Focus on Firefighter Physiology

Physiological Recovery from Firefighting Activities in Rehabilitation and Beyond

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Abstract

Objectives. The primary objective of this study was to document the timeline of physiologic recovery from firefighting activities in order to inform emergency medical services (EMS) of vital sign values that might be expected during incident rehabilitation and in developing rehabilitation protocols to make decisions about when to return personnel to the fireground. Secondarily, we compared two different incident rehabilitation strategies to determine effectiveness in reducing physiologic strain following firefighting. **Methods.** A repeated-measures randomized crossover design was utilized in which firefighters conducted a controlled set of firefighting activities, after which they completed incident rehabilitation in one of two conditions: 1) similar to currently used rehabilitation protocols and 2) with active cooling and nutritional intervention. Following 15 minutes of rehabilitation, each firefighter was asked to perform a simulated rescue "dummy drag" and then recover for 120 minutes in a quiet area. Core temperature and heart rate were recorded throughout the study. Blood pressures and subendocardial viability ratios were obtained before firefighting, after firefighting, and at standardized times during rehabilitation and recovery. **Results.** Heart rate and core temperature increased during firefighting, and core temperature continued to increase for 7 minutes after completion of firefighting activities. These values did not return to baseline until at least 50 minutes after firefighting activity. Systolic blood pressures were significantly reduced during rehabilitation (15.2%), and recovered 7.7% during the first 50 minutes of recovery, but remained significantly lower than before firefighting for at least 120 minutes. An index of subendocardial perfusion was also significantly depressed for up to 110 minutes after firefighting. Differences between rehabilitation protocols were minimal. **Conclusions.** The timeline for recovery from firefighting activities is significantly longer than the typical 10–20-minute rehabilitation period that often is provided on the fireground. Modifications from the current rehabilitation protocol do not appear to improve the recovery timeline when rehabilitation is conducted in a cool room. While firefighters often are concerned about elevated blood pressures, this study suggests that firefighters and EMS personnel should also be cognizant of the potential dangers of hypotension. **Key words:** rehabilitation; blood pressure; body temperature; heart rate; firefighter

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Introduction

Emergency medical services (EMS) personnel are commonly dispatched to the scene of a working fire to support fireground incident rehabilitation practices. However, little fact-based evidence has been provided to EMS or fire personnel to determine typical vital signs of a firefighter who is recovering from a bout of strenuous fireground activity. As such, there are few scientifically based indicators to support decisions to release a firefighter, to hold firefighters from activity, or when to transport firefighters to the hospital.[1]

Each year, approximately 100 firefighters lose their lives in the line of duty and tens of thousands are injured. Over the past 10 years, approximately 40–50% of line-of-duty deaths have been attributed to heart attacks.[2] Another 650–1,000 firefighters suffer from nonfatal heart attacks in the line of duty each year.[3] It is well recognized that firefighting leads to increased cardiovascular and thermal strain.[4,5] However, the time course of recovery from firefighting is not well documented despite the fact that a large percentage of firefighting fatalities occur shortly after firefighting activities have ended.[6]

Incident rehabilitation has been broadly recommended to mitigate the cardiovascular and thermal strain associated with performing strenuous firefighting activity. While there has been some effort to understand the effect of different cooling strategies on firefighters' tolerance time and core temperature,[7,8] the efficacy of different nutritional interventions has not been documented, despite the fact that the National Fire Protection Association (NFPA) has specific recommendations regarding the provision of nutrition. Finally, during rehabilitation, medical monitoring usually consists of collection of traditional vital signs such as heart rate and blood pressure. However, central aortic blood pressure may be a better predictor of clincial outcome than brachial pressure,[9,10] and with current technology this measurement can be implemented in a rehabilitation unit if found to be useful.

The purpose of this study was to describe the acute effects of firefighting on traditional vital signs as well as several novel vascular measures (e.g., central aortic blood pressure, subendocardial viability ratio) and to document the time course of recovery. Additionally, we compared two incident rehabilitation strategies (control and enhanced) to determine the extent to which an "enhanced" rehabilitation might facilitate recovery from firefighting activities.

METHODS

Human Subjects

Local career and volunteer male firefighters between the ages of 19 and 39 years were recruited to participate in this study. Prior to participation in the testing, the participants completed a health history questionnaire. Firefighters who indicated that they had a diagnosed history of atherosclerotic cardiovascular disease, were taking medications for high blood pressure or cholesterol, or were taking aspirin, acetaminophen, ibuprofen, or cold or asthma medications were excluded from participating in the study.

Participants were fully informed of the purpose of the study, were provided with an opportunity to ask questions of the investigators, and were informed of the requirements of participation. Participants signed an informed consent document indicating that they understood the risks and benefits of participation and that their participation was voluntary. This study was approved by the University of Illinois Institutional Review Board.

Study Design

Twenty-three firefighters were recruited to participate in a within-subject, randomized, repeated-measures study designed to investigate the time course of recovery from strenuous firefighting and the effectiveness of incident rehabilitation interventions. The repeated rehabilitation trials were separated by a minimum of 48 hours and administered in a counterbalanced fashion to ensure that half of the participants received the control condition first and half of the participants received the enhanced condition first. Of the 23 enrolled subjects, 21 firefighters completed both trials of the study. Two subjects did not complete both trials: one because of a prolonged illness and the other because of a workplace injury (not related to this study).

Only the incident rehabilitation protocol differed between the two trials. During the "control" rehabilitation trial, the participants completed a set of standard firefighting drills in a training structure and then removed their helmet, hood, gloves, and bunker coat and sat in a rehabilitation area in a cool room (approximately 20°C). Participants were provided with water ad libitum. This control condition was meant to reflect what is typically done at a fire scene—although we recognize there is great variability. During the "enhanced" trial, the participants completed the same set of firefighting drills and then were required to remove all of their turnout gear (including bunker coat and pants) and consume up to 500 mL of water and at least 355 mL of a commercially available sport drink (Gatorade, Chicago, IL; 21 g carbohydrate [CHO]), and were aggressively cooled using cold towels. However, hydration was not withheld from any participants who felt they needed more, nor was it required of those who did not feel as if they could consume more. Participants sat in the same area as they did during the control rehabilitation trial. In addition, during the first 10 minutes in recovery in the "enhanced" trial, firefighters drank 355 mL of a commercially available recovery drink (Endurox, PacificHealth Laboratories, Matawan, NJ; 20 g CHO, 5 g protein [PRO]).

