Sudden Cardiac Events in the Fire Service:

Understanding the Cause and Mitigating the Risk

Skidmore College

Health and Exercise Sciences

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FP&S grants support projects that enhance the safety of the public and firefighters from fire and related hazards. In fiscal year 2005, U.S. Congress reauthorized funding for FP & S and expanded the eligible uses of funds to include Fire Safety Research and Development (R&D). Research and Development activities emphasize reducing injuries to firefighters. Priorities include studies in areas of clinical, behavioral, and social sciences research; technology and product development; and health database systems.

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Part One: Theoretical Foundation

Dangers of Firefighting

Firefighting is an inherently dangerous and physically demanding activity. During the course of their duties, firefighters are exposed to several potentially life-threatening dangers, including burn injury, hazardous chemicals, asphyxiation, collapse, explosion, and entrapment. Despite these myriad dangers, it is the physiological consequences of firefighting that poses the greatest threat to firefighters. In fact, the leading cause of line-of-duty death for firefighters is a sudden cardiac event (Fahy, 2005).

Cardiac Events in the Fire Service

Each year approximately 45% of firefighter deaths are caused by sudden cardiac events, or heart attacks (Fahy, 2005). In addition to the fatalities, approximately 800–1,000 firefighters suffer nonfatal heart attacks while on duty each year. Strokes (cerebral vascular accidents; CVA) are vascular events that add to cardiovascular fatalities each year.

Figure 1 presents data on the nature of line-of-duty deaths. Taken together, heart attacks and cerebrovascular accidents (both cardiovascular events) account for nearly 60% of all fatalities.

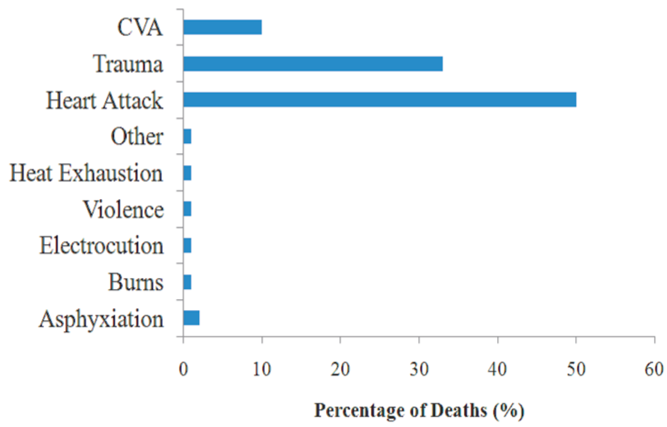


Figure 1: Firefighter Deaths by Nature of Injury (USFA, 2009)

Sudden cardiac events may be caused by heart attacks or fatal arrhythmias. Heart attacks occur when a blood clot blocks a coronary artery and deprives the heart muscle of oxygen. Heart attacks occur in individuals with underlying cardiovascular disease. Arrhythmias can cause the heart to beat ineffectively or to stop beating, thus leading to sudden cardiac death. Furthermore, a heart attack may lead to an arrhythmia. In the Fire Service, the term "sudden cardiac event" is often used to describe any event (heart attack or arrhythmia) that leads to sudden cardiac death. In fact, in many instances, it is not clear whether the death was caused by a heart attack or arrhythmia.

Firefighting may act as a trigger for sudden cardiac events in vulnerable individuals. A study by a Harvard research team found that while firefighters spend only a small percentage of their time engaged in firefighting activity, a large percentage of their fatalities occur within a short time after firefighting activity (Table 1; Kales et al., 2007). Based on a national sample of firefighters, it was estimated that firefighters spend approximately 1% of their time engaged in active firefighting.

In contrast, more than 32% of fatalities occurred *during* or *shortly after* fire suppression activity. Based on the estimate of time spent in firefighting and the percentage of deaths on scene or shortly thereafter, the researchers calculated that a firefighter is 136 times more likely to suffer a fatal sudden cardiac event after firefighting than nonemergency duties (station activity).

In addition to the disproportionate number of fatalities that occur during or shortly after fire suppression activity, Table 1 clearly shows that there is an increased risk of sudden cardiac events after an alarm. In fact, surprisingly, about 13% of cardiac fatalities occur in response to the alarm but before the firefighter arrives at the scene, reflecting a 14-fold increased risk of a sudden cardiac event in this time period.

Table 1: Type of Firefighter Duty Divided Into Time Spent and Fatalities That Occur from Each Type of Duty* (Kales et al., 2007)

	Time Spent	Fatalities	Odds Ratio
Fire Suppression	1%	32.1%	136
Alarm Response	4%	13.4%	14.1
Return from Call	7%	17.4%	10.5
Nonfire Emergencies	15%	9.4%	2.6
Physical Training	8%	12.5%	6.6
Nonemergency Duties	65%	15.4%	1.0

* From National Dataset

Part One: Theoretical Foundation

Understanding the risk of sudden cardiac events associated with various types of duties may provide insight into the mechanisms by which sudden cardiac events occur in firefighters. For example, firefighting results in very high levels of physiological strain due to the combination of heavy work, heat stress, and psychological stress, which may precipitate a sudden cardiac event in vulnerable individuals. Alternately, cardiac events that occur after an alarm may be due to an adrenaline surge and subsequent hemodynamic changes.

Figure 2: Summary of Physiological Responses to Firefighting

Physiological Strain of Firefighting

Firefighting can be among the most strenuous activities that humans undertake. Not surprisingly then, firefighting affects every system of the body. Figure 2 summarizes some of the primary effects of firefighting on the systems of the body. The following section briefly details research findings on the effect of firefighting on the major systems of the body.

→ **Cardiovascular** (Increased HR and BP, Decreased Stroke Volume)

→ **Hematological** (Decreased Plasma Volume, Hemoconcentration)

→ **Thermoregulatory** (Elevated Core Temperature, Dehydration)

→ **Respiratory** (Increased Breathing Rate and Oxygen Consumption)

→ **Metabolic** (High Oxygen Cost, Increased Lactate, Fatigue)

→ **Immune/Endocrine** (Increased Leukocytes and Hormones)

→ **Nervous** (Sympathetic Surge and Increased Adrenaline)

→ **Muscular** (Increased Oxygen Use and Heat Production)

Cardiovascular and Hematological

While firefighting results in significant physiological strain affecting nearly every system of the body, statistically, the greatest risks to the firefighter come from the cardiovascular and thermal strain associated with firefighting. Strenuous firefighting activities lead to near maximal heart rates (HR) that can remain high for extended periods of time.

In addition to high heart rates, research has demonstrated that the amount of blood pumped per beat (stroke volume; SV) can actually decrease following strenuous firefighting activity (Smith et al., 2001a). The decrease in stroke volume may limit the delivery of blood to vital organs.

Firefighting is associated with profuse sweating and hence a decrease in plasma volume. A 15% reduction in plasma volume has been reported after 18 minutes of strenuous firefighting drills (Smith et al., 2001a). The decrease in plasma volume contributes to the reduction in stroke volume noted above and leads to hemoconcentration. Hemoconcentration causes a change in blood electrolytes and increases blood viscosity (Smith et al., 2001b).

Thermoregulatory

Given that firefighters wear heavy, insulative personal protection equipment (PPE) that often weighs in excess of 50 pounds and are called upon to perform strenuous muscular work in very hot environments, it is no surprise that firefighting leads to thermal strain. Challenges to the thermoregulatory system include elevated core temperature (hyperthermia) and dehydration.

Hyperthermia and dehydration are very serious problems in the Fire Service because these twin challenges can:

- hasten the onset of fatigue and limit work time;
- add to cardiovascular strain;
- lead to fatal heat illnesses (including heat stroke);
- impair cognitive function;
- increase the risk of injury.

Research indicates that core temperature increases rapidly but does not reach drastically high levels during short-term firefighting. Eighteen to twenty minutes of firefighting has been reported to cause an average increase in body temperature of 1.5 to 2.5 °F (Smith et al., 2005; Horn et al., 2011). Prolonged firefighting or repeated evolutions of training would cause greater elevations in body temperature.

In addition to elevated body temperature, firefighting also causes profuse sweating. The body sweats in an attempt to cool itself through evaporative cooling; however, PPE creates a warm, moist, and stagnant air layer next to the skin, which severely limits the evaporation of sweat. Without the evaporation of sweat, the body becomes unable to use evaporative cooling as a method for temperature control. Profuse sweating can also decrease plasma volume, placing additional strain on the cardiovascular system and further impairing thermoregulation. Sweat loss of 2.8 pounds per hour has been reported during exercise in a hot environment while wearing PPE (Selkirk & McLellan, 2004). Sweat loss is particularly problematic during hot days and during live fire training; individuals engaged in prolonged firefighting may experience excessive sweat loss.

Respiratory System

In addition to causing severe cardiovascular and thermal strain, firefighting also affects many other body systems. Firefighting stresses the respiratory system and can lead to very high breathing rates and air consumption. During simulated firefighting activities lasting approximately 22 minutes, the amount of air consumed has been reported to average 82 liters per minute and to exceed 100 liters per minute in some cases (Holmer & Gavhed, 2007). In the same study, the researchers reported average air consumption of 102 liters per minute and maximal values of 138 liters per minute during a 3-minute strenuous activity. Such high air consumption reflects high levels of work and the need to bring in and supply oxygen to the working muscles and vital organs. The high rate of air consumption also has significant implications for air management.

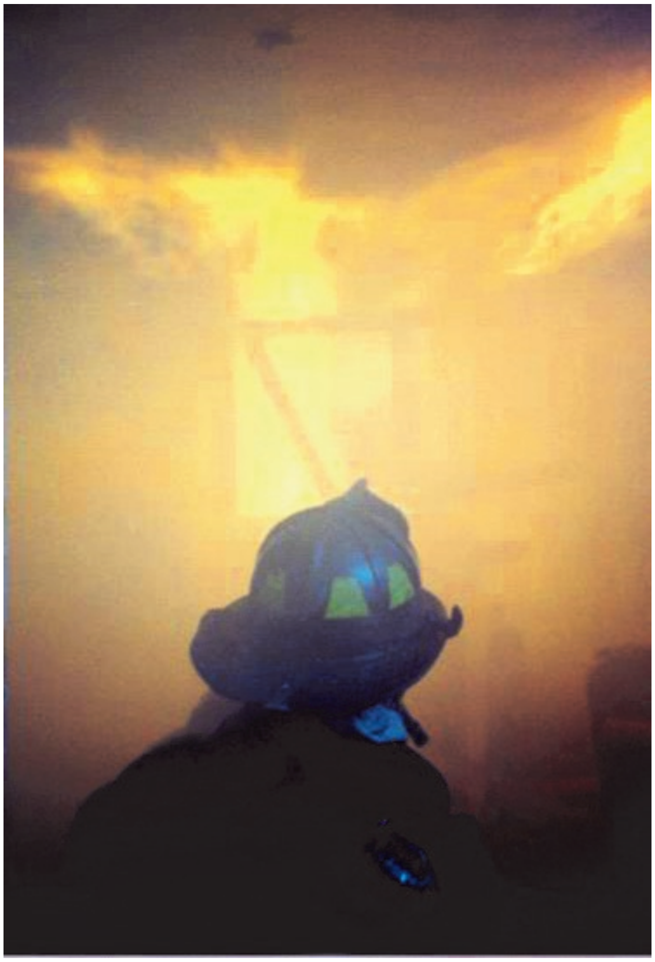
Metabolic System

Firefighting is strenuous work that requires a great deal of metabolic energy. The energy production to support firefighting activity relies on both aerobic and anaerobic sources. Strenuous firefighting operations have been found to require oxygen consumption in excess of 40 $mL \cdot kg^{-1} \cdot min^{-1}$ and to result in blood lactate levels of up to 13 mM (Gledhill & Jamnik, 1992; Barr et al., 2010). Given the high energy output of firefighters, and the extreme environmental conditions under which they work, it is not surprising that the metabolic strain is high; however, the high-energy demands of firefighting also mean that muscular fatigue is a problem that must be managed on the fireground.

Part One: Theoretical Foundation

Immune and Endocrine Systems

Although limited research has been conducted on the immune and endocrine responses to firefighting, there is some evidence that both systems are disrupted by the stress of firefighting. Firefighting leads to an acute elevation in white blood cells—a condition known as leukocytosis (Smith et al., 2004, 2005, 2011). Leukocytosis is not unexpected given the strenuous nature of firefighting. Of particular interest, following 90 minutes of recovery with aggressive rehydration, there was evidence of a decrease in the number of a specific type of immune cells (lymphocytes).



Firefighting also leads to hormonal disruption. Researchers have reported increases in adrenocorticotropic hormone (ACTH), cortisol, epinephrine and norepinephrine following firefighting drills (Smith et al., 2005; Horn et al., 2011). These changes are likely related to the "fight or flight" response and help prepare the body for the stress of firefighting.

Nervous System

Clearly, firefighting causes an increase in sympathetic nervous stimulation—a condition firefighters often refer to as an "adrenaline rush". The activation of the sympathetic nervous system occurs from the moment the alarm tone sounds. Physiological responses to firefighting are due to a combination of sympathetic nervous stimulation, heat stress (due to work, fire, and PPE), and the muscular work that firefighters perform in the course of fire attack and suppression activities.

Muscular System

Obviously, firefighting can lead to muscular fatigue and may increase the likelihood of injuries on the fireground—especially injuries due to slips, trips, and falls. Also, the muscular work that firefighters perform increases metabolic heat production and contributes greatly to increased body temperature that occurs with firefighting.

In short, all physiological systems are affected by firefighting. However, given the high rate of duty-related cardiovascular events, this project focuses primarily on the cardiovascular system.

Part One: Theoretical Foundation

Cardiovascular Disease

Cardiovascular disease is the leading cause of death in the general population, and it is the leading cause of line-of-duty death in the Fire Service. Understanding cardiovascular disease progression and taking proactive steps to lessen risk factors for cardiovascular disease are essential steps to reducing the number of firefighter fatalities due to cardiovascular events.

