant time effects were detected for average HR ($p = 0.019$) and time rate of change in core temperature (cooling rate, $p = 0.012$). Average HR measured during the second cycle was significantly lower than the third cycle. The cooling rate shows a visual trend towards a higher rate of cooling at later cycles, but was only significantly faster for the third rest period than the first. As Table 6 indicates, there are relatively strong correlations between rest duration and minimum HR achieved ($r = -0.687$, $p < 0.001$), average HR ($r = -0.482$, $p = 0.011$) and minimum core temperature ($r = -0.584$, $p = 0.001$). The minimum core temperature achieved during the rest cycle was weakly correlated with the minimum HR achieved ($r = 0.470$, $p = 0.013$) and average HR ($r = 0.403$, $p = 0.011$). There were no significant correlations between cooling rate and any of the other variables included in this study.

Relationships between descriptive variables for each firefighter and the physiological changes during work (Table 7) and rest (Table 8) were also investigated. Firefighter age was significantly correlated with resting HR measured prior to firefighting activities ($r = 0.641$, $p < 0.001$) and with the peak HR ($r = -0.609$, $p < 0.001$) achieved during firefighting activities. BMI was negatively correlated with peak HR ($r = -0.710$, $p < 0.001$), average HR ($r = -0.583$, $p < 0.001$), maximum core temperature ($r = -0.519$, $p = 0.001$) and rate of core temperature rise during work ($r = -0.628$,

Table 4. Correlation matrix for HR and core temperature data from all work cycles ($n = 36$).

		Duration (min)	HR_{peak} (bpm)	HR_{ave} (bpm)	$T_{co,max}$ (°C)	$\Delta T_{co}/\Delta t$ (°C/min)	Δt_{peaks} (min)
Duration (min)	r	1	−0.344	−0.515	−0.318	−0.346	−0.002
	p		0.040	0.001	0.058	0.039	0.991
HR_{peak} (bpm)	r	−0.344	1	0.690	0.508	0.676	−0.087
	p	0.040		0.000	0.002	0.000	0.612
HR_{ave} (bpm)	r	−0.515	0.690	1	0.643	0.513	−0.070
	p	0.001	0.000		0.000	0.001	0.687
$T_{co,max}$ (°C)	r	−0.318	0.508	0.643	1	0.427	−0.209
	p	0.058	0.002	0.000		0.009	0.221
$\Delta T_{co}/\Delta t$ (°C/min)	r	−0.346	0.676	0.513	0.427	1	−0.386
	p	0.039	0.000	0.001	0.009		0.020
Δt_{peaks} (min)	r	−0.002	−0.087	−0.070	−0.209	−0.386	1
	p	0.991	0.612	0.687	0.221	0.020	

HR_{ave}, average heart rate; HR_{peak}, peak heart rate; $T_{co,max}$, maximum core temperature; $\Delta T_{co}/\Delta t$, time rate of change in core temperature; Δt_{peaks}, time delay between end of peak HR and peak core temperature.

Table 5. Mean HR and core temperature data from rest cycles ($n = 9$).

	Rest cycle		
	1	2	3
Duration (min)	27.2 (15.7)	36.3 (18.5)	21.4 (5.5)
HR_{min} (bpm)	103.0 (16.0)	98.2 (10.7)	109.9 (8.4)
HR_{ave} (bpm)	132.7 (10.9)	127.2 (10.0)[a]	140.0 (8.0)[b]
$T_{co,min}$ (°C)	38.00 (0.34)	37.71 (0.38)	37.93 (0.43)
$\Delta T_{co}/\Delta t$ (°C/min)	−0.016 (0.011)[a]	−0.022 (0.012)	−0.029 (0.019)[c]

HR_{ave}, average heart rate; HR_{min}, minimum heart rate; $T_{co,in}$, minimum core temperature; $\Delta T_{co}/\Delta t$, time rate of change in core temperature.
[a] Different than cycle 3 ($p < 0.05$).
[b] Different than cycle 2 ($p < 0.05$).
[c] Different than cycle 1 ($p < 0.05$).

Table 6. Correlation matrix for HR and core temperature data from all rest cycles ($n = 27$).