Experimental Protocol

A schematic description of the timeline for each trial is shown in Figure 1. As outlined in the Measurements section, baseline data were collected prior to firefighting activities. The participants then performed prescribed firefighting drills in full personal protective equipment (PPE; including self-contained breathing apparatus [SCBA]), followed by an immediate postfirefighting data-collection session. The postfirefighting data collection required approximately 7 minutes to complete; thus to fully account for changes in vital signs throughout the study, separate postfirefighting and entry-to-rehabilitation data were collected for

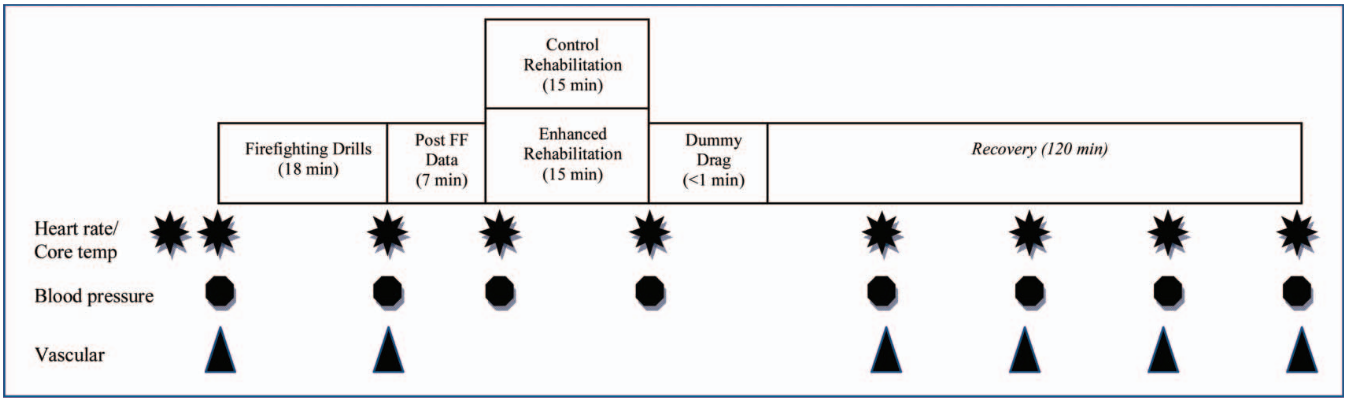

FIGURE 1. Schematic of study design and timeline. Note that time is not drawn to scale. FF = firefighting; vascular = vascular function based on several novel measures.

heart rate, core temperature, and blood pressure. Participants then underwent rehabilitation for 15 minutes (control or enhanced condition). Next, firefighters performed a dummy drag protocol (84 kg; 12 meters; approximately 9 seconds) to assess their ability to perform a simulated rescue. Following rehabilitation and the dummy drag, participants changed into dry clothes and walked to an adjacent building (fire station) where they remained during the 120-minute recovery period. During recovery, firefighters were in the seated position and engaged in classroom activities or reading to mimic what may occur at a fire station following a fire call (assuming the suppression crew was relieved of overhaul and cleanup duties).

The firefighting drills lasted 18 minutes (requiring approximately 1 cylinder of air for most participants) and consisted of nine 2-minute periods of alternating rest and work. The work cycles included stair climbing, simulated forcible entry, a simulated search, and simulated hose advance. The live-fire drills were completed on the second story of a training building. These live-firefighting drills were similar to those employed in previously published studies.[4,5,11–16]

Each participant was paired with a trained member of the research staff, who safely escorted the participant throughout the protocol. During each test, the escort monitored the participant's heart rate and work completed in each cycle. At the conclusion of each station, the participant rested for 2 minutes in a kneeling position on the floor as the safety escort demonstrated the next task.

Three thermocouples were installed in the building near the search station located 0.15 m above the floor, 1.2 m above the floor, and 2.4 m above the floor (~0.3 m below the ceiling) to measure room temperature. Type K (Chromel-Alumel) thermocouples with factory-welded beads were utilized in conjunction with a digital data-acquisition system (Omega Engineering, OM-DAQPRO-4300; Stamford, CT) that sampled data every 10 seconds. Throughout the burn, trained stokers controlled the temperature in the training structure by monitoring the thermocouple readings and adding small fuel packages to the firesets sequentially and controlling the ventilation conditions in the room. The temperatures at the midlevel point were maintained at roughly 71–82°C and the floor temperatures were maintained at 35–41°C. The prescribed firefighting activities required participants to work almost exclusively in the vertical area between the middle and floor thermocouple.

Measurements

Height, weight, body composition/percentage body fat (via chest, abdomen, and thigh skinfolds; calculated using the Jackson-Pollock 3-site equation[17]), and fasting glucose level and full cholesterol profile from a fingerstick sample (Cholestech, Hayward, CA) were assessed prior to participating in the live-fire training.

Throughout firefighting, rehabilitation, and recovery, body temperature was continuously measured using a monitor and a silicone-coated gastrointestinal (GI) core-temperature capsule (Mini Mitter, VitalSense; Philips Respironics, Bend, OR). Participants swallowed a small disposable core-temperature-sensor capsule the night before the study was conducted. Firefighters wore a heart rate monitor throughout the firefighting and recovery protocol (Polar Electro, Inc., Kempele, Finland). Blood pressure was assessed via auscultation immediately before and after firefighting, before and after rehabilitation, and every 30 minutes during recovery by EMS personnel trained at the emergency medical technician (EMT)-basic level or higher.

Applanation tonography was used to assess central blood pressure and subendocardial viability ratio pre- and postfirefighting activity and during recovery. Radial artery pressure waveforms were attained in the seated position from a 10-second epoch using applanation tonometry and a high-fidelity strain-gauge transducer (Millar Instruments, Houston, TX). Central aortic pressure waveforms were constructed from the radial artery pressure waveforms (SphygmoCor, AtCor Medical, West Ryde, New South Wales, Australia) using a validated transfer function[18] that has also been verified during exercise.[19] The subendocardial viability ratio (SEVR) was calculated from the central aortic waveform as the ratio of the area under the diastolic pressure–time portion of the waveform to the systolic pressure–time waveform integral. The SEVR is related to heart rate, ejection duration, and arterial load[20,21] and provides an estimate of the arterial system's ability to perfuse myocardial tissue in order to meet the heart's energy requirements. If the SEVR decreases from baseline levels, the heart will be faced with a reduced energy reserve, potentially resulting in lower tolerance for strenuous physical activities such as fighting a fire.[22,23] Finally, the rate–pressure product (RPP) was calculated as the product of systolic blood pressure (SBP) and heart rate divided by 100. The RPP provides an estimate of myocardial oxygen consumption.[24]

Immediately after rehabilitation, the firefighters performed a dummy drag task to assess their ability to perform a strenuous activity (e.g., a rescue) after the rehabilitation period.[25] In this case, the firefighters were asked to drag an 81.5-kg manikin across a concrete floor over a distance of 12 m. The time to complete the task was measured via laser triggering at the start and end of the course.