Cardiovascular disease is a pathological condition that affects the heart, blood vessels, or the clotting potential of the blood. Atherosclerotic heart disease is the most common form of heart disease. In this condition, plaque buildup in the arteries decreases blood flow to tissue and results in less oxygen being delivered to the heart tissue.

One of the challenges to understanding cardiovascular disease is the number of terms that are used to describe the condition. Sometimes these terms refer to the same condition and sometimes they differentiate types of a condition. For example, if the plaque buildup is found in the coronary arteries (the vessels supplying blood to the heart muscle), the disease may be called coronary artery disease or coronary heart disease. Furthermore, if the plaque buildup causes severe reductions in blood flow, the disease condition may be called obstructive coronary heart disease, and it is also sometimes referred to as ischemic heart disease if the decrease in blood flow creates conditions of low oxygen availability (ischemia) in the heart tissue. As seen in Figure 3, atherosclerosis is characterized by plaque buildup in the arteries. Rupture of a vulnerable plaque can cause the formation of a blood clot that completely occludes an artery. This sequence of events leads to a heart attack if the clot is in a coronary artery or a stroke if the clot is in a cerebral artery.

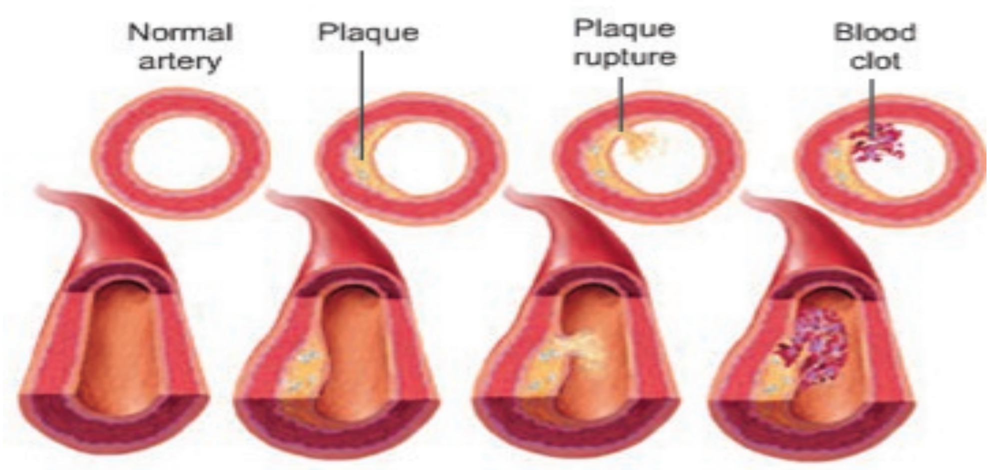


Figure 3: Atherosclerosis Characterized by Plaque Buildup in the Arteries
American Heart Association, http://www.americanheart.org/presenter.jhtml?identifier=4440

Atherosclerotic heart disease develops over a period of many years. There are multiple processes involved in plaque accumulation in the arterial wall, but the primary characteristics of atherosclerosis are:

- damage to the vessel wall;
- cholesterol (especially LDL) collecting in the wall of the vessel;
- inflammation in the vessel wall.

There are several risk factors that increase the likelihood of an individual developing atherosclerosis and of having a sudden cardiac event. Factors that increase the risk but cannot be modified, include age, gender, and family history. Several factors can and should be modified (Table 2). Reducing these risk factors can lessen the progression of atherosclerosis. For example, smoking, high blood pressure, and high glucose levels are factors that can damage the vessel wall and increase plaque formation. Plaque is composed primarily of fatty substances, especially cholesterol, which gets deposited in the vessels when blood levels of cholesterol are elevated.

Medical evaluations for firefighters should include an assessment of cardiovascular risk factors. Firefighter health and wellness programs should be designed to improve overall fitness, which will have a positive effect on several of the cardiovascular risk factors. Additionally, wellness programs should provide educational programs to lessen all cardiovascular risk factors and improve overall health.

Table 2: Risk Factors Associated with Cardiovascular Disease

Modifiable Risk Factors	Normal/Desirable Level	Risk Factor Threshold	Your Values	Strategies to Reduce Risk Factor
Tobacco	No use of tobacco products	Any use of tobacco products		Do not smoke or chew tobacco products
Blood Pressure (mmHg)	< 120 / 80	> 140 / 90		Exercise, healthy diet, medication
High Cholesterol ($mg \cdot dL^{-1}$)	LDL ≤ 100 HDL > 60 Total < 200	LDL ≥ 190 HDL <40* Total ≥ 240		Lower body fat, healthy diet
High Blood Sugar** ($mg \cdot dL^{-1}$)	≤ 100	≥ 100		Lower body fat, healthy diet
Excess Body Fat (BMI- weight/height^2)	< 25	> 30		Exercise, healthy diet
Physical Inactivity (minutes/week)	120 (moderate activity) or 60 (vigorous activity)	30 (moderate activity)		Increase daily physical activity

* HDL < 50 for women, ** fasting blood sugar values

Sudden Cardiac Events

Although cardiovascular disease progresses over the course of many years, it may transition into an acute life-threatening condition in which death occurs within seconds or minutes. Sudden cardiac events often occur when a vulnerable plaque ruptures and a blood clot forms, thus occluding a coronary artery (Figure 3). Sudden cardiac events can also result from a primary arrhythmia that interferes with the electrical conduction in the heart. Many times, these conditions overlap, so for example, a clot may lead to a fatal arrhythmia.

Figure 4 provides a simplified model by which firefighting may trigger a sudden cardiac event in individuals with underlying cardiovascular disease. The conditions on line 1 are known to occur as a result of firefighting activity. Line 2 depicts physiological responses that have been reported by researchers following firefighting activity and are linked to the changes in line 1. Line 3 presents potential pathophysiological responses that theoretically link the physiological responses to firefighting to a sudden cardiac event. Importantly, there are many interrelationships between the responses presented in this model and these responses often occur concurrently.

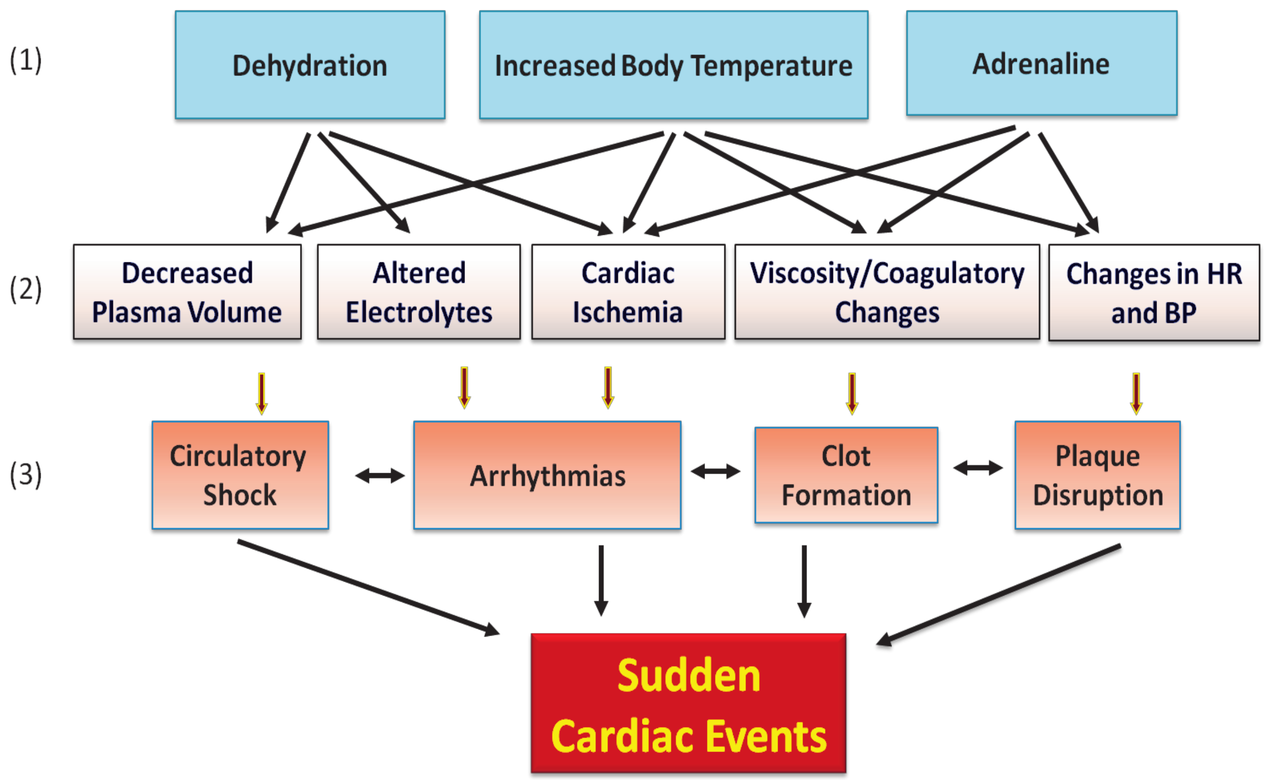


Figure 4: Potential Mechanisms Leading to Sudden Cardiac Events

Firefighting as a Trigger for Sudden Cardiac Events

As shown in Figure 5, firefighting combines a unique set of stressors that all contribute to the physiological strain experienced by the firefighter. These stressors may help explain how firefighting can serve as a trigger for a sudden cardiac event in individuals with underlying cardiovascular disease.

Obviously, firefighters perform strenuous work. The work that is performed is dependent upon task assignment (water application, laddering, overhaul, ventilation, forcible entry, search and victim removal, salvage, control of utilities) and the specifics of any given emergency operation. Firefighting routinely involves climbing stairs, carrying and operating heavy equipment, and advancing charged hose lines. This work is performed while wearing PPE that provides valuable protection but also adds to the physiological strain because of its weight and insulative properties. Furthermore, firefighting is obviously performed in a hot and dangerous environment. The fire scene is noisy and chaotic, and within the structure, firefighters are often forced to operate in conditions of low visibility, high heat, and time urgency.

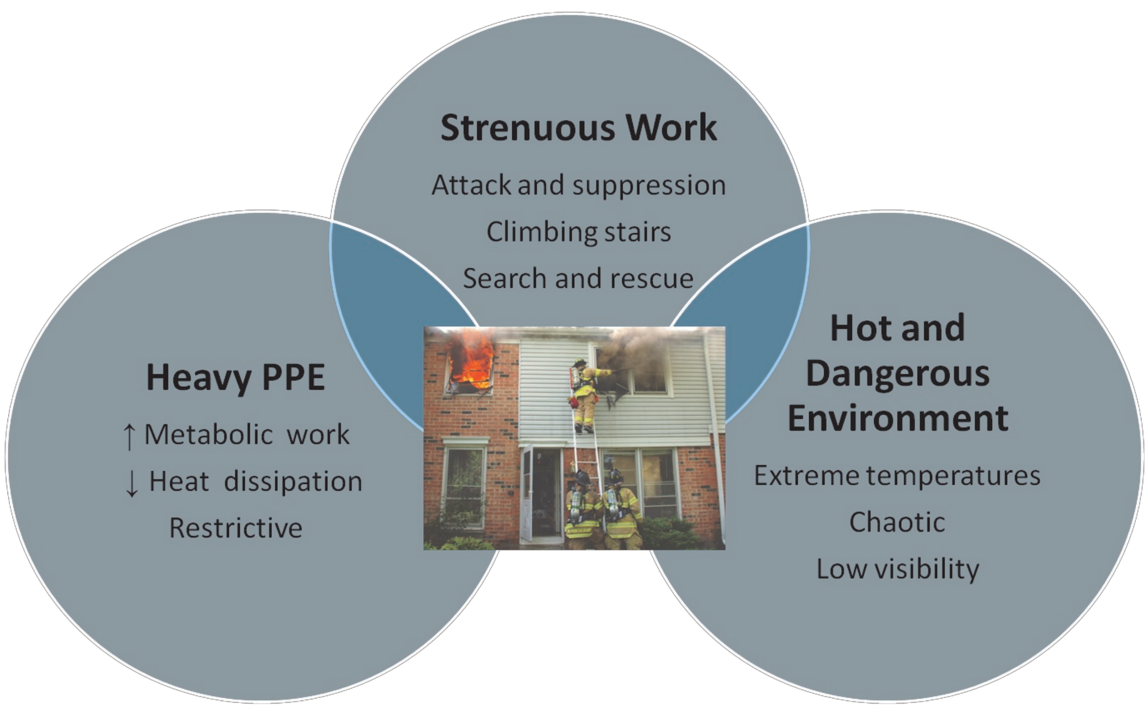


Figure 5: Unique Combination of Work Stressors Faced by Firefighters

Understanding and Mitigating the Cardiovascular Strain of Firefighting

Given the information presented previously, it is imperative that firefighters understand the magnitude of the physiological strain of firefighting, and in particular, the cardiovascular strain experienced during fireground operations. As seen in Figure 6, an understanding of the magnitude of the strain should inform strategies that prepare firefighters to meet the physiological demands of the job (preparation) and to hasten recovery from the work of firefighting (recovery).

In order to minimize the risk of cardiac emergencies, firefighters should prepare themselves for strenuous work by doing the following:

- Know their own CV risk factors and work with health care providers to aggressively lessen those risk factors;
- Obtain medical clearance to engage in structural firefighting;
- Learn the signs and symptoms of a heart attack;
- Prepare physically for the demanding tasks of firefighting by participating in a well-structured fitness program;
- Use incident rehabilitation to hasten physiological recovery from firefighting.