		Duration (min)	HR_{min} (bpm)	HR_{ave} (bpm)	$T_{co,min}$ (°C)	$\Delta T_{co}/\Delta t$ (°C/min)
Duration (min)	r	1	−0.687	−0.482	−0.584	0.011
	p		0.000	0.011	0.001	0.957
HR_{min} (bpm)	r	−0.687	1	0.706	0.470	0.109
	p	0.000		0.000	0.013	0.590
HR_{ave} (bpm)	r	−0.482	0.706	1	0.403	−0.059
	p	0.011	0.000		0.037	0.769
$T_{co,min}$ (°C)	r	−0.584	0.470	0.403	1	0.334
	p	0.001	0.013	0.037		0.088
$\Delta T_{co}/\Delta t$ (°C/min)	r	0.011	0.109	−0.059	0.334	1
	p	0.957	0.590	0.769	0.088	

HR_{ave}, average heart rate; HR_{min}, minimum heart rate; $T_{co,in}$, minimum core temperature; $\Delta T_{co}/\Delta t$, time rate of change in core temperature.

Table 7. Correlations between firefighter descriptive characteristics and HR/core temperature from all work cycles ($n = 36$).

		Age (yr)	BMI (kg/m^2)	HR_{rest} (bpm)	Duration (min)	HR_{peak} (bpm)	HR_{ave} (bpm)	$T_{co,max}$ (°C)	$\Delta T_{co}/\Delta t$ (°C/min)	Δt_{peaks} (min)
Age (yr)	r	1	0.246	0.641	0.130	−0.609	−0.237	−0.003	−0.308	0.091
	p		0.148	0.000	0.451	0.000	0.164	0.986	0.068	0.596
BMI (kg/m^2)	r	0.246	1	0.502	0.225	−0.710	−0.583	−0.519	−0.628	0.256
	p	0.148		0.002	0.187	0.000	0.000	0.001	0.000	0.132
HR_{rest} (bpm)	r	0.641	0.502	1	0.175	−0.668	−0.495	−0.084	−0.389	0.010
	p	0.000	0.002		0.307	0.000	0.002	0.628	0.019	0.952

BMI, body mass index; HR_{ave}, average heart rate; HR_{peak}, peak heart rate; HR_{rest}, resting heart rate; $T_{co,max}$, maximum core temperature; $\Delta T_{co}/\Delta t$, time rate of change in core temperature; Δt_{peaks}, time delay between end of peak HR and peak core temperature.

Table 8. Correlations between firefighter descriptive characteristics and HR/core temperature from all rest cycles ($n = 27$).

		Age (yr)	BMI (kg/m^2)	HR_{rest} (bpm)	Duration (min)	HR_{min} (bpm)	HR_{ave} (bpm)	$T_{co,min}$ (°C)	$\Delta T_{co}/\Delta t$ (°C/min)
Age (yr)	r	1	0.246	0.641	0.073	0.204	0.050	0.119	0.246
	p		0.148	0.000	0.717	0.307	0.803	0.554	0.216
BMI (kg/m^2)	r	0.246	1	0.502	−0.310	0.147	−0.219	0.086	0.286
	p	0.148		0.002	0.115	0.465	0.273	0.669	0.148
HR_{rest} (bpm)	r	0.641	0.502	1	−0.070	0.067	−0.336	−0.004	0.009
	p	0.000	0.002		0.729	0.740	0.087	0.985	0.964

BMI, body mass index; HR_{ave}, average heart rate; HR_{min}, minimum heart rate; HR_{rest}, resting heart rate; $T_{co,in}$, minimum core temperature; $\Delta T_{co}/\Delta t$, time rate of change in core temperature.

$p < 0.001$), while the measure was positively correlated with resting HR ($r = 0.502$, $p = 0.002$). Resting HR was negatively correlated with peak HR ($r = -0.668$, $p < 0.001$) and rate of core temperature rise during work ($r = -0.389$, $p = 0.019$).

4. Discussion

This study extends our understanding of the cardiovascular and thermal strain associated with firefighting by investigating repeated bouts of simulated live firefighting activity. The majority of published results have investigated firefighting activity lasting 20 min or less. The most important results of this study are that (1) the magnitude of core temperature rise and rate of rise increase to higher levels than previously reported during long-duration firefighting activities commonly encountered in training or prolonged operations, (2) core temperature and HR increase to higher levels and the rate of core temperature increase rises in subsequent work cycles, (3) having a higher BMI and resting HR was associated with lower HRs, core temperatures and rate of rise in core temperature during the work cycles and (4) the recovery of HR and core temperature is strongly correlated with the time allowed between work cycles and is unrelated to individual descriptive characteristics or the previous amount of work completed.