Analytical Methods

The effect of firefighting activities and incident rehabilitation interventions on heart rate and core temperature measures was examined using a repeated-measures mixed multivariate analysis of variance (MANOVA, 2 [intervention: control, enhanced] × 9 [measurement period: baseline, before firefighting, immediately after firefighting, during rehabilitation (entry, exit), and during recovery (30, 60, 90, and 120 minutes)]. The effect of the incident rehabilitation interventions on blood pressure during rehabilitation and recovery was examined using a repeated-measures MANOVA (2 [intervention: control, enhanced] × 8 [measurement period: before firefighting, immediately after firefighting, during rehabilitation (entry, exit), and during recovery (30, 60, 90, and 120 minutes)]. Vascular function was assessed as a function of the firefighting activities and incident rehabilitation intervention again using a repeated-measures MANOVA (2 [intervention: control, enhanced] × 6 [measurement period: before firefighting, immediately after firefighting, and throughout recovery (30, 60, 90, and 120 minutes)]. The effects of rehabilitation interventions on subsequent performance (i.e., time to complete) in a simulated rescue were compared using a paired t-test.

Data were analyzed using SPSS version 18 (SPSS Inc., Chicago, IL). Descriptive data are expressed as mean ± standard deviation for tables and mean ± standard error for graphs. Statistical significance was set at $p < 0.05$ for all analyses.

RESULTS

Table 1 presents descriptive data on the firefighters who participated in this study. Overall, our participants were relatively young (25.6 ± 5.2 years), apparently healthy firefighters. In the control rehabilitation condition, firefighters consumed 480 ± 182 mL of water, whereas they consumed 380 ± 192 mL of water and 366 ± 83 mL of sports drink in the enhanced condition.

There was a significant time effect ($p < 0.001$) and condition effect ($p = 0.028$) for heart rate. As seen in Figure 2, heart rate increased significantly with firefighting activity. Heart rate increased from 77.3 ± 10.4 $b\cdot min^{-1}$ prior to entering the training course to 161.0 ± 16.4 $b\cdot min^{-1}$ by the second task (forcible entry) and remained elevated to this level after each subsequent task (data not shown). Heart rate then decreased rapidly after completion of the training drill. In the 7 minutes between postfirefighting and entry to rehabilitation, heart rate dropped from 162.0 ± 15.4 $b\cdot min^{-1}$ to 110.8 ± 16.0 $b\cdot min^{-1}$, but only reduced to 101.5 ± 14.2 $b\cdot min^{-1}$ during the remaining 15 minutes of rehabilitation. Heart rate remained significanly elevated from baseline until between 70 and 130 minutes after the beginning of the study (30 and 90 minutes into recovery).

Heart rate was significantly higher for firefighters in the enhanced condition compared with the standard condition during the recovery period. A post hoc analysis was conducted with a paired t-test at each time point and showed that the control and enhanced condition trials were not significantly different until the recovery period; however, the enhanced rehabilitation condition resulted in significantly higher heart rates at the 70-minute (82.7 ± 8.2 vs. 77.6 ± 9.3 $b\cdot min^{-1}$) and 100-minute (81.1 ± 10.3 vs. 73.9 ± 10.5 $b\cdot min^{-1}$) time points (30 and 60 minutes into recovery). The post hoc analysis also showed that heart rate returns to

TABLE 1 Descriptive Statistics for the Recruited Firefighter Subjects

	Mean (SD)	Range
Age, yr	25.6 (5.2)	19–39
Height, m	1.81 (0.01)	1.65–1.98
Weight, kg	83.3 (11.2)	67.1–111.1
Body mass index, kg/m^2	25.4 (2.0)	20.6–28.8
Body fat,%	15.5 (4.5)	6.0–24.4
Total cholesterol, mg/dL	172.2 (36.8)	126–271
LDL, mg/dL	106.1 (30.3)	68–195
HDL, mg/dL	45.4 (12.7)	24–67

HDL = high-density lipoprotein (cholesterol); LDL = low-density lipoprotein (cholesterol); SD = standard deviation.

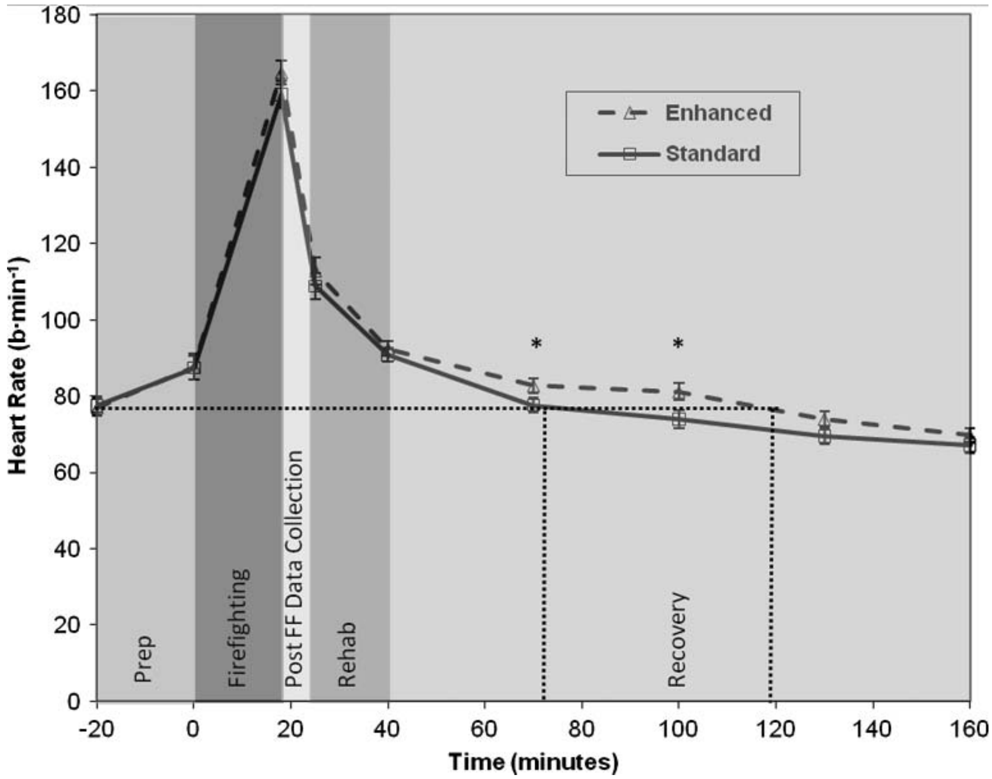

FIGURE 2. Changes in heart rate throughout the test protocol ($n = 21$). Dotted lines indicate the times when heart rate returns to baseline levels. *Significant condition affect at these time points. FF = firefighting.

baseline condition (e.g., no longer statistically elevated) between 70 and 100 minutes for the standard condition (i.e., at least 50 minutes after firefighting), but between 100 and 130 minutes for the enhanced rehabilitation condition (i.e., at least 80 minutes after firefighting activities have ceased).