Figure 6: Theoretical Framework of Mitigating the Cardiovascular Strain of Firefighting

Part Two: Research Projects

Study 1:
Physiological Monitoring During Firefighting Duty:
A Field Study

Study 2:
Cardiovascular Recovery from Exercise-Induced Heat Stress:
A Laboratory Study

Part Two: Research Projects

Project Background

The cause of sudden cardiovascular events in the Fire Service is difficult to study. There is overwhelming research evidence that the combination of physiological work and hyperthermia leads to significant cardiovascular strain, and compelling data from national databases reveal nearly 50% of firefighter fatalities are the result of cardiovascular events (including sudden cardiac arrest and stroke). Despite this evidence, however, there is a relative lack of data that documents the physiological responses to firefighting. Additionally, there is far less data documenting what happens during recovery from firefighting. The data that does exist fails to directly link the physiological stress of firefighting with the pathophysiological mechanisms that result in sudden cardiac death. Furthermore, few studies have systematically investigated the time periods where firefighters are most vulnerable to sudden cardiac death — on the fireground (i.e., in response to a fire alarm) and *following* firefighting activity.

Investigating cardiovascular strain (especially as it relates to sudden cardiac events) is complicated and requires multiple approaches. Therefore, we examined cardiovascular strain associated with firefighting activities and quantified the effects of physical fitness on physiological responses to firefighting and the recovery period in two separate studies:

Study 1. The "Physiological Monitoring During Firefighting Duty" study involved collecting 24 hours of physiological data on career firefighters during 24-hour work shifts. In this **field study**, we focused on the heart rate response to an alarm and responses to working fires using a Physiological Status Monitor (PSM).

Study 2. In the "Cardiovascular Recovery from Exercise-Induced Heat Stress" study, we carefully documented cardiovascular responses (focusing on cardiovascular and autonomic nervous system responses) during recovery from a standardized exercise session in full PPE in a controlled **laboratory study**.

Part Two: Research Projects

Several studies have documented the metabolic cost and cardiovascular strain associated with simulated firefighter activities. However, because of the difficulties in obtaining accurate data over prolonged periods and during strenuous fireground operations, relatively little data is available regarding physiological responses of firefighters during their scheduled work shift.

The **field study**, Physiological Monitoring During Firefighting Duty, allowed us to describe heart rate responses to a variety of firefighting activities, most notably, physiological response to alarms. Additionally, we were able to document the heart rate responses to the work of firefighting and to describe the influence of cardiovascular risk factors on these physiological responses.

While field studies are useful in describing real life situations, laboratory studies allow us to control many outside influences so we can document the physiological response to a discrete task.

The **laboratory study**, Cardiovascular Recovery from Exercise-Induced Heat Stress, documented the time course of recovery of multiple hemodynamic variables (heart rate, stroke volume, blood pressure, etc.) and the autonomic nervous system (parasympathetic and sympathetic tone) following a standardized amount of work on a treadmill while wearing full PPE. This exercise testing protocol has been shown to cause an increase in heart rate and core temperature that is similar to that seen during short-term fire suppression activities. We were interested in the time course of recovery following work in PPE because of the high number of cardiac fatalities that occur *after* firefighting activity.

The overall goal of this entire project was to better understand the cardiovascular strain associated with work in PPE and specifically the strain associated with firefighting. This goal is motivated by the fact that firefighters suffer a disproportionate number of sudden cardiac events following an alarm, and following fire suppression activity. Furthermore, we believe that mitigating the strain associated with firefighting requires a better understanding of the actual stress associated with discrete time periods.

The following sections describe the two research studies undertaken as part of this integrated research project aimed at improving firefighter health and safety and decreasing cardiac events.

Study 1: Physiological Monitoring During Firefighting Duty: A Field Study

Introduction

Although the Fire Service is aware that firefighting is strenuous work, it has been difficult to document the physiological strain associated with actual firefighting activity. Given the nature of the emergency response, it is not practical to instrument a firefighter with technology after an alarm bell and prior to a response; however, recent advances in technology have greatly increased our ability to unobtrusively measure firefighters over a 24-hour shift. This technology allows us to capture vital physiological data during the entire duty shift, and importantly, allows us to collect information in response to an alarm, during firefighting activity and during recovery from firefighting activity. Documenting the response to an alarm is especially important because approximately 13% of fatal cardiac events occur after the alarm bell and before arrival on scene (Kales et al., 2007).

Purpose

The primary purposes of this study were to: 1) quantify the cardiovascular strain of actual firefighting activities, specifically in response to an alarm and during fire suppression activities; and 2) determine the role of physical fitness, obesity, and age in the physiological response to firefighting.

Methodology

Study Design

Firefighters enrolled in the study were asked to wear a physiological status monitor (PSM) during 24-hour shifts for approximately 4 months of data collection and to keep a log of calls and activities during each shift.

Participants

Participants were career firefighters from Oxnard Fire Department (Oxnard, CA; n=34) and Boston Fire Department (n=16) between the ages of 23 and 61 years.

All firefighters were fully informed of the purpose and requirements of the study, were told that their participation was voluntary, and told that their personal information would be kept confidential. Prior to participation, firefighters were required to

complete a health history questionnaire and physical activity logs to classify participants into a fitness group: strength-trained, aerobically-trained, cross-trained, or low-fit. The inclusion criteria for aerobically-trained was at least 3 days a week of planned aerobic activity for a minimum of 30 minutes. The inclusion criteria for the strength-trained group was at least 3 days a week of planned weight lifting workouts (a weight lifting regimen that emphasizes strength) for the last 3 months (ACSM, 2010). The inclusion criteria for cross-trained was meeting the criteria for both aerobic and strength-trained groups. The low-fit group included all firefighters who did not meet the criteria for any of the fitness groups.

Physiological Status Monitor (PSM)

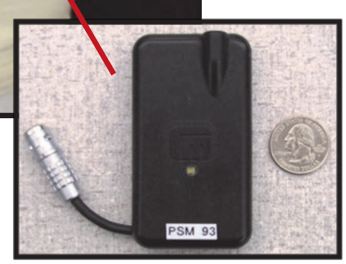
Firefighters wore the PSM during each of their 24-hour shifts for the study period. The PSM was developed by QinetiQ North America and consisted of three components:

- an e-textile platform integrated into a flame retardant T-shirt;
- a data processor / radio and logging device (a "PUC");
- a software application for downloading the data.

The QinetiQ PSM T-shirt was fabricated from flame resistant fabric. Integrated into the garment was an e-textile bus containing silver fabric electrodes for heart rate, a thermistor for skin temperature detection and a woven capacitive sensor to detect respiratory effort.

Attached to the T-shirt platform was a removable electronics module (the PUC) that included a microcontroller for sensor transduction, beat time logging and calculation of heart rate, respiration rate, skin temperature and activity from a triaxial accelerometer. This device also contained a radio for data downloading and memory for data storage. The unit was approximately 1 inch by 3 inches and weighs less than 3 ounces (see photo below).

The PUC collected up to 24 hours of data, which was wirelessly downloaded from the PUC and saved to a computer at the fire station. Downloaded PUC data was subsequently parsed into two data files for additional processing: time-stamped inter-beat interval (IBI) events, and time-stamped physiological variables (e.g., heart rate, respiration rate).



PSM worn by
Boston firefighters

This data was subsequently reviewed, and specific segments were identified for analysis based on information from dispatch records and firefighter logs

Data Collection Process. Firefighters kept a daily log of their activities throughout their shift (e.g., sleep, exercise, alarms). Information from the logs was used by research staff to identify specific time periods of interest, such as the occurrence of an alarm, the time of arrival on scene, time of return from scene and time of daily exercise. The physiological data from these selected periods were then identified for analysis and statistical aggregation. This process involved several discrete steps to identify the physiological data of interest and to prepare that data for statistical analysis. Figure 7 provides a flow chart of how the data from each log was processed.

Firefighter's involvement. Prior to starting the study, each firefighter was measured and fitted for a PSM T-shirt. Firefighters received several shirts so they could be changed throughout the day as needed. At the outset of the study, firefighters were trained how to don and doff the garment, how to plug in and unplug the PUC from the shirt, how to charge the PUCs when not in use and how to launder the T-shirt. Firefighters were also trained on how to complete their activity log at the end of each shift. Specific members of each group were trained on how to download the data from the PUCs to the study-dedicated computer at each fire station.

Firefighters donned and doffed the system without assistance. They were responsible for the laundering of the shirts and charging of the PUCs.

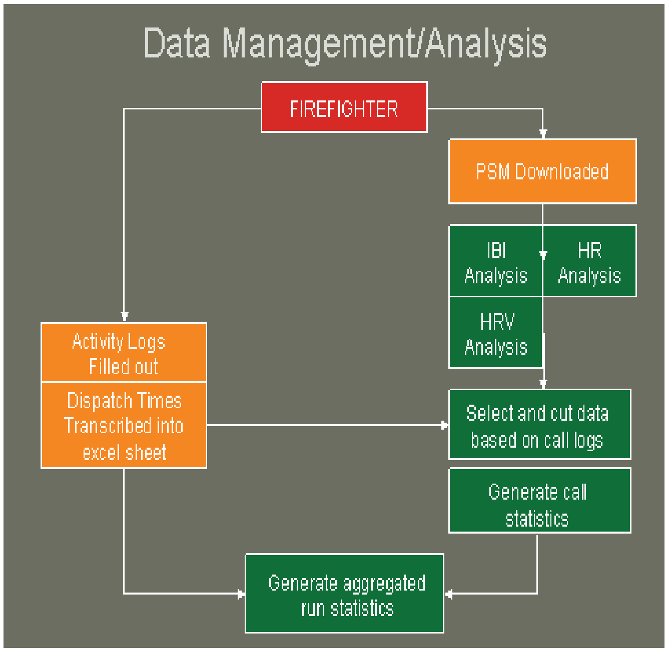


Figure 7: PSM Data Logging and Storage

PSM worn by Oxnard firefighters

Data Management. Recorded data was downloaded at the end of a shift and was periodically collected from the computers at each fire station. Because data was collected for a 24-hour period on each firefighter over a 4-month period, an enormous amount of data was collected. In fact, it is estimated that more than 50 million heart-beats were collected! Therefore, specific time periods (events) of interest had to be identified. Essentially this entailed reviewing dispatch records (and firefighter logs) to identify emergency calls. Computer programs helped identify selected periods from the downloaded data that was then segmented into event

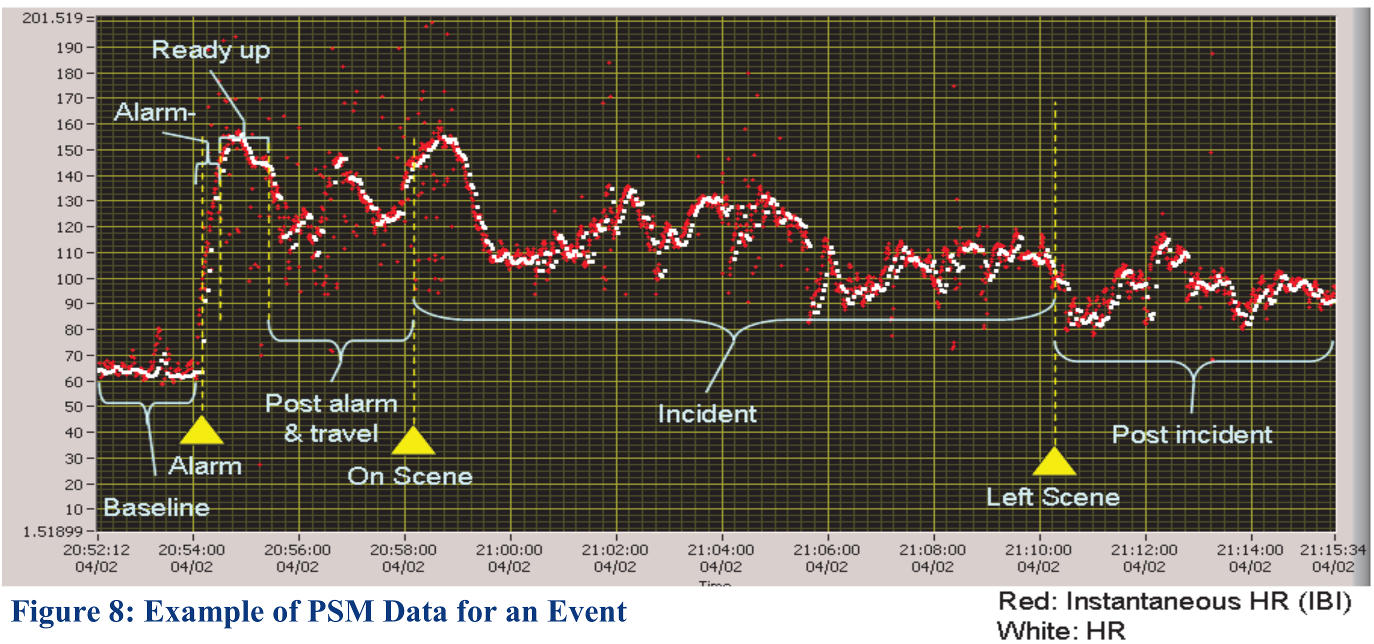


Figure 8: Example of PSM Data for an Event

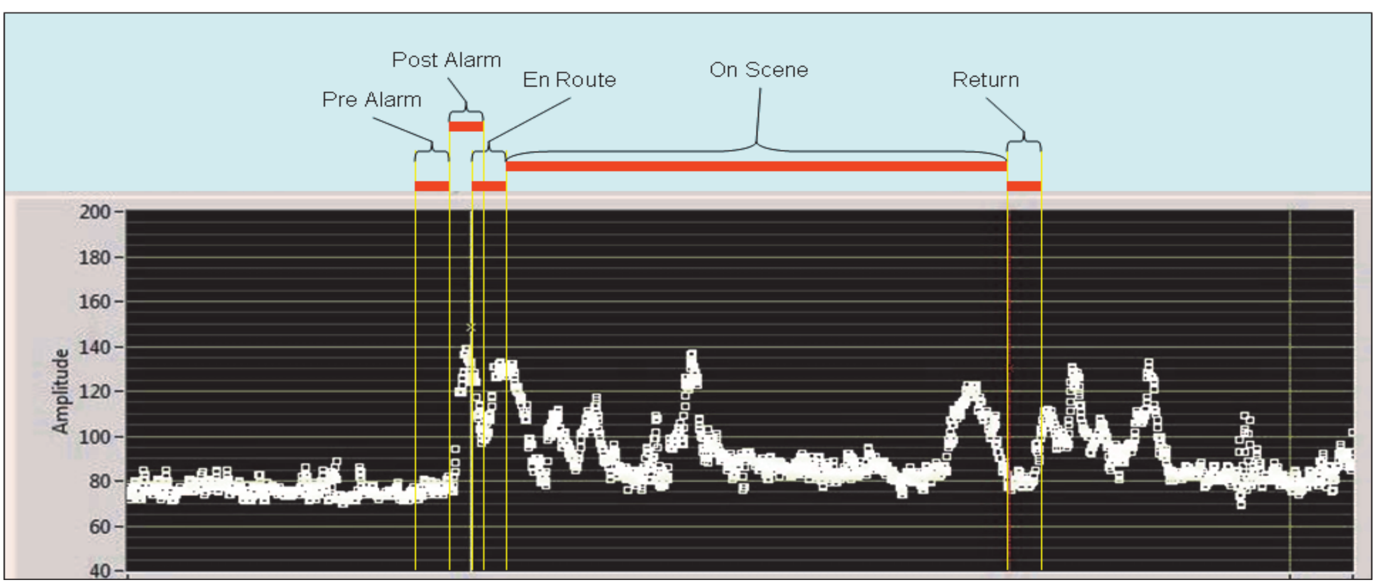


Figure 9: Segmentation of Event into Specific Periods of Interest

periods based on call logs or user-logged activity entries (Figure 8). For each event, further segmentation was performed (e.g., Pre Alarm period and a Post Alarm period) based on specific periods of interest. In some cases, the further segmented periods overlapped one another (e.g., Post Alarm overlaps the En Route period) (Figure 9).