4.1. Descriptive characteristics

Firefighters recruited for this study were male ($n = 6$) and female ($n = 3$) and represented a wide range of ages and body sizes. While the mean age was 32.8 years, participants ranged from 20 to 45 years old and BMI ranged from just under 22 to nearly 38. Five firefighters would be considered lean based on BMI, while the remaining four were overweight ($n = 1$) and obese ($n = 3$). Resting HR and core temperature were within the normal range for healthy individuals.

In this diverse group of firefighters, we found that age was only correlated with peak HR achieved and resting HR. It is well established that firefighters work to near maximal levels during strenuous operations (Smith, Manning, and Petruzzello 2001; Barnard and Duncan 1975). Furthermore, maximum HR is known to decrease as an individual ages, so the typical firefighting activity is expected to result in lower peak HRs in older firefighters. With this group of participants, firefighter age was not significantly correlated with the BMI ($r = 0.246$, $p = 0.148$).

BMI was negatively correlated with peak HR achieved and average HR, suggesting that those with higher BMI did not work as hard as those with lower BMI, independent of their age. Furthermore, BMI (a measure of fatness) was positively correlated with resting HR (an indirect measure of fitness). In addition, resting HR was negatively correlated with peak HR achieved and rate of core temperature rise during work. Together, these findings may suggest that heavier and less fit firefighters did not work as hard as leaner and more fit firefighters in this study during each of the work cycles. Maximum core temperature and rate of rise of core temperature were also significantly and negatively correlated with BMI; thus, despite the larger body mass, their core temperature did not increase as significantly, again suggesting that perhaps the heavier firefighters were not working as hard as the lean firefighters.

4.2. Work cycles

Consistent with previous work, firefighting activities increased HR to near age-predicted maximal levels (220-age). For each of the four work periods, firefighters achieved on average at least 95% of their predicted maximal HR. Importantly, in each successive bout of firefighting activity, peak HRs continued to increase as did the average HR during the firefighting activity, even with rest periods lasting between 20 and 35 min. During actual operation, firefighters typically take a very short break while the air cylinder is replaced for the first time and incident rehabilitation is only initiated after a firefighter has used two air cylinders (~40 min of work).

On average, core temperature increased to 1.5°C by the end of the first firefighting training evolution and reached more than a 1.8°C rise after the final work cycle was completed. Core temperature increases measured in this study are larger than those reported in previous studies focusing on single bouts of short-term firefighting activities (Table 1). Due to difficulties in accurately measuring core temperature during emergency operations, there have been no reports of changes in core temperature due to actual fire response. However, Table 1 provides an overview of studies that have focused on measuring core temperature from live fire training and research activities. Studies that report changes in core temperature as a result of treadmill walking or bicycle riding while wearing PPE are not included here. The live-fire studies are included in this table only if they report the pre- and post-firefighting temperature along with the duration of activity or explicitly quantify the average rate of rise of core temperature. There is significant variability in the data based on the type of activity undertaken, the activity of the firefighter participants and the location of the participants within the burn structure. Firefighters who performed intermittent firefighting work – such as those conducting live-fire drills (e.g. Eglin, Coles, and Tipton 2004; Romet and Frim 1987) or participating in controlled exercise during a 2-min work–rest cycle (e.g. Horn et al. 2011; Smith et al. 2011) – have a significantly lower rate of rise than those who are conducting strenuous tasks continuously for 5–8 min [Smith, Manning, and Petruzzello 2001; Eglin, Coles, and Tipton 2004 (during 'Fire Attack'), Smith et al. 2005]. In this study, the average time rate of change during the work cycles (0.032–0.048°C/min) was similar to those reported in previous reports for activities in which significant rest was interspersed within the work (e.g. Horn et al. 2011; Romet and Frim 1987; Smith et al. 2011). However, the time rate of change in the final two work cycles was more rapid than that during the first two work cycles. Furthermore, the maximum time rate of change we found during activities for each firefighter was 0.123 ± 0.055°C/min when averaged over 1-min time intervals or 0.080 ± 0.030°C/min when averaged over 5-min time intervals. Thus, for short bouts during the longer work cycles, core temperature may increase much more rapidly than previously reported.