For the core temperature data shown in Figure 3, we experienced signficant data loss ($n = 12$) due to difficulties in retaining the core-temperature pills. However, there was a significant time effect ($p < 0.001$) for core temperature, which increased from 37.1°C ± 0.2°C to 37.8°C ± 0.4°C during the short bout of firefighting activities. Unlike heart rate, core temperature continued to increase (to 37.9°C ± 0.4°C) between the end of firefighting and the beginning of rehabilitation. After this time, core temperature decreased rapidly, but a post hoc analysis again showed that core temperature did not return to baseline levels (i.e., did not cease to be statistically elevated) until 100 minutes (60 minutes into recovery). Despite the addition of active cooling and complete removal of bunker gear in enhanced rehabilitation, there was no significant condition effect on core temperature ($p = 0.820$).

There was a significant time effect for SBP ($p < 0.001$) and diastolic blood pressure (DBP, $p = 0.025$) but no significant condition effect for either SBP or DBP (Fig. 4). Prefirefighting SBP averaged 133.9 ± 11.4 mmHg, whereas postfirefighting SBP averaged 134.2 ± 11.7 mmHg in this group of young, relatively healthy firefighters. The SBP dropped rapidly during rehabilitation. On average, the SBP decreased 20.5 ± 13.1 mmHg—from 134.2 ± 11.7 mmHg at 18 minutes (immediately after firefighting) to 113.7 ± 10.5 mmHg at 40 minutes (15.2% by the end of rehabilitation). In 11 trials, the SBP dropped by more than 20 mmHg during the rehabilitation period and in four cases this decrease was larger than 30 mmHg. The average prefirefighting SBP for subjects participating in these 11 trials was 134.6 ± 13.7 mmHg, which is not significantly different from that for the rest of the sample. In the four cases in which SBP dropped by more than 30 mmHg, the prefirefighting SBP was significantly higher compared with that for the rest of the population ($p = 0.02$, 142.5 ± 9.3 vs. 132.9 ± 11.2 mmHg). However, there was no correlation between the prefirefighting SBP and the drop in SBP during rehabilitation ($r = 0.096$). In fact, in five subjects, the SBP declined by more than 20 mmHg in the first 5 minutes of rehabilitation, despite prefirefighting blood pressures that were, on average, not significantly different from those for the rest of the sample. After rehabilitation and the dummy drag, the SBP values during recovery averaged approximately 123.2 ± 10.4 mmHg, a recovery of 7.7%, and were stable throughout recovery.

As shown in Figure 5, aortic blood pressure followed a similar pattern to peripheral blood pressure obtained via auscultation; there was a significant time effect for

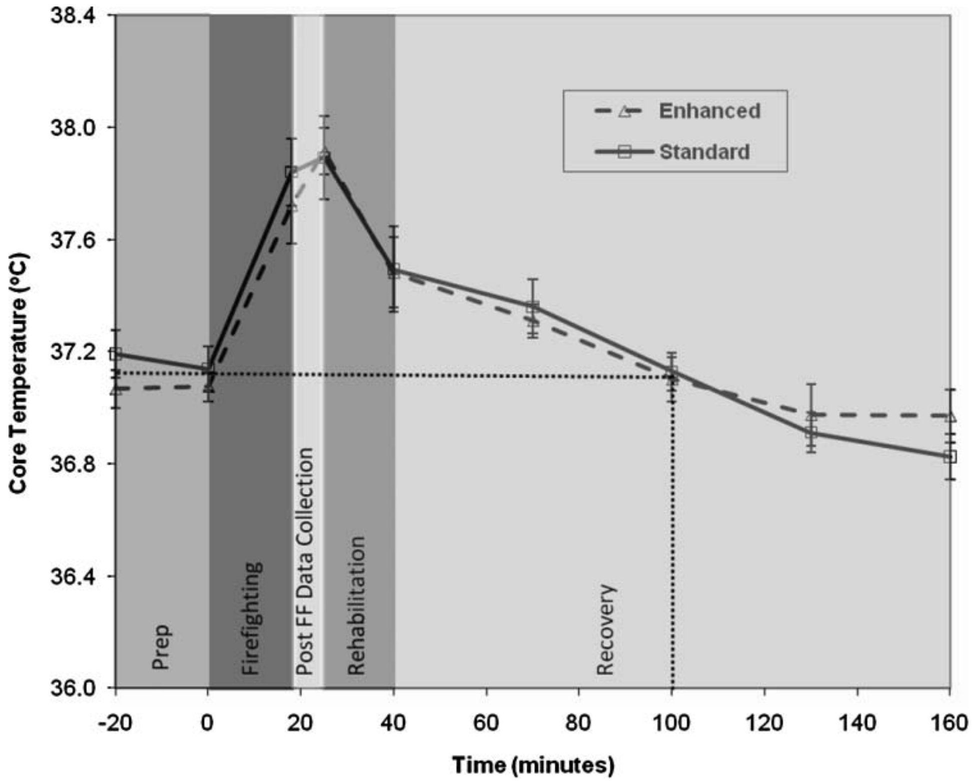

FIGURE 3. Changes in core temperature throughout the test protocol ($n = 12$). Dotted line indicates the time when core temperature returns to baseline levels. FF = firefighting.