Data Handling. The heart rate files were analyzed for descriptive statistics and these statistics were stored for later aggregation. Data automation tools assisted in the processing of the data. These tools broke the process down into several steps that operated on the files. Figure 10 presents the processing steps used for handling data.

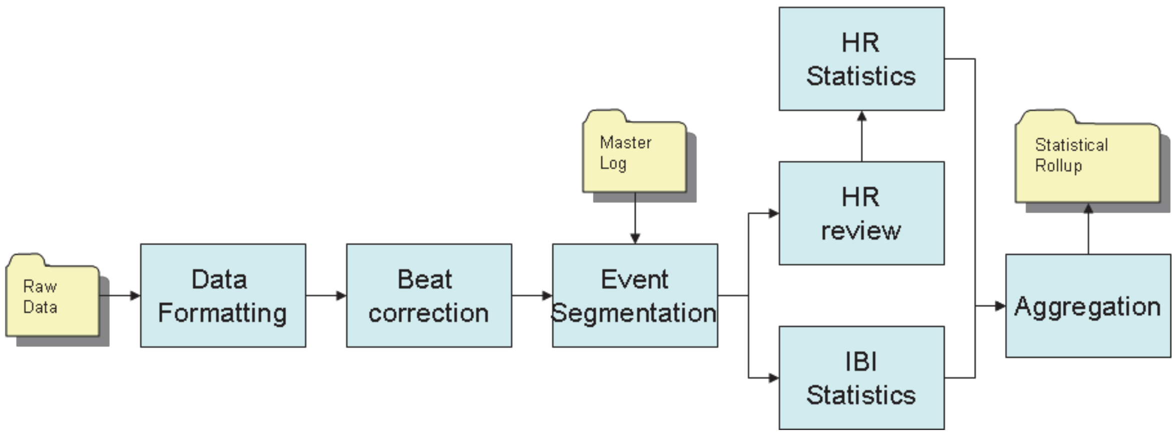


Figure 10: Automated Tools Used for Data Processing

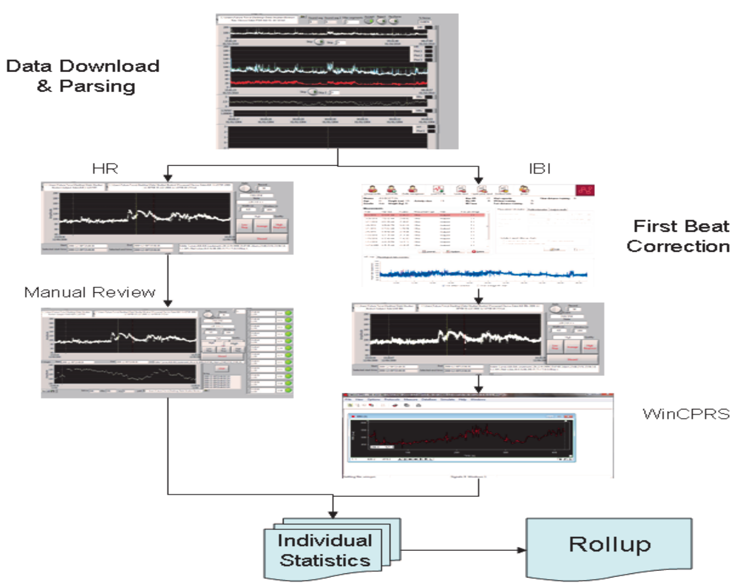


Figure 11: Computer Programming Steps

Computer programming tools were developed to assist in each of these processing steps. The process followed several steps (Figure 11):

1. Download and store the data;
2. Parse the data into numeric data files;
3. Using the fire logs, cut segments from the data files;
4. Process and create statistics for the cut segments;
5. Aggregate the statistics and create a spreadsheet.

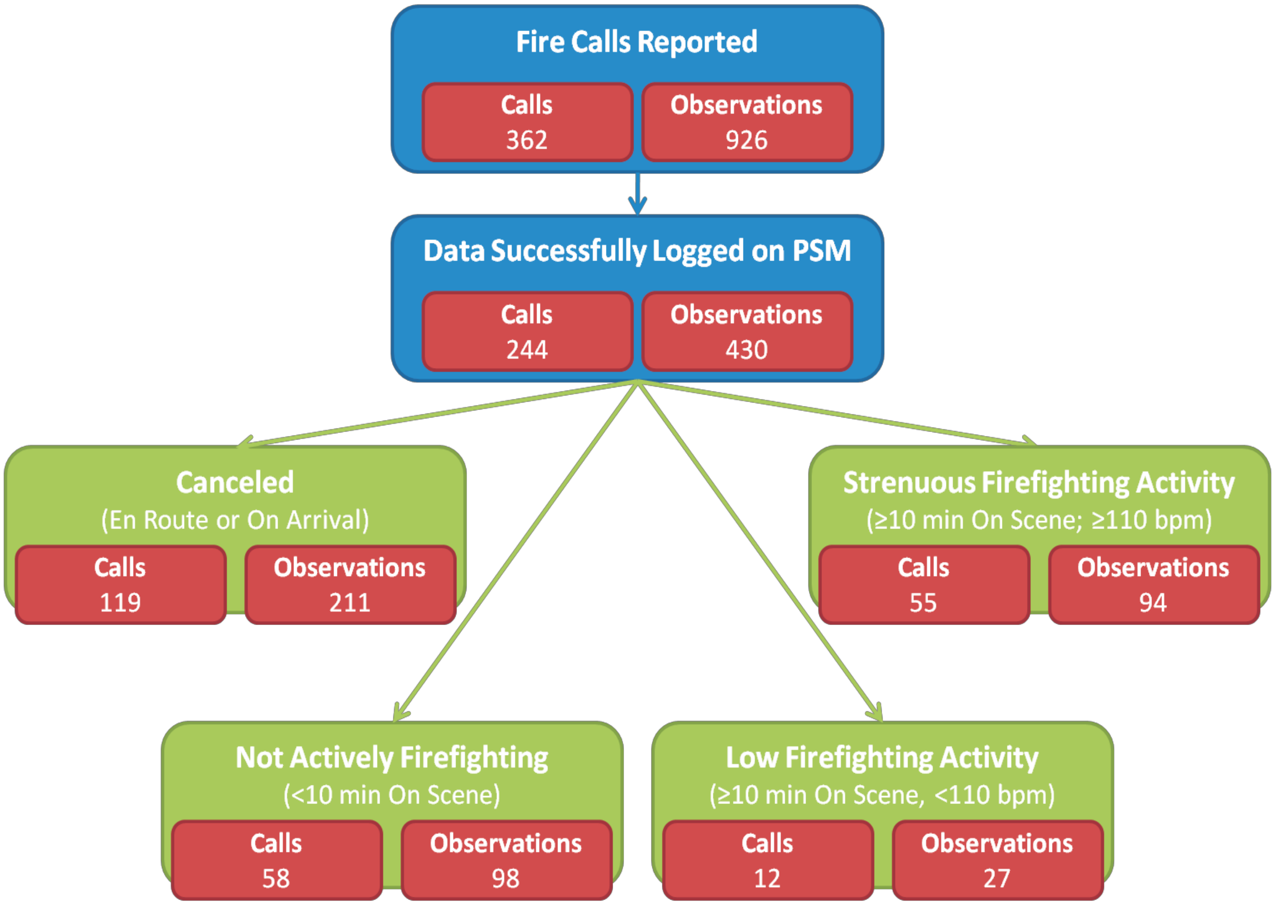


Figure 12: Number of Fire Calls Successfully Logged and Their Distribution
Calls = alarms recorded by a firefighter
Observations = the number of firefighters that responded to the alarm

Data Capturing. A review of data reported by firefighters (based on their logs) about the number of calls they responded to versus the number of events successfully recorded by the PSM indicates that not all data was captured. Figure 12 provides quantitative information about the number of fire calls that were reported (by dispatch and logs) versus the calls that were successfully logged by the PSM. A call indicates the number of fire alarms that were responded to, whereas observations indicate the number of firefighters on whom data was collected.

Several issues occurred that contributed to the loss of data. These issues included:

1. No download, due to
   - RF download failure
   - Insufficiently charged battery
   - Unplugged charging station
   - Operator error
   - Crushed or damaged device
2. A defect in memory resulting in data file corruption
   - Poor "noisy" lead contact
   - Log coding entry (e.g., an incorrect day or time)

Furthermore, even during calls when physiological data was recorded, a careful review of the data indicated that in some cases the firefighter was unlikely to be directly involved in actual firefighting. Researchers identified three categories of fire calls based on the length of time on-scene and the peak heart rate recorded: 1) not actively firefighting (firefighters were on-scene less than 10 minutes or their heart rates were less than 100 bpm); 2) low level firefighting activity (on-scene more than 10 minutes but heart rates did not exceed 110 bpm); and 3) strenuous firefighting (on-scene more than 10 minutes and heart rates above 110 bpm). Figures 13 and 14 provide examples of a strenuous fire call and a low firefighting call, respectively.

Calculation of Heart Rate from PSM. Several methods were used to calculate heart rate and then characterized how well each method performed across the range of logged activities. The same interbeat interval (IBI) data set was used to calculate the heart rate values:

- HRgov – a Government HR method used in the Warfighter PSM program;
- HRQinetiQ – a QinetiQ adaptive filter;
- HRFirstbeat™ – a reference HR derived from corrected IBI data.

Both the reference Government PSM heart rate method (HRgov) and a QinetiQ heart rate method (HRQinetiQ) used the raw uncorrected IBI data.

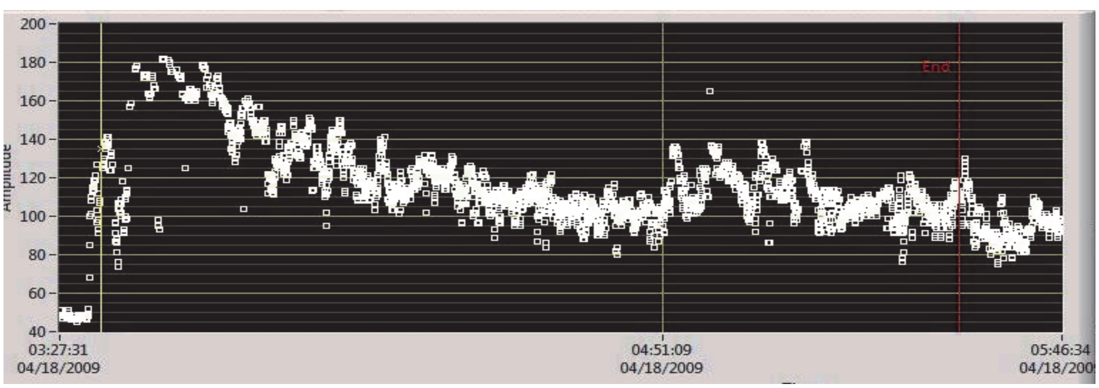


Figure 13: Strenuous Fire Call

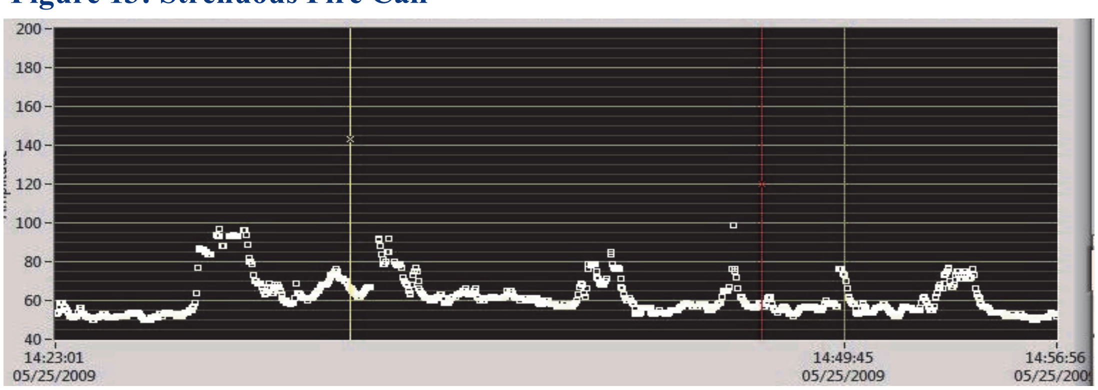


Figure 14: Low Firefighting Activity

These calculations were undertaken to correct the data for "noisy" signals that could artificially inflate heart rate values. Figure 15 shows the calculated heart rate values from each method (HRQinetiQ, HRgov, HRFirstbeat) as compared to the actual raw heart rate beats.