The time lag between the end of activity and peak in core temperature varied from just over 5 min to nearly 11 min. The average time lag for the first three cycles increased from 6 min to more than 8 min, suggesting that more time may need to be provided after each successive bout of firefighting activity. This time frame is more than that typically available during an SCBA air cylinder change and approximately that which may be available during a quick rehabilitation assignment. We found significant person-to-person variation in the time lag of core temperature peak, probably related to activity level and conditions during recovery, as well as individual variability in body size, fitness and gear doffing procedures. Even though firefighters were encouraged to doff their gear and hydrate during the rest periods, each individual was free to rehabilitate as they determined most beneficial (as is the case at most emergency operations). While several authors have pointed out that the peak in firefighter core temperature typically occurs significantly after the bout of activity has ceased (Smith and Petruzzello 1998; Smith, Manning, and Petruzzello 2001; Hostler et al. 2009), this is the first report on changes during subsequent work cycles.

4.3. Rest cycles

The physiological recovery from firefighting operations appears to be closely tied to the duration of rest that was allowed regardless of the duration and intensity of firefighting operations that occurred prior to the rest cycle. The negative correlations indicate that longer rest periods result in lower HRs and core temperature, or more significant recovery. HR decreased to the lowest level, had the smallest average value and core temperature recovered the most during the second rest cycle, which was, on average, at least 9 min longer than the other two rest cycles. We have previously shown that firefighters' HRs and core temperatures decrease rapidly during rest periods, but do not return to baseline until ~50–80 min post-firefighting despite a rapid initial recovery (Horn et al. 2011). In this study, even with the longest breaks (35 min), the average HR remained nearly 30 bpm higher than baseline, and core temperature was still more than 0.8°C higher than pre-firefighting resting values.

The rate of core temperature reduction increased more during the last rest cycle than during the first. This may be due to the increased driving force for cooling that resulted from a larger temperature differential as the firefighter's core temperature increased through the training evolution. Importantly, the average rate of core temperture reduction (cooling rate) during rest was approximately half of the average rate of core temperature increase during firefighting activities.

Several strong, negative correlations were detected between HR/core temperature during work and both BMI and resting HR, yet no significant correlations were detected involving the rest cycles and these descriptive characteristics.

4.4 Limitations

While this study was conducted with a relatively diverse cross-section of firefighter's ages and body sizes, the cohort was relatively young (~33 years) and was screened for pre-existing cardiovascular diseases, therefore it may not be representative of the entire firefighting population. The number of participants was relatively small such that it was not possible to quantify effects of BMI and age in a more rigorous statistical approach.

Core temperature and HR were measured on two independent devices and synchronised using a master clock. However, core temperature was only recorded every 60 s, while HR was recorded every 5 s. The accuracy in quantifying the time lag between peak HR and peak core temperature would be improved with core temperature data collected more rapidly.

Firefighting activities took place in controlled training structures and firefighters were given significant breaks to cool and rehydrate between cylinders of air. Furthermore, the trained instructors typically provided shorter exposure to live fire later in the day as they regularly do during training as a safety measure, thus, somewhat mitigating the magnitude of the total core temperature rise. While the values measured here are larger than any reported before, it is important to note that with shorter breaks and subsequent firefighting activities as long as the first, core temperature values may increase significantly beyond those reported here.

5. Conclusions

We have quantified the effect of repeated bouts of firefighting activities performed over an extended period of firefighter training on core temperature and HR in a synchronised manner for the first time. Our data show that firefighter core temperatures can increase to a larger magnitude than previously reported and core temperatures continue to increase during subsequent work cycles even after breaks of more than 30 min. The rate of core temperature increase during work continues to increase later in the training exercise, increasing the risk for exertional heat stress particularly if long-duration activity is required later in the firefighting period. Maximum core temperature and rate of core temperature increase are positively correlated with the peak HR achieved and average HR during the work cycles. On the other hand, strong negative correlations were detected between HR and core temperature measurements with BMI and resting HR, suggesting that those who are overweight and less fit do not work as hard during the firefighting activities. HR and core temperature recovery from firefighting activities is closely related to the time that is provided for rest, regardless of firefighter obesity and fitness or the intensity/duration of firefighting activities that preceded the recovery. Importantly, the average cooling rates during recovery are found to be roughly half of that during work cycles.

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