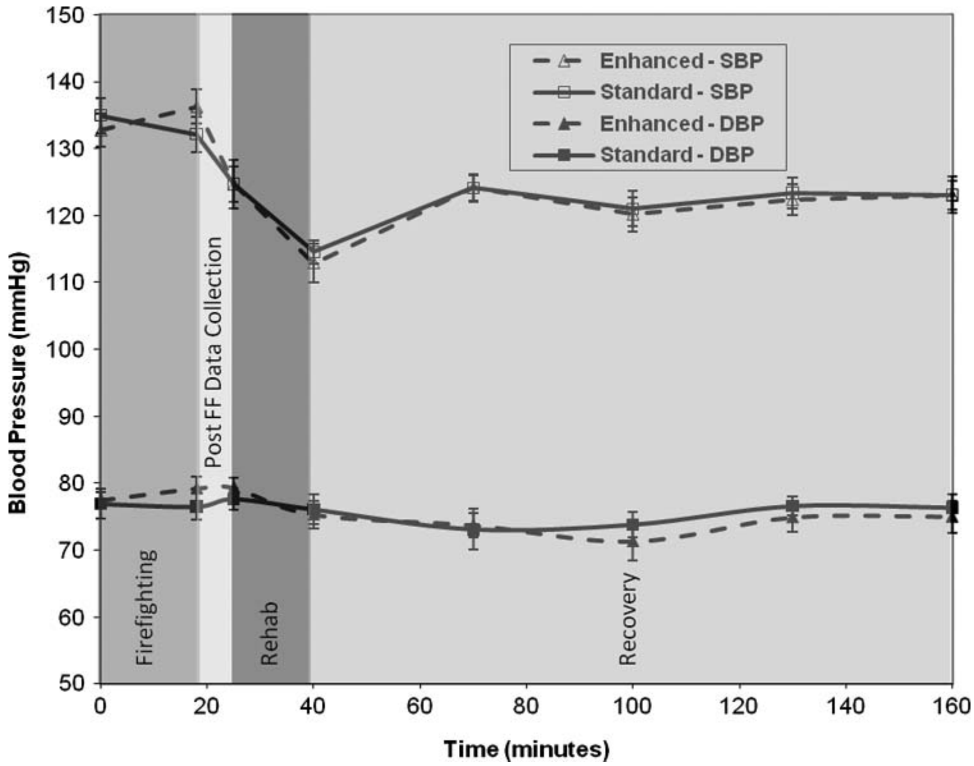

FIGURE 4. Changes in systolic blood pressure (SBP) and diastolic blood pressure (DBP) throughout the test protocol ($n = 20$). After the prefire-fighing level, SBP remains reduced throughout the study, whereas DBP remains unchanged. FF = firefighting.

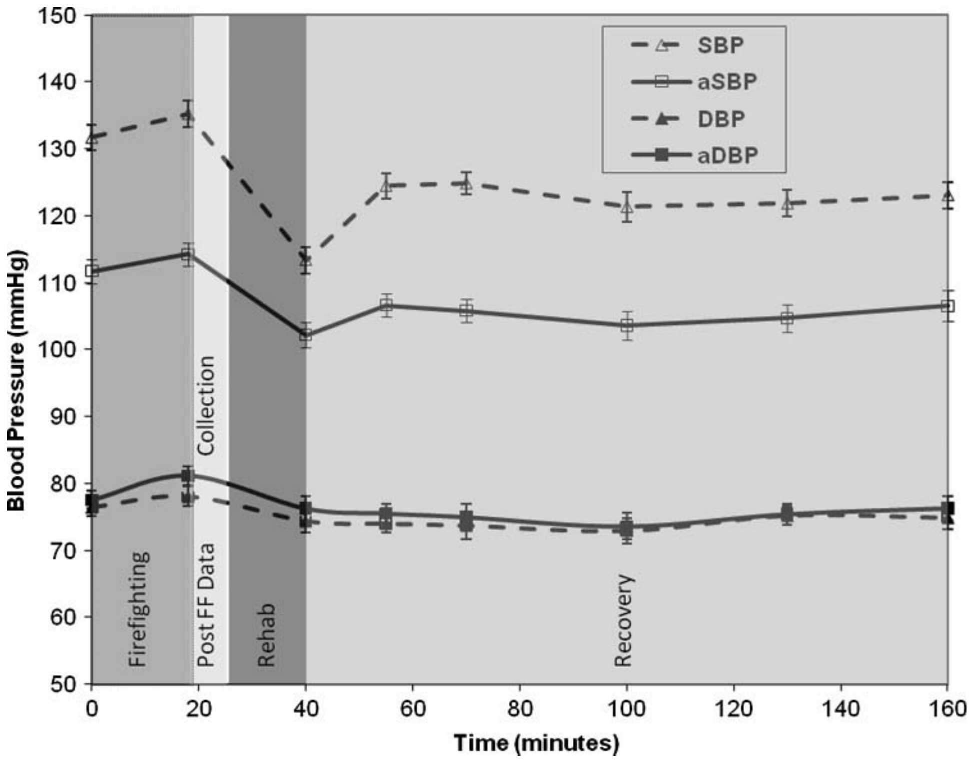

FIGURE 5. Changes in peripheral and aortic systolic blood pressure (SBP, aSBP) and diastolic blood pressure (DBP, aDBP) throughout the test protocol. Data from complete sets combined standard and enhanced conditions as there was no significant condition effect ($n = 31$). FF = firefighting.

aortic SBP (aSBP, $p < 0.001$) and mean arterial pressure ($p = 0.001$; not shown in Fig. 5) but not for aortic DBP (aDBP), and there was no significant condition effect. Table 2 shows the Pearson correlation coefficient between each of the 31 trials at each measurement period. In each case, the Pearson correlation is significant ($p < 0.001$) and shows strong correlation (average $r = 0.928$).

As shown in Figure 6, there was a significant time effect ($p < 0.001$), condition effect ($p = 0.012$), and time × condition interaction ($p = 0.010$) for the RPP. As expected, the RPP increased significantly during firefighting activity because of the increase in myocardial oxygen consumption during firefighting. However, the RPP rapidly decreased below prefirefighting values by the first 30 minutes of recovery. There was a significant condition effect, with the RPP being significantly lower in the control condition.

There was a significant time effect ($p < 0.001$), condition effect ($p = 0.002$), and time × condition interaction ($p = 0.048$) for the SEVR. The SEVR was significantly reduced after firefighting and recovered relatively slowly during rehabilitation and into recovery (Fig. 7).