While each heart rate calculation has slightly different responsiveness (due to different averaging periods), they all tracked the dynamic changes in heart rate. During periods of noise, the original heart rate method (HRgov) drifted from the actual heart rate as shown below while the HRQinetiQ was better able to work through the artifact (Figure 16).

One important characteristic of the HRQinetiQ design is that the heart rate value is not reported if excessive noise in the IBI results in reporting an incorrect heart rate (Figure 17). The results reported in this document only used the heart rate calculated with the adapting filter developed by QinetiQ.

Manual Review. HRQinetiQ method was used for the heart rate data presented in this report. These data sets were manually reviewed to further validate heart rate measures. Of the 980,392 calculations of heart rate from logged events, 122 (.01%) were manually identified as suspect and discarded. This was possible because noise-induced errors had a discontinuity from surrounding rates. Figure 18 presents an event that was reviewed and found to contain two heart rate data points that were identified as noise (blue circle).

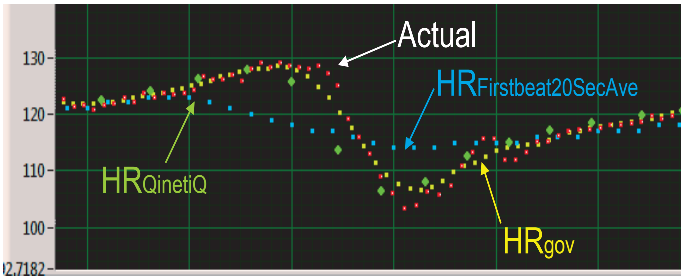


Figure 15: Calculated Heart Rates

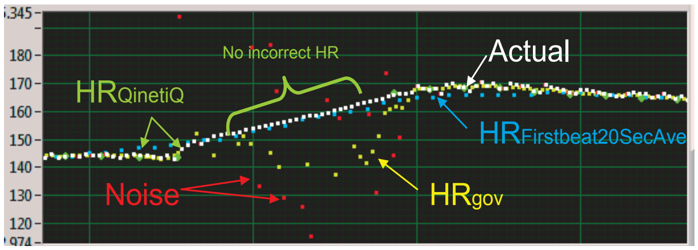


Figure 17: HRQinetiQ Stability

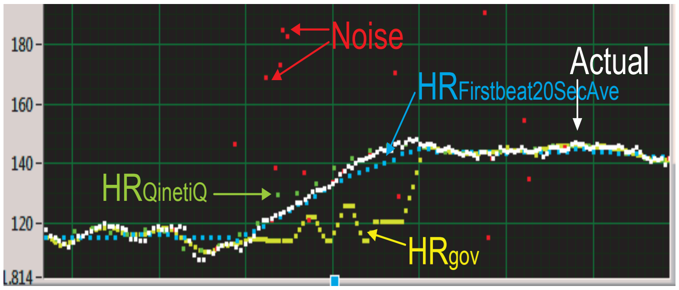


Figure 16: Drift in Heart Rategov Method

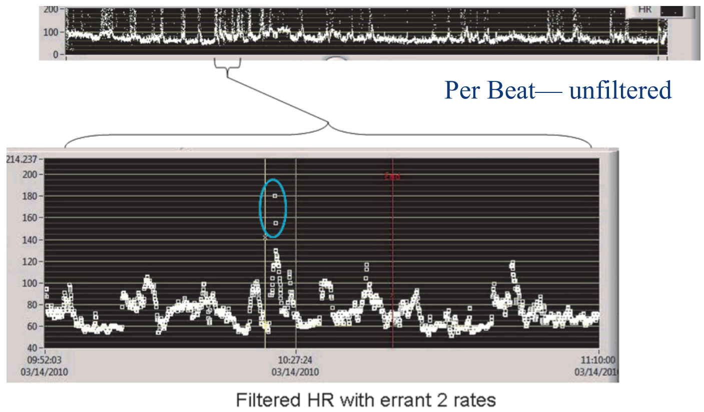


Figure 18: Example of Heart Rate Noise

Results and Discussion

As seen in Table 3, the Oxnard firefighters were younger and had less firefighting experience than the Boston firefighters. The Oxnard firefighters were significantly lighter; they had an average BMI of 26.4 whereas the Boston firefighters had an average BMI of 30.5. These data are consistent with other studies documenting a high incidence of overweight and obesity in the United States Fire Service (Soteriades et al., 2005; Fahs et al., 2009). Based on self-reported activity habits, 14% (7/50) of our participants were classified as strength-trained, 22% (11/50) were aerobically-trained, 40% (20/50) were cross-trained, and 24% (12/50) were placed in the low-fit control group.

Table 3: Descriptive Characteristics of Firefighters in Field Study (n=50)

	Oxnard	**Boston**	**Total**
	n=34	n=16	N=50
Age (yrs)	34.8±10.1	47.9±8.6†	39.0±11.4
Years of Service	9.1±9.5	18.5±10.3†	12.1±10.6
Height (in)	70.2±2.7	69.5±2.3	70.0±2.6
Weight (lbs)	185.0±22.8	209.9±30.3†	192.9±26.7
BMI (wt/ht^2)	26.4±2.5	30.5±3.6†	27.7±3.5
Fitness Classification			
Strength-Trained (n)	4	3	7
Aerobically Trained (n)	10	1	11
Cross-Trained (n)	17	3	20
Low-Fit (n)	3	9	12

†Boston FD significantly greater than Oxnard FD; $p<0.05$

Alarm Data

Table 4 presents data on all alarms received (reported by the firefighters on logs) by each fire department and the distribution across time of day and type of call. In total, 1,518 calls were logged and 2,127 observations recorded.

Of the 1,518 calls logged, 75% were collected at the Oxnard Fire Department. These calls reflect four different fire stations and 34 firefighters, while Boston data reflects two companies and 16 firefighters. It should also be noted that although Boston logged fewer overall calls, they logged 60% of all fire calls for this study.

This distribution of calls reflects what is commonly seen across the country, namely that fire departments respond to many medical and rescue calls. Furthermore, large metropolitan areas respond to more structure fires.

Table 4: Summary of Alarm Data by Fire Department

	Oxnard		**Boston**		**Total**	
Total Number of Calls *	1132		386		1518	
Total Number of Observations *	1520		607		2127	
	Calls	**Obs**	**Calls**	**Obs**	**Calls**	**Obs**
Time of Day						
Morning (0600-1159)	183	241	58	81	241	322
Afternoon (1200-1759)	200	261	67	18	267	369
Night (1800-2359)	380	514	145	222	**525**	736
Early Morning (0000-0559)	369	504	116	196	485	700
Type of Alarm						
Fire	**96**	**206**	**148**	**224**	**244**	**430**
Medical	733	888	63	105	796	993
Motor Vehicle Accident	126	204	74	118	200	355
Fire/Water Alarm	51	62	59	90	110	152
Rescue	8	13	30	50	38	63
Other	118	147	12	20	130	167

*Calls = An alarm that was recorded by a firefighter
*Observation (obs) = The number of firefighters that responded to an alarm; this number is always larger than the calls

Heart Rate Responses to Alarm

The alarm bell causes activation of the sympathetic nervous system, and thus, an increase in heart rate. Figure 19 depicts the overall heart rate response to an alarm. The prealarm values represent the average heart rate for the 90 seconds before an alarm, and the postalarm heart rates are the peak heart rate recorded within the 90-second period following the alarm. Figure 19 confirms what is often reported anecdotally; that is, firefighters have a greater heart rate response to a call for a structure fire than to other calls. In this case, there was a significantly greater heart rate response to fire

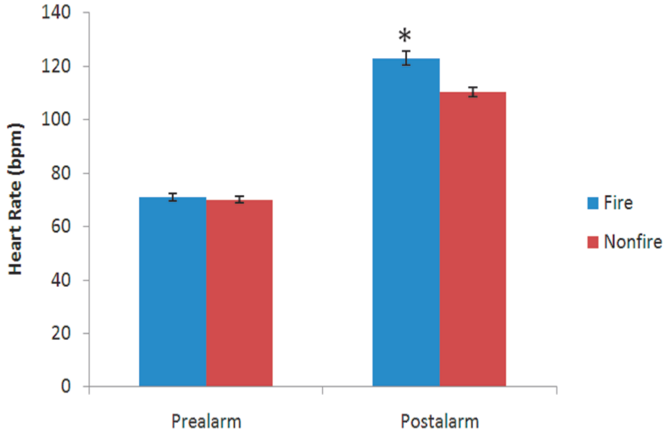


Figure 19: Fire Alarms vs. Nonfire Alarms: Heart Rate Response
* Fire > Nonfire, p<.05

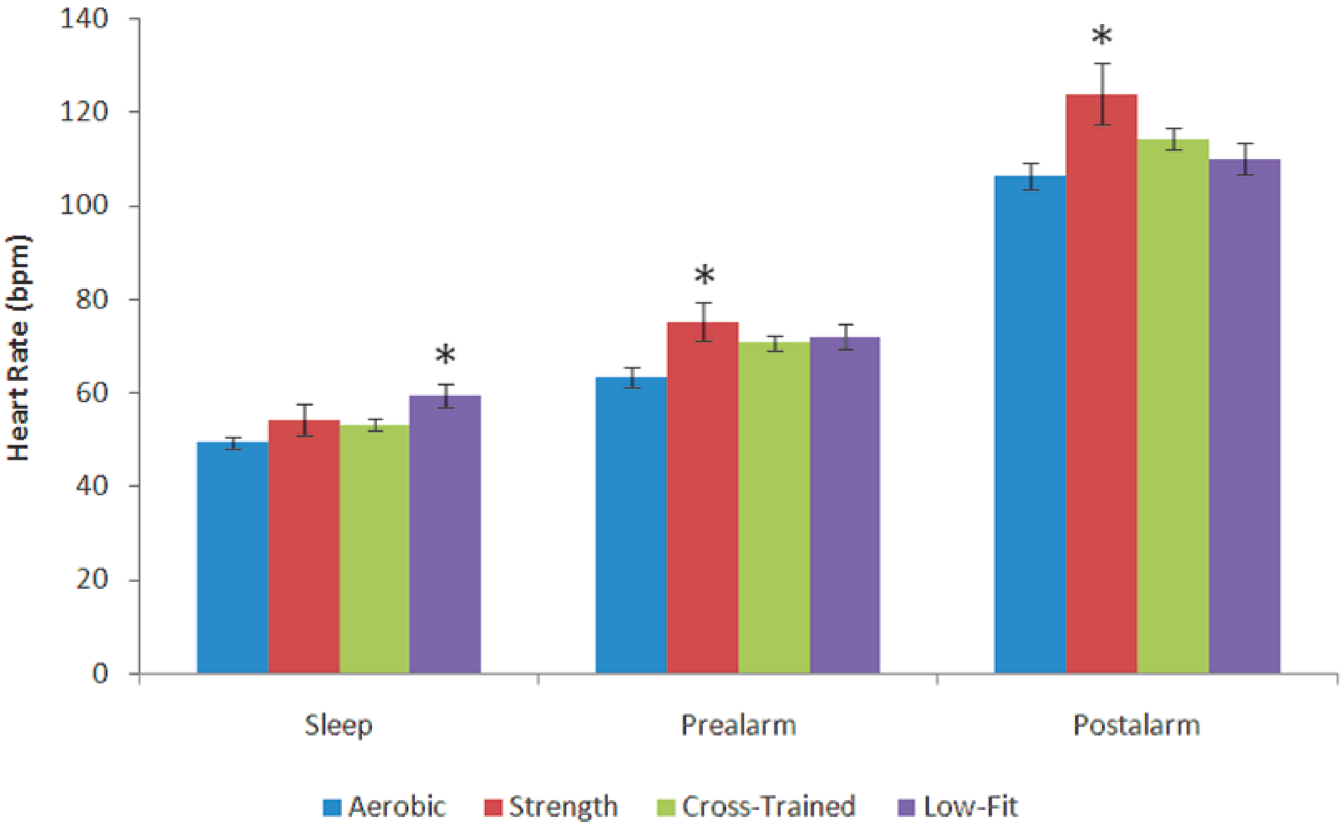


Figure 20: Heart Rate Response to Alarms by Fitness Group
* Significantly greater than Aerobic group, p<.05

alarms compared with all other alarms (123 bpm vs. 110 bpm, respectively). The increase in heart rate (pre to postalarm) to a fire alarm represents a 53-beat increase in heart rate. This rapid increase in heart rate is likely due to sympathetic nervous system activation (and the resulting “adrenaline surge”) and an increase in physical activity reflecting the donning of gear and rushing to get to the apparatus.

Figure 20 presents the effect of fitness classification on heart rate response to an alarm. In this graph, heart rate response to all alarms was included (not just fire calls). In addition to reporting the heart rate in the 90 seconds before and after an alarm, this graph also shows average resting heart rate during a period of sleep. As expected, heart rate is lower during sleep than during a period of normal activity preceding an alarm. Importantly, fitness category affected heart rate at each time period. During sleep, the aerobically-trained firefighters had significantly lower heart rates when compared to the low-fit firefighters (10 beats lower). This low heart rate in the aerobically trained firefighters represents an increase in vagal tone (parasympathetic nervous system). During the pre- and postalarm times, the aerobically trained firefighters had significantly lower heart rates than the strength-trained firefighters. In fact, there is an 18-beat lower heart rate observed in the postalarm period in the aerobically-trained firefighters verses the strength-trained firefighters.

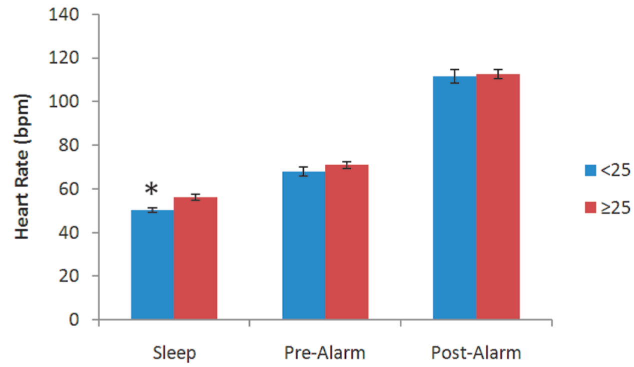


Figure 21: Heart Rate Response to Alarms: by Body Mass Index (BMI)
* Significantly greater than ≥25 BMI, p<.05

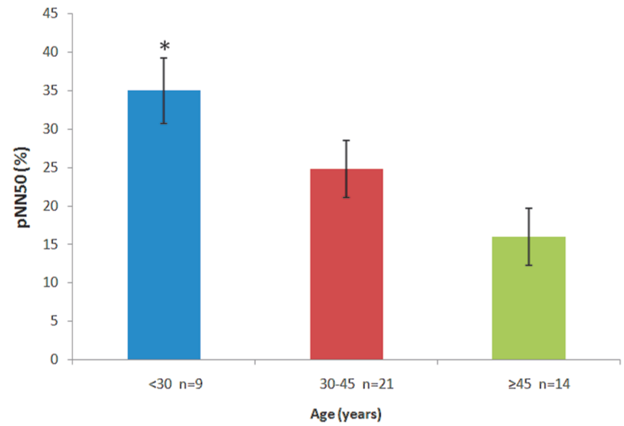


Figure 22: pNN50 (Heart Rate Variability): by Age
pNN50 is an indicator of vagal tone—the lower the tone, the higher risk of cardiac instability
* Significantly greater than ≥45 years, p<.05

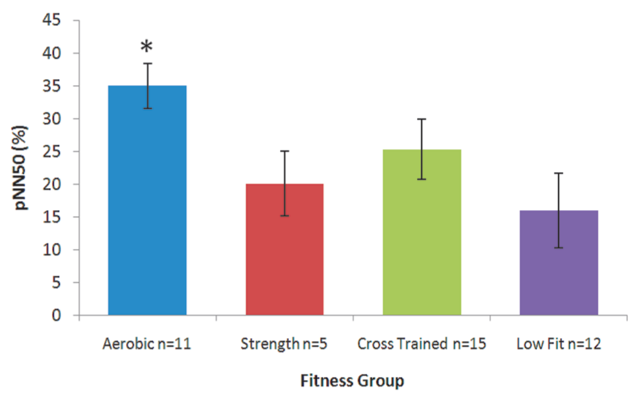


Figure 23: pNN50 (Heart Rate Variability): by Fitness
* Significantly greater than other fitness groups, p<.05

These results are consistent with research highlighting the importance of aerobic fitness and reinforce current recommendations in the Fire Service that all firefighters engage in aerobic fitness activities.

Body mass index (BMI) is an easily assessed measure of body fatness. The American Heart Association categorizes a BMI up to 25 as normal weight, a BMI of 25-29.9 as overweight, and a BMI≥30 as obese (AHA, 2010). It is clear that increasing levels of obesity (or of BMI) are associated with impairments in work performance and greater risk of cardiovascular events. As shown in Figure 21, there was no statistically significant difference in prealarm or postalarm heart rate between firefighters who were less than or greater than a BMI of 25, but there was a tendency for heart rates to be higher in the heavier firefighters. Furthermore, there was a significantly lower heart rate during sleep (rest) in those firefighters with a lower BMI. These data further reinforces the need for firefighters to maintain an appropriate body weight.

The balance between sympathetic nervous system and parasympathetic nervous system is an important determinant of heart rate and can provide an index of cardiovascular health. Specifically, heart rate variability (HRV) reflects the balance of the autonomic nervous system; the greater the HRV, the healthier the nervous system. One measure of HRV, pNN50, represents the percentage of time between normal beats (NN) that varied by 50 milliseconds (ms) or more. The data for HRV presented in this study were taken during sleep (an uninterrupted time of 10-20 minutes). As seen in Figure 22, pNN50 decreases with advancing age. It is well known that the incident rate of sudden cardiac events increases along with age. The decrease in HRV (pNN50), which indicates a higher risk of cardiac instability, may be an important mechanism explaining the increased cardiac risk in older individuals.

Figure 23 reports the pNN50 of study participants based on fitness category. The aerobically-trained individuals had a significantly higher value, indicating less risk of cardiovascular instability. There was also a tendency for cross-trained individuals to have a higher pNN50. Clearly, regular physical fitness training confers many benefits to firefighters. Based on this data, an increase in heart rate stability can be added to the long list of benefits of aerobic fitness training.

Heart Rate Responses to Strenuous Working Fires

For this analysis, we only included heart rate responses to fires that were categorized as "strenuous working fires" (Figures 24-26) so that we could focus our attention on calls that were likely to induce significant cardiovascular strain. Our analysis showed that many fire calls do not require strenuous physical work. On many calls, firefighters investigate reports of smoke or respond to reports of an automatic alarm. For this analysis, we addressed only fires that appeared to be "working fires", where the responses were thought to include representative activities such as fire attack and suppression.

Figure 24 shows the peak heart rate attained during firefighting activities in firefighters who are less than or greater than 30 years of age. Younger firefighters had a significantly higher heart rate response to firefighting activities. There are several potential explanations that may account for these results. Younger firefighters may be fitter and stronger and thus able to do more work; younger firefighters may be less accustomed to firefighting activity and therefore their heart rates may be more influenced by a "stress response"; and the older firefighters may be more likely to be serving as officers who are "directing" operations rather than doing as much manual work.

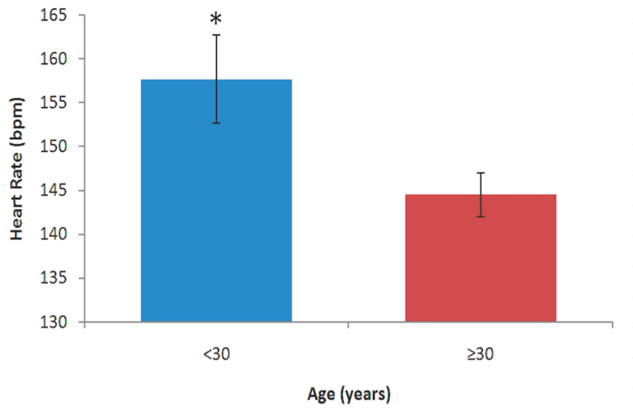


Figure 24: Heart Rate Response During Strenuous Firefighting Activity: by Age
* Young age > Older age, $p<.05$

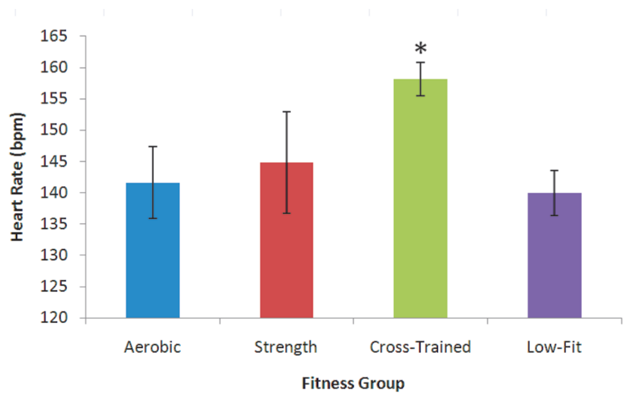


Figure 25: Heart Rate Response During Strenuous Firefighting Activity: by Fitness
* Cross-Trained > Aerobic and Low-Fit, $p<.05$

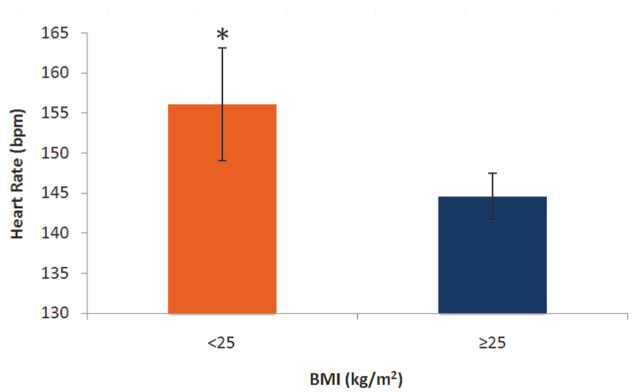


Figure 26: Heart Rate Response During Strenuous Firefighting Activity: by BMI
BMI (Body Mass Index)
* Leaner > Heavier group, $p<.05$

Figure 25, depicts the peak heart rate during firefighting activities of firefighters in the various fitness groups. Cross-trained firefighters had the highest heart rate responses to strenuous firefighting activity. This may be explained by the fact that cross-trained individuals can do more work as a result of their muscular strength and muscular endurance and therefore the heart rate is higher.

Figure 26 presents the peak heart rate responses during firefighting activities in firefighters who were normal weight (BMI<25) versus overweight (BMI≥25). Normal weight firefighters achieved a higher peak heart rate, indicating that they were able to do more work at the scene of a working fire.

The heart rates reported in this study are similar to earlier studies that investigated heart rate responses to firefighting drills and actual firefighting activity. As early as the mid-1970's, researchers had instrumented individuals with electrocardiograms (ECG) and found that strenuous firefighting can lead to near maximal heart rates (Barnard & Duncan, 1975). The technology was cumbersome and ECG tracings were difficult to interpret during heavy work periods. Furthermore, the authors only reported heart rate responses during the most demanding firefighting work (victim rescue).

A study conducted in 1987 reported heart rate responses of firefighters participating in six different firefighting scenarios and performing specific tasks (Romet & Frim, 1987). The study was small, often involving only 3 or 4 participants per evolution, but it did demonstrate that heart rate responses vary greatly depending upon the work that is being performed. The nozzleman was the most strenuous position investigated, with heart rates averaging 153 bpm during a 24 minute drill. Exterior firefighting, in contrast, caused an average heart rate of 123 bpm.

Studies have confirmed that strenuous live firefighting drills can result in near maximal heart rates (Smith et al., 2001a, 2011). Furthermore, a recent study found that actual firefighting results in widely variable heart rates depending upon the individual characteristics of the fire call (Brown & Stickford, 2007). Again, victim rescue results in very high heart rates. Clearly, firefighting can cause maximal heart rates. However, elevated heart rates are not a problem per se. In fact, people who engage in strenuous physical exercise routinely engage in activity that causes near maximal heart rates and this activity leads to positive adaptations in the cardiovascular system. However, high heart rates may be dangerous in individuals with underlying cardiovascular disease. The higher the heart rate, the harder the heart is working. In an individual with atherosclerosis, the diameter of the vessel may not be large enough to allow the increased blood flow that is necessary to meet the increased need for oxygen. This imbalance of oxygen demand and oxygen supply could lead to ischemia, and could potentially induce a cardiac arrhythmia. Alternately, high heart rates could increase sheer stress within the vessels and cause a vulnerable plaque to rupture, this initiating a clot formation and a myocardial infarction. See Figure 4 for a review of possible mechanisms by which firefighting may induce a sudden cardiac event.

Part Two: Research Projects

Summary

Firefighting activity is associated with an increased risk of sudden cardiac events. Kales and colleagues have shown that firefighters are 14 times more likely to suffer a sudden cardiac event following an alarm and 136 times more likely to have a sudden cardiac event after fire suppression activities (Kales et al., 2007). Therefore, we investigated heart rate responses to alarms and to working fires, and examined that data when firefighters were placed into categories based on age, BMI, and fitness level.

- Cardiac instability (as measured by heart rate variability) is greater in older firefighters than younger firefighters at rest, potentially explaining some of the increased risk of sudden cardiac events in this group.
- Low-fit firefighters had greater cardiac instability at rest when compared with aerobically trained firefighters.
- There is a sudden and marked increase in heart rate in response to an alarm, and heart rate response is greater to a potential structure fire than other emergency calls.
- Peak heart rate responses to a strenuous fire call can reach high levels. We reported average peak values of approximately 160 bpm in our cross-trained firefighters, with individual peak values as high as 180 bpm.
- Our data suggest that cross-trained, younger, and leaner firefighters are able to perform more work and thus achieve higher heart rates during strenuous firefighting activities.

Study 2: Cardiovascular Recovery from Exercise-Induced Heat Stress: A Lab Study

Introduction

A disproportionate number of sudden cardiac events occurs shortly after firefighting or strenuous physical work. Therefore, this study focused on cardiovascular and autonomic nervous system *recovery* following exercise in PPE. This study was conducted in carefully controlled laboratory conditions that allowed us to follow a standardized work protocol and obtain laboratory measures of vascular and autonomic nervous system (ANS) functions following exercise in PPE. Although a laboratory study does not include all the physical and psychological strain associated with actual firefighting activity, it does include physical work in PPE, and it allows us to obtain more precise and descriptive measurements in a controlled environment.

Purpose

The primary purpose of this study was to document the time course of recovery for cardiovascular hemodynamic variables and autonomic nervous system balance following treadmill exercise in PPE.

Methodology

Study Design

Firefighters enrolled in this study were asked to report to the First Responder Health and Safety Laboratory at Skidmore College on two occasions. During these visits, firefighters were asked to participate in two exercise trials consisting of:

- Walking for 20 minutes in full PPE (carrying SCBA) and then recovering in the supine position for 90 minutes, and
- Walking for 20 minutes in T-shirt and shorts and then recovering in the supine position for 90 minutes.

The two exercise trials were identical except for the clothing worn. Physiological measurements (including hemodynamic and autonomic nervous system measures) were obtained before and immediately after exercise, and approximately every 30 minutes during supine recovery in a thermoneutral laboratory.

Participants
A total of 14, apparently healthy (no known cardiovascular disease), moderately trained, male firefighters between 24 -50 years of age participated in this study. Prior to testing, all participants were informed of the nature, purpose, and risks of the study and were asked to read and sign a written informed consent document indicating that they were participating voluntarily and that they understood what they were being asked to do. The firefighters who participated in this study were from the following New York fire departments:

- Albany
- Glens Falls
- Greenville
- Gloversville
- Halfmoon
- Poughkeepsie
- Saratoga Springs
- Schenectady
- Troy
- Wilton
- Watervliet

Firefighters completed a health/history questionnaire and received a comprehensive health screening by a physician prior to participation. Firefighters were excluded from participation for any disease or prescription medication that affected cardiovascular or autonomic function (including cardiovascular disease, diabetes, hypertension, gastrointestinal abnormalities, and multiple sclerosis), history of heat illnesses, smoking, and/or the ingestion of drugs such as beta-blockers, ACE inhibitors, anti-inflammatory agents, or any other drug that may affect the microvasculature.