On average, the firefighters required just over 9 seconds (9.1 ± 1.2 sec control; 9.3 ± 2.1 sec enhanced) to complete the dummy drag task. There was no significant condition effect on the time required to perform the dummy drag task, indicating that the ability to

TABLE 2. Peripheral and Aortic Systolic and Diastolic Blood Pressures at Each Measurement Point ($n = 31$), Presented as Mean (Standard Deviation)

Time (min)	SBP (mmHg)	aSBP (mmHg)	r	DBP (mmHg)	aDBP (mmHg)	r
0	131.7 (10.3)	111.7 (10.1)	0.886	76.5 (7.3)	77.6 (7.5)	0.996
18	135.3 (11.0)	114.3 (9.5)	0.935	78.0 (8.3)	81.2 (7.9)	0.983
40	113.4 (10.8)	102.2 (10.4)	0.777	74.4 (9.5)	76.3 (10.1)	0.890
55	124.5 (10.5)	106.6 (9.4)	0.891	74.0 (7.7)	75.5 (7.6)	0.961
70	124.8 (9.2)	105.8 (9.8)	0.933	73.7 (11.4)	75.0 (11.1)	0.994
100	121.3 (12.1)	103.6 (11.6)	0.911	72.9 (10.5)	73.6 (11.0)	0.985
130	121.8 (10.8)	104.7 (11.6)	0.901	75.2 (7.7)	75.4 (8.8)	0.906
160	123.1 (11.1)	106.5 (12.9)	0.943	74.9 (10.0)	76.3 (9.9)	0.950

The peripheral and aortic values are highly correlated as seen by the Pearson correlation at each time (in all cases $p < 0.001$).
aDBP = aortic diastolic blood pressure; aSBP = aortic systolic blood pressure; DBP = diastolic blood pressure; SBP = systolic blood pressure.

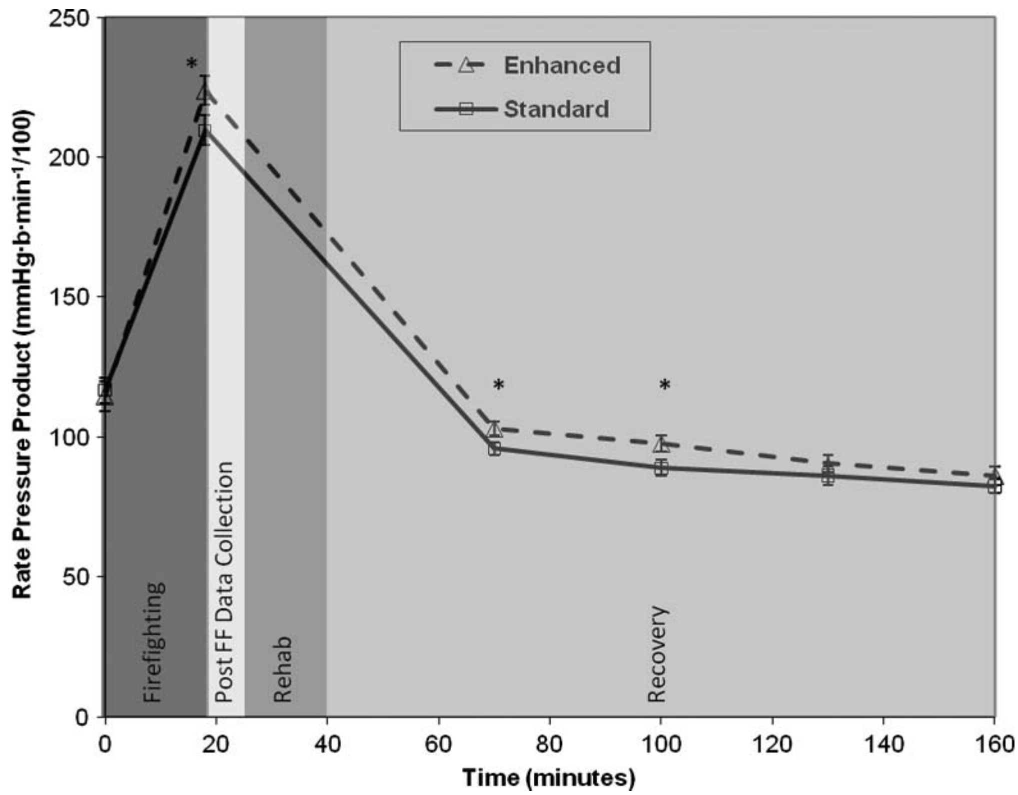

FIGURE 6. Changes in rate–pressure product (RPP) throughout the test protocol ($n = 20$). All time points are significantly different from those for the prefirefighting condition, dropping below this level before the 30-minute recovery time period. *Significant condition effect. FF = firefighting.

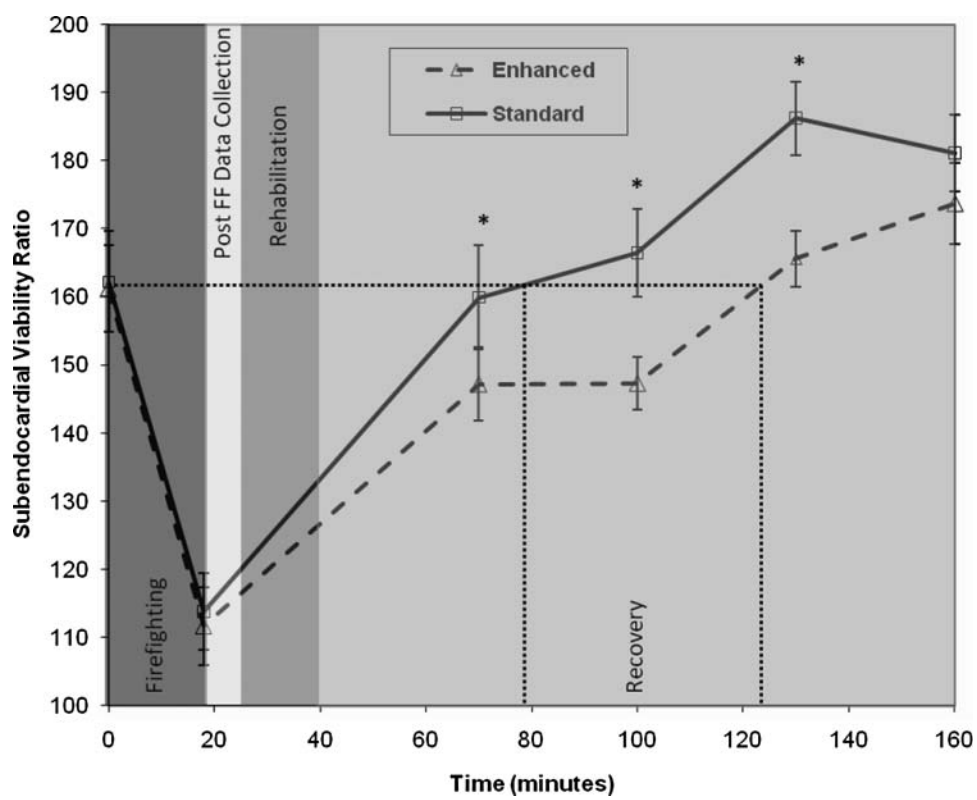

FIGURE 7. Changes in subendocardial viability ratio (SEVR) throughout the test protocol ($n = 18$). Dotted lines indicate the times when SEVR returns to prefirefighting levels. *Significant condition affect at these time points. FF = firefighting.

perform high-intensity anaerobic work was not influenced by rehabilitation protocols.