Descriptive Measurements
Height and body weight were measured using a digital stadiometer and a calibrated digital scale. Body fat percentage and bone mineral density were analyzed using a total body dual energy x-ray absorptiometry (DXA) scan. A cardiac ultrasound was performed to assess cardiac structure and function.


Cardiac Ultrasound

Standardization
Firefighters were asked to abstain from caffeine, alcohol, and food for a minimum of eight hours prior to testing. They also abstained from strenuous exercise during the 24 hours before testing. Approximately one hour prior to each exercise protocol, participants consumed a standardized meal replacement drink (300 kcal). In addition, firefighters ingested an activated core temperature pill approximately eight hours prior to arrival for testing. Firefighters did not report for testing immediately following a 24-hour work shift.

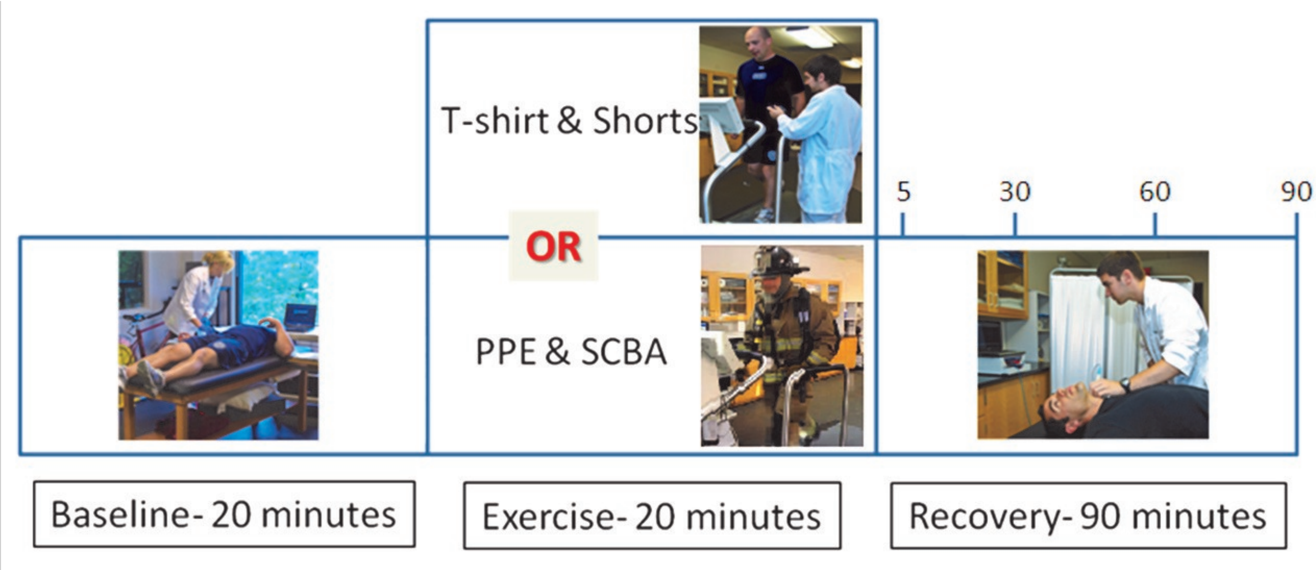


Figure 27: Research Protocol for Laboratory Study

Exercise Protocol

Each firefighter performed two experimental trials consisting of exercise in firefighting PPE or exercise in T-shirt and shorts (control) with trials separated by at least 48 hours (Figure 27). For the PPE condition, the participants wore shorts and T-shirt underneath their PPE. Firefighting PPE consisted of bunker coat and pants, leather boots, nomex hood, fire gloves, helmet. Firefighters wore a 60-minute self-contained breathing apparatus (SCBA) but were not on air. The average weight of the gear and SCBA was about 51 pounds.

Each exercise trial consisted of 20 minutes of walking on a treadmill at 2.2 mph at a 10% grade. Treadmill speed and/or grade of incline were altered slightly based on the participants' heart rate in order to maintain <95% of heart rate maximum. Firefighters wore a mouth piece and nose clip for the last 10 minutes of exercise to collect expired gas for the quantification of oxygen consumption (energy cost). During exercise, heart rate and core temperature were recorded every minute and ratings of perceived exertion (RPE) and thermal sensation (TS) were assessed every 5 minutes (see photos below).

Each firefighter wore a heart rate monitor during 20 minutes of walking. They then recovered in the supine position for 90 minutes with measurements taken at 5, 30, 60, and 90 minutes (Figure 27).

Perceptual Scales

Postexercise Measurements
At the completion of exercise, gear was doffed (in the PPE condition), and a second body weight was obtained (to calculate fluid loss). Supine measurements were repeated post exercise (within 3-8 minutes) and at 30, 60, and 90 minutes of recovery. Participants remained supine for the entire 90 minutes of the recovery period.

Hemodynamic Assessment. Hemodynamic measurements, including cardiac output, stroke volume, blood pressure, heart rate, and total peripheral resistance were assessed noninvasively via beat-to-beat blood pressure monitoring.

Autonomic Nervous System Assessment. Assessment of autonomic nervous system function was completed by heart rate variability analysis of the ECG tracings. Parasympathetic tone was assessed using pNN50 and low frequency (LF) power domains. High frequency (HF) power domain was considered a reflection of sympathetic and parasympathetic influence.

Applanation Tonography at the radial artery

Arterial Stiffness. Pulse wave analysis (PWA) measurements were obtained using applanation tonography at the radial, carotid, and femoral arteries. The data was stored and analyzed upon the completion of testing.

Subendocardial Viability Ratio (SEVR). Also referred to as the Buckberg Index, SEVR is the ratio between oxygen supply to oxygen demand of the heart. We used applanation tonography to obtain radial waveforms, and calculated the ratio of area of the diastolic phase to systolic phase of the heart beat. This provides an index of myocardial blood supply.

Endothelial Function. Endothelial function was measured using venous occlusive plethysmography (VOP). We measured resting blood flow and maximal blood flow (called reactive hyperemia).

Blood Sampling. A venous blood sample was obtained by a trained phlebotomist and used to provide a complete blood count (CBC).

Blood Sampling

Results and Discussion

Descriptive Characteristics

Descriptive data of the firefighters is reported in Table 5. Our participants were approximately 38 years of age and had been in the Fire Service for nearly 11 years. On average, the firefighters were overweight with a BMI of 28.4 and body fat of 25.6%.

Table 5: Descriptive Data of Participants

Height (cm)	179.9 ± 6.8
Weight (kg)	91.7 ± 11.2
Age (years)	37.9 ± 8.1
BMI (kg/m^2)	28.4 ± 3.0
Body Fat (%)	25.6 ± 4.8
Years of Service	10.9 ± 4.4

Mean±SD; BMI (body mass index)

Baseline cardiovascular measurements are reported in Table 6. On average, the participants had a low resting heart rate and cardiovascular structure and function measures that fell within the normal range. However, we did note some cardiac abnormalities in our participants. Three firefighters had septal thickness measurements that were greater than normal values (>10 mm). Increased ventricular wall thickness (hypertrophy) may be caused by hypertension or valve problems. Evidence of left ventricular hypertrophy is concerning because it increases the likelihood of sudden cardiac events (Levy et al., 1990; Siegel, 1997).

Table 6: Cardiovascular Assessment of Participants (mean±SD)

Resting Heart Rate (bpm)	63.0 ± 6.3
Resting Blood Pressure (mm Hg)	
Systolic Blood Pressure	120.7 ± 6.3
Diastolic Blood Pressure	72.7 ± 8.7
Intimal Medial Thickness (mm)	0.49 ± 0.09
Cardiac Ultrasound Measures	
Interventricular Septal Thickness; Diastole (mm)	9.43 ± 1.95
Left Ventricular Internal Diameter; Diastole (mm)	52.79 ± 2.22
Left Ventricular Posterior Wall Thickness; Diastole (mm)	10.43 ± 1.70
Left Ventricular Internal Diameter; Systole (mm)	33.64 ± 4.99
Left Ventricular Mass (g)	234.50±55.05
Stroke Volume (mL)	86.50 ± 11.02
Ejection Fraction (%)	65.05 ± 9.92
Fractional Shortening (%)	36.45 ± 7.52

Mean±SD; Diastole (measurement taken during diastole); Systole (measurement taken during systole)

Exercise Results

As reported in Figure 28, heart rate increased with the onset of exercise in both conditions, however heart rate in the PPE condition was significantly higher than in the control condition at all time points. At the end of exercise, heart rate values for the PPE and control condition were 161 and 116 bpm, corresponding to 88.5% and 63.5% of age-predicted maximum heart rate, respectively. It is important to note that just walking in PPE resulted in nearly a 50-beat increase in heart rate compared to shorts and a T-shirt because of the added weight and insulative properties of the gear. The heart rate of 161 bpm seen at the end of exercise is consistent with values that have been reported after 15-20 minutes of simulated firefighting activity (Romet & Frim, 1987; Smith et al., 2011) and are similar to the average heart rate values we reported during working structure fires.

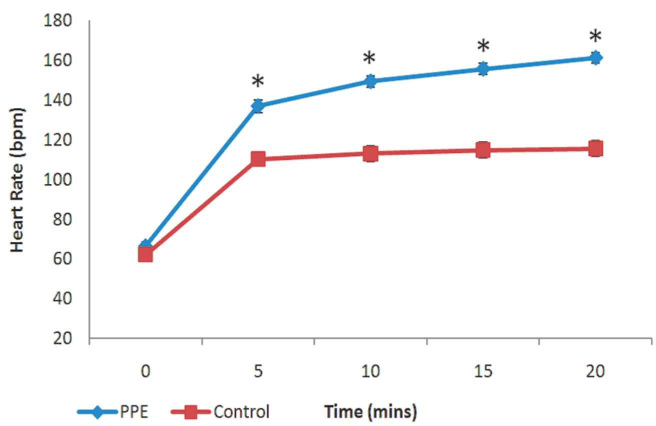


Figure 28: Comparison of Heart Rate Response in PPE vs. T-shirt and Shorts During Exercise
* PPE > Control, p<.05

Table 7 presents the average physiological and perceptual values at the end of exercise in the two conditions. As discussed above, heart rate was higher at the end of exercise in PPE. Also at the end of exercise, core temperature was significantly higher in the PPE condition compared to the control condition. However, core temperature only reached 37.44 °C at the end of exercise in the gear. Rating of Perceived Exertion (RPE), Thermal Sensation (TS), and oxygen consumption (VO_2) were also significantly higher at the end of exercise in PPE than in the shorts and T-shirt condition. The thermal sensation of 5.7 indicates that by the end of the PPE trial, the firefighters felt "hot".

Table 7: Average Physiological and Perceptual Variables During the Last Five Minutes of Exercise (n=14)

	PPE	Control
Heart Rate (bpm)	161.2 ± 10.0*	115.6 ± 14.8
Tco (°C)	37.44 ± 0.3*	37.18 ± 0.3
RPE	4.6 ± 1.5*	2.3 ± 1.2
TS	5.7 ± 0.8*	4.3 ± 1.1
VO_2 (ml·kg^{-1}·min^{-1})	27.1 ± 2.2*	19.0 ± 1.5

Tco (Core Temperature); RPE (Rate of Perceived Exertion); PPE (Personal Protective Equipment); TS (Thermal Sensation); mean±SD
* PPE > Control, p<.05

Exercise Recovery Results

There were no significant changes in body weight from baseline to postexercise for either condition (PPE vs. control; -0.02 ± 0.03 kg) suggesting significant dehydration did not occur during this protocol.

Heart rate was significantly elevated during recovery in the PPE condition compared with the control condition for all time points with the exception of 90 minutes. Within the PPE condition, heart rate did not return to baseline until 90 minutes of recovery (Figure 29).

Systolic blood pressure (SBP) was lower than baseline throughout the entire recovery period following exercise in the PPE condition. When T-shirt and shorts were worn, systolic blood pressure was lower after exercise but recovered more quickly (Figure 30).

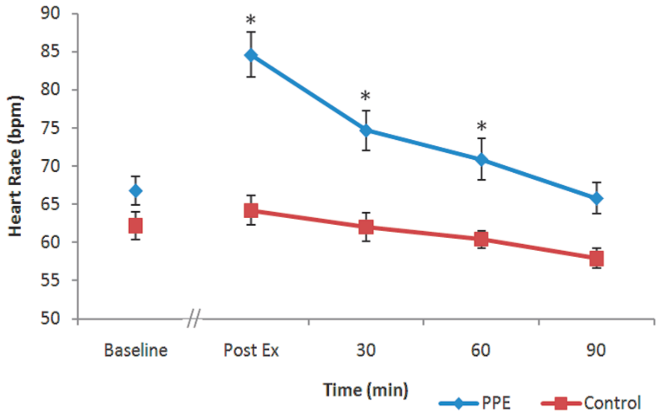


Figure 29: Comparison of Heart Rate Response in PPE vs. T-shirt and Shorts

* PPE > Control, p<.05

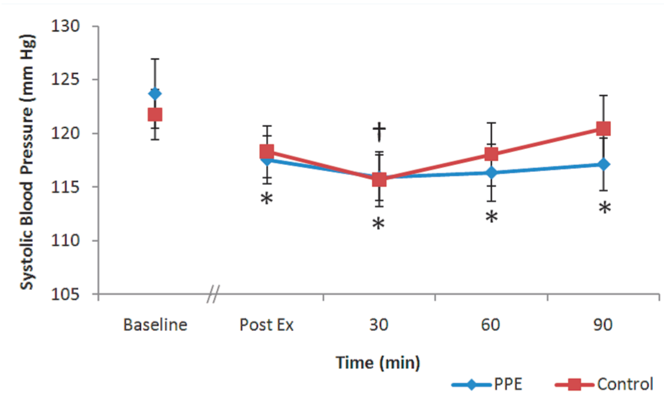


Figure 30: Comparison of Systolic Blood Pressure Response in PPE vs. T-shirt and Shorts

* PPE significantly decreased from baseline, p<.05

† Control significantly decreased from baseline, p<.05

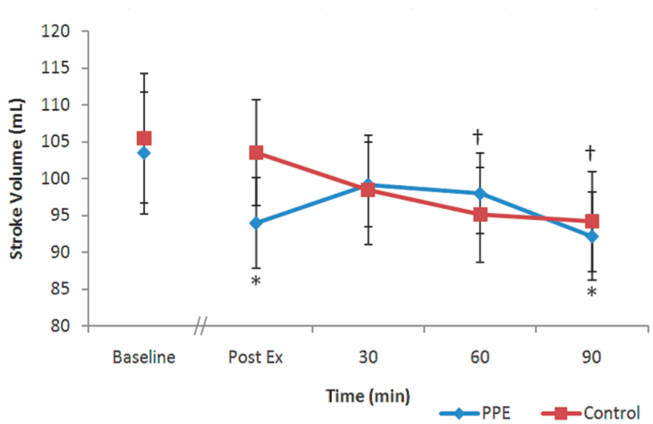


Figure 31: Comparison of Stroke Volume in PPE vs. T-shirt and Shorts

* PPE significantly decreased from baseline, p<.05

† Control significantly decreased from baseline, p<.05

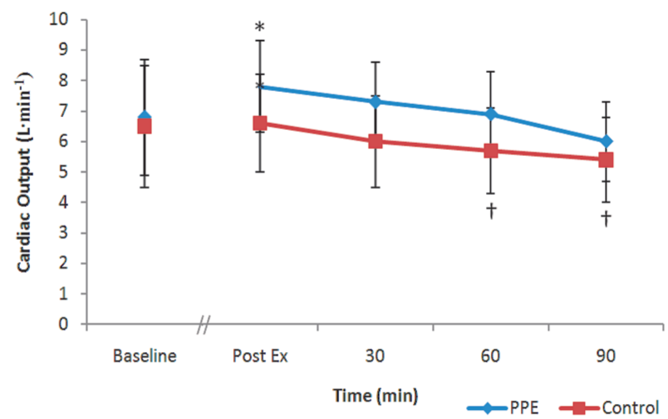


Figure 32: Comparison of Cardiac Output in PPE vs. T-shirt and Shorts

* PPE significantly greater than baseline, p<.05

† Control significantly decreased from baseline, p<.05

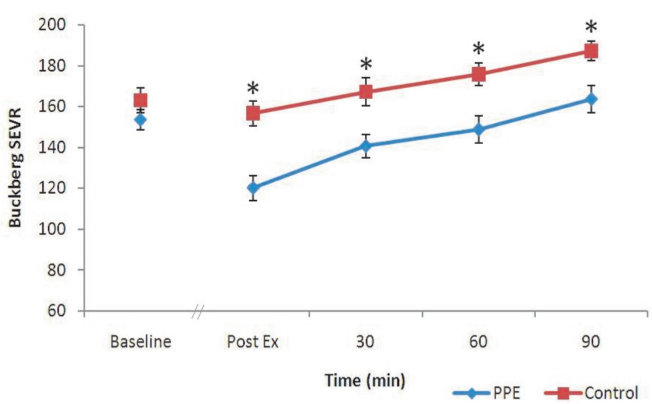


Figure 33: Comparison of Buckberg Index (SEVR) in PPE vs. T-shirt and Shorts

* Control > PPE, p<.05

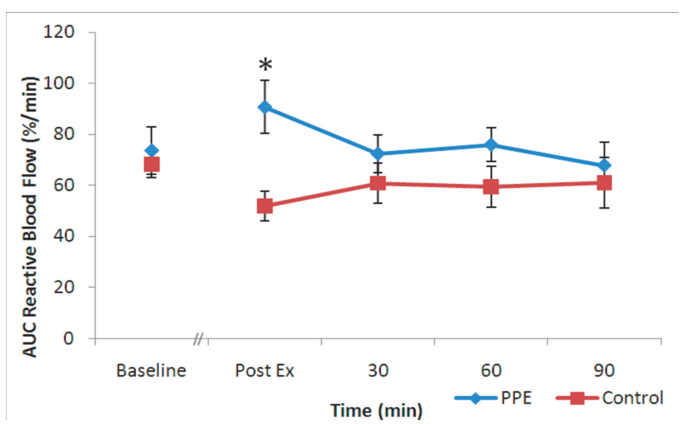


Figure 34: Comparison of Reactive Blood Flow in PPE vs. T-shirt and Shorts

* PPE significantly greater than baseline, p<.05

Diastolic blood pressure (DBP) in the PPE condition was also significantly reduced during the entire recovery period, while in the control condition, DBP was unchanged. There was a significant hypotensive response in both SBP and DBP in the PPE condition. The hypotensive response has also been reported as a result of live fire training and is of potential concern to the Fire Service because of the risk of syncope during recovery (Horn et al., 2011).

Stroke volume (SV) was significantly lower than baseline during recovery in both the PPE and control conditions (Figure 31). Stroke volume has been reported to be decreased following firefighting activity (Smith et al., 2001a). The researchers speculated that this decrease in stroke volume was likely due to a decrease in plasma volume and a decrease in total peripheral resistance. Our results suggest that stroke volume may decrease even in the absence of dehydration.

Cardiac output (HR x SV) was elevated postexercise in the PPE condition (Figure 32). The increase in cardiac output in the PPE condition is the result of a higher heart rate in that condition.

The subendocardial viability ratio (SEVR, or Buckberg Index) is an indicator of myocardial oxygen supply. The SEVR was significantly decreased at all time points during recovery (Figure 33). Within the PPE condition, all measures were well below baseline throughout the recovery period. The decrease in SEVR reflects a decrease in myocardial perfusion relative to cardiac workload. It is possible that the decrease in SEVR during recovery from work in PPE reflects ischemia, or the potential for ischemia. The effect of work in general, and exercise-induced heat stress in particular, on SEVR warrants further investigation as myocardial ischemia may be a trigger for a sudden cardiac event (see Figure 4 for potential mechanisms to explain sudden cardiac events).

Endothelial Function. Endothelial function refers to the ability of the vessel to dilate as needed to accommodate increased blood flow. Endothelial dysfunction is an early clinical indicator of cardiovascular

disease and is related with increased cardiac morbidity and mortality. Endothelial function can be measured by determining maximal blood flow in response to short term (5 minutes) occlusion of blood flow. Forearm blood flow was measured repeatedly for several minutes. The area under the curve (AUC) was used as an index of endothelial function. Endothelial function increased after exercise in PPE and did not change as a result of exercise in shorts and a T-shirt (Figure 34).

Autonomic Nervous System Recovery. We obtained several measures of autonomic nervous system balance. There was a significant decrease in indicators of parasympathetic tone (pNN50 and HF) and sympathetic and parasympathetic balance (LF) during recovery from exercise in PPE (Figures 35-37). These changes persisted for a greater duration in the PPE condition for all variables compared with the control condition. The disruptions seen in this study are similar to what has been reported in exercise studies (Pober et al., 2004; Terziotti et al., 2001). Pober and colleagues had young healthy men exercise for one hour on a bicycle ergometer (low intensity) and reported that parasympathetic values (pNN50) returned to baseline after 60 minutes of recovery. However, the exercise studies cited above used a different exercise intensity and duration than the 20 minutes of walking used in the present study, thus a direct comparison of results is difficult. Importantly, the current study is one of the first to investigate the effect of heat stress from PPE on autonomic nervous function.

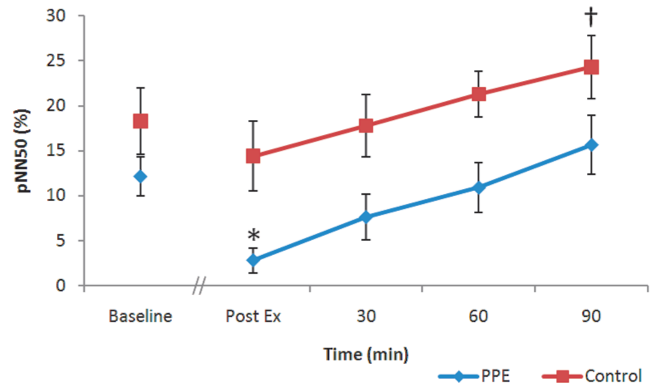


Figure 35: Parasympathetic Control (pNN50) following exercise in PPE vs. T-shirt and Shorts
* PPE significantly decreased from baseline, p<.05
† Control significantly greater than baseline, p<.05

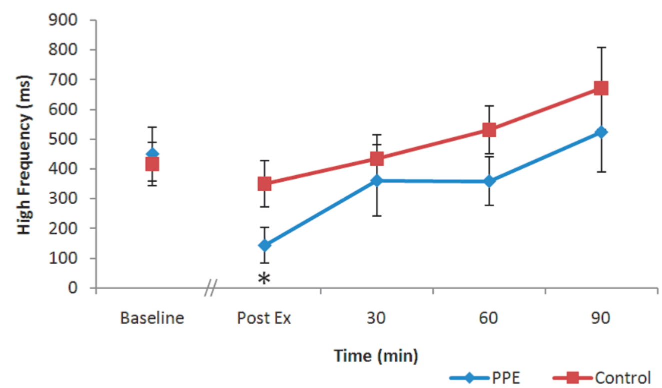


Figure 36: Parasympathetic Control following exercise in PPE vs. T-shirt and Shorts
* PPE Significantly decreased from baseline, p<.05

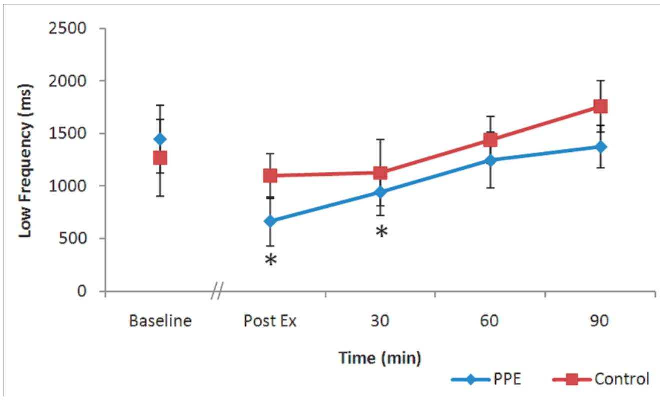
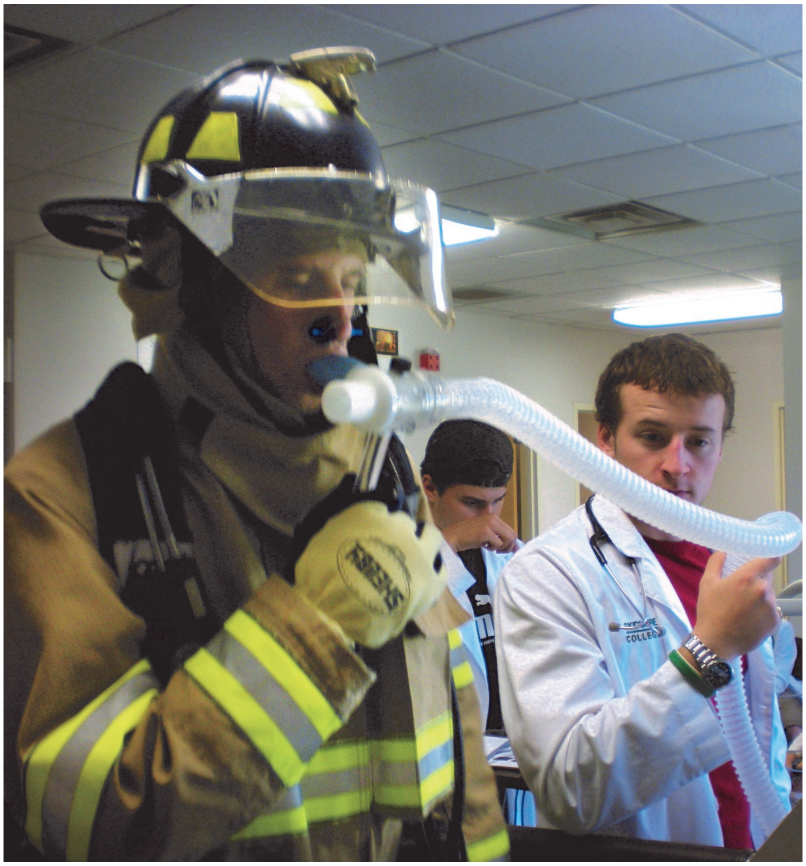


Figure 37: Parasympathetic and Sympathetic Balance following exercise in PPE vs. T-shirt and Shorts
* PPE Significantly decreased from Control and baseline, p<.05

This study indicates that there is considerable autonomic nervous system disruption following even a short bout of exercise while wearing firefighting PPE. Specifically, parasympathetic nervous system tone is decreased as indicated by the lower pNN50 and high frequency (HF) results. These decreases are more evident following exercise in PPE compared to the T-shirt and shorts condition. Furthermore, this disruption extends well into the recovery period. It is well known that many cardiac events occur in the minutes and hours after firefighting.

Additional research is needed to better understand if the autonomic nervous system disruption reported in this study could be related to cardiac events in the hours following strenuous firefighting.



Summary

The primary purpose of this study was to document the time course of recovery for cardiovascular hemodynamic variables and autonomic nervous system balance following exercise in PPE.

The study focused on collecting sophisticated laboratory measures during the 90 minutes after exercise in PPE because so many cardiac events occur shortly after completing firefighting activities.

The major findings of this study include:

- A 20 minute bout of exercise in PPE causes significantly greater cardiovascular and thermal strain compared to exercise in shorts and a T-shirt, as evidenced by a higher heart rate, core temperature, rating of perceived