DISCUSSION

The major findings of this study are that recovery from even a short bout of firefighting activity in healthy relatively young firefighters occurs over a much longer time period than is typically provided by incident rehabilitation on the fireground. Furthermore, we documented a significant drop in SBP during rehabilitation, and the magnitude of that drop was greater than what is normally associated with postexercise hypotension (PEH). Though rehabilitation personnel are often focused on the risks associated with elevated blood pressures, the risk of hypotension (i.e., syncope) must also be considered. Modifications to current rehabilitation protocols, including adding active cooling and a nutrition intervention, did not provide significant improvements when rehabilitation was conducted in a cool, dry room with an ample supply of water.

Our participants were young, healthy firefighters (Table 1). The mean body mass index (BMI) for this group was between lean and overweight: Eight firefighters had a BMI between 20 and 25 kg/m^2, whereas 12 firefighters fell in the overweight range (25 kg/m^2 $<$ BMI $<$ 30 kg/m^2). None of the recruited firefighters were obese based on BMI. Total mean cholesterol level was in the desirable range; mean low-density lipoprotein (LDL) cholesterol level was in the near-optimal range and mean high-density lipoprotein (HDL) cholesterol level was in the average range. Thus, our findings suggest rather drastic changes in heart rate, blood pressure, and body temperature even in these very healthy individuals.

Heart Rate and Core Temperature

During firefighting activities, heart rates were elevated at approximately 84% of maximal age-predicted levels until the firefighters exited the burn room. This level of exertion is commonly seen with firefighter subjects.[4,5] However, this study shows that firefighters' heart rates do not return to baseline until approximately 50 to 80 minutes after firefighting. Furthermore, the standard (or control) rehabilitation condition appears to allow the heart rate to return to baseline levels more rapidly during the recovery period than during the enhanced rehabilitation condition. At the completion of rehabilitation, heart rates were not different between the enhanced and control rehabilitation conditions (92.4 ± 9.2 vs. 90.8 ± 8.1 $b{\cdot}min^{-1}$, respectively). However, during recovery, the enhanced condition was significantly higher than in the control condition (an average of 7.2 $b{\cdot}min^{-1}$ higher at 60 minutes into recovery).

Core temperature increased an average of 0.7°C during firefighting (rate of 0.037$°C{\cdot}min^{-1}$), which is similar to that measured during previous studies of similar duration.[4,5,26] While this magnitude of core temperature increase would suggest mild hyperthermia, the most significant concern is with the rate of rise, which can rapidly reach a level of severe hyperthermia if multiple cylinders of air are consumed prior to rehabilitation. The rate of core temperatue rise is also similar to what Romet and Frim (1987) have reported, though they suggested that the rate of rise in core temperature during firefighting is affected by the activity of the firefighter, with the nozzleman's (lead hand's) having the greatest rate of rise.[26] During the first 7 minutes after firefighting, core temperature continued to rise at a rate of approximately 0.020$°C{\cdot}min^{-1}$ despite removal of the bunker coat. This finding is consistent with previous research documenting that core temperature continues to rise after the cessation of exercise or work in protective clothing and following firefighting activities.[4,5,27] Once core temperatures peaked, they declined rapidly during the first few minutes of rehabilitation. However, we found that core temperature did not return to baseline until approximately 50–80 minutes after firefighting, and this outcome was not improved by providing active cooling during rehabilitation.

The effectiveness of different rehabilitation interventions in lowering core temperature has been a subject of much debate in the fire service and among researchers.[7,8] Two previous studies in which firefighter cooling protocols were assessed suggested that active cooling is more effective than passive cooling 1) in increasing tolerance time and total work time after firefighters worked in an environmental chamber[7] and 2) in reducing core temperature after conducting controlled live-fire training.[8] Espinosa and Contreras (2007) also studied several different active cooling strategies and suggested the use of cold towels was as effective as other techniques, yet operationally more feasible.[8] A recent study in which Hostler et al. compared active cooling devices with passive cooling after repeated work bouts involving walking on a treadmill while wearing PPE found that active cooling did not enhance firefighter recovery over passive cooling under moderate ambient conditions (24°C).[28] These authors also reported that 20 minutes was not a sufficient amount of time to permit core temperature to return to baseline following 50 minutes of walking in PPE. In the current study, we did not find a significant improvement in heart rate or core temperature recovery when using cold towels compared with passive cooling. Differences in ambient temperature may help explain the seemingly contrary results in the studies above. In the current project, rehabilitation was conducted in a room with ambient temperatures between approximately 18°C and 21°C and thus passive evaporative cooling could take place. Similarly, in the study conducted by Hostler et al., the ambient temperature averaged 24°C; thus, the participants could effectively cool themselves during the rehabilitation period. On the other hand, the studies by Selkirk et al.[7] and Espinosa and Contreras[8] were conducted under high ambient temperatures (35°C, 50% relative humidity [RH][7]; 29°C, 46% RH[8]). Under these conditions, evaporative cooling is limited and active cooling appears to confer an advantage over passive cooling. Thus, environmental conditions are an important factor that must be considered when determining whether to provide active or passive cooling.

Blood Pressure

A single bout of moderate-intensity exercise lasting 30–60 minutes typically produces postexercise SBP reductions of approximately 5–10 mmHg, which is the phenomenon known as postexercise hypotension (PEH).[29] The firefighters in the present study exhibited reduced SBP following firefighting, consistent with data on PEH. The reduction in SBP in the firefighters immediately after firefighting (22.5 mmHg) was considerably greater than expected, especially considering that the active firefighting lasted only 18 minutes. Postexercise hypotension is thought to be caused by a reduction in vascular resistance, mediated by changes in the autonomic nervous system and vasodilator substances.[30] Work in hot environments or in PPE can exacerbate PEH because of loss of plasma volume and a greater drop in vascular resistance due to vasodilation of the cutaneous circulation.[31]

Even after SBP increased slightly during recovery, it remained lower than expected. In 17 of the 42 observations made in this study (40.5%), the difference between postfirefighting and recovery SBP values was greater than 10 mmHg, and in six of the 42 cases (14.3%), the difference in SBP was greater than 20 mmHg. One individual whose prefirefighting SBP was 157 mmHg had a drop in SBP from 153 mmHg to 106 mmHg in the first 5 minutes of rehabilitation; his SBP remained at approximately 110 mmHg throughout rehabilitation, and then returned to approximately 122 mmHg and remained constant during the last 90 minutes of recovery.

Following rehabilitation and the simulated rescue, the mean SBP increased to approximately 120 mmHg and remained remarkedbly stable at this level until the end of the recovery period. This value is still considerably lower than the prefirefighting blood pressure, thus it appears that even short-term firefighting produces substantial PEH for a prolonged period. This is again consistent with the PEH typically reported following aerobic exercise. Moderate-intensity exercise and high-intensity exercise have been shown to result in similar levels of PEH.[32] What is novel about our findings is the more exaggerated reduction in SBP observed during the rehabilitation period (in the 15-minute period after firefighting) compared with the recovery period. These findings also suggest that the locomotion after rehabilitation (during the simulated rescue) may have increased venous return and/or produced some vasoconstriction leading to a slight increase in blood pressure, which was then maintained for the duration of the recovery period.

It is well established that PEH is greater in people with high blood pressure compared with normotensive individuals.[33] Our prefirefighting values suggest that our average participant was prehypertensive, and this may have contributed to the greater-than-expected reduction in blood pressure. However, it is also possible that our preactivity blood pressure values reflect some anticipation about the firefighting activity that the participants were about to undertake, and thus do not represent true baseline blood pressures.

Elevated blood pressure at rest is an established risk factor for future cardiovascular events.[34] Furthermore, an exaggerated blood pressure response to exercise stress is a strong predictor of cardiovascular mortality from myocardial infarction and stroke.[35,36] Current NPFA guidelines (NFPA 1584) recommend monitoring blood pressure during incident rehabilitation.[1] While there are well-established guidelines detailing what constitutes an exaggerated blood pressure response to a standardized exercise stress test (SBP > 250 mmHg or DBP > 150 mmHg[37]), there is a paucity of data available regarding normal blood pressure responses to the stress of firefighting. Futhermore, while elevated blood pressure following firefighting is undoubtedly of concern, our data suggest that EMS personnel overseeing medical monitoring of firefighters during rehabilitation should also be concerned about hypotension and the attending risk of syncope.

Central aortic blood pressure may be a better predictor of clincial outcome than is brachial pressure.[9,10] Aortic blood pressure values in this study followed a similar pattern to that of blood pressure obtained via auscultation, but, as expected, the aortic SBPs were considerably lower than those obtained via auscultation. In our study, the central and brachial blood pressures mirrored each other throughout the rehabilitation and recovery period, suggesting that brachial blood pressure is an adequate method of blood pressure monitoring following firefighting.

Myocardial Oxygen Supply and Demand

The decrease in SEVR immediately after firefighting reflects a decrease in myocardial perfusion relative to cardiac workload, whereas the significant increase in RPP reflects an increase in the myocardial tissue demand for oxygen. However, as Figure 6 shows, the RPP rapidly returns to levels below prefirefighting values by the first recovery time period. As the prefirefighting RPP levels may be slightly elevated from baseline because of increase in heart rate at the preactivity time point and the RPP remains relatively stable throughout recovery, it is expected that the RPP has recovered to near-baseline levels by this time period. However, the SEVR does not return to prefirefighting levels until some time between the 30- and 60-minute time points for control rehabilitation and between 60 and 90 minutes for enhanced recovery. Thus, even though the myocardial demand for oxygen rapidly returns to baseline levels, the subendocardial perfusion remains reduced for another 30–90 minutes. Additional research is needed to determine whether a reduced SEVR during recovery may be related to an increased vulnerability to sudden cardiac events or whether there is in fact a balance between oxygen supply and demand.

LIMITATIONS

Several limitations may have affected our results. First, this study used simulated firefighting activities in a training structure that contained live fires. This situation is less dangerous and thus less stressful than actual firefighting activities. As such, our results likely underestimate the actual cardiovascular strain associated with firefighting activity. Also, our prefirefighting activity measurements may reflect an anticipatory response on the part of the participants as they mentally prepared for the firefighting activity. Thus, our prefirefighting activity values may not reflect true "resting" values. Additionally, we did not control the fluid intake during the control trial in which participants had ad libitum access to fluids. This resulted in participants' consuming different amounts of fluids in the two trials.

CONCLUSIONS

This study examined the acute effects of firefighting on traditional vital signs and novel vascular measures, documented the time course of recovery, and compared two incident rehabilitation strategies to determine the extent to which an "enhanced" rehabilitation might facilitate recovery from firefighting activities.

Our study involved a sample of young, healthy firefighters who were immediately removed from the firefighting activities into a controlled, relaxed environment. The firefighters were provided with 15 minutes of rehabilitation prior to completing a 10-second simulated rescue task and then recovered for 120 minutes without physical or psychological interruption. This scenario represents a likely best case. Often firefighters will return to firefighting work after consuming one cylinder of air. Then, once the firefighting operation has ended, they will be involved in overhaul and cleanup operations, which may further exacerbate the perturbations measured and the time rate of recovery. Keeping in mind the points made above, several important conclusions can be drawn from this study regarding the effect of firefighting activities on the cardiovascular system and the time rate of recovery of several important measures.

- Firefighting activities resulted in a significant elevation of core temperature and heart rate. Importantly, the recovery from these effects occurred over a time course of hours, even after a short bout of firefighting in this young, healthy sample of participants.
- The SBP values displayed a significant and rapid decline shortly after firefighting activities and into the rehabilitation period. During recovery, the SBP increased above its nadir but remained lower than prefirefighting levels for at least 120 minutes. This finding is consistent with PEH responses seen during a bout of high-intensity aerobic exercise. However, in this group of young, healthy firefighters, there was wide variability in the blood pressure response to firefighting and the recovery from firefighting. While firefighters are often concerned about elevated blood pressures, this study suggests that firefighters should be aware of the potential dangers of hypotension during rehabilitation and recovery as well.
- Aortic blood pressure responses very closely match blood pressure values determined via auscultation.
- Depressed SEVR measurements imply that firefighters may have a reduced subendocardial perfusion for up to 110 minutes after an initial firefighting activity has ceased.
- The enhanced rehabilitation condition appeared to have little effect on physiologic recovery under the moderate environmental conditions in this study. The rehabilitation conditions had no effect on core temperature, suggesting that the cooling portion of the intervention had no effect when rehabilitation was conducted in a cool room. The rehabilitation condition also had no effect on firefighters' ability to conduct a postrehabilitation simulated rescue as measured by a dummy drag protocol.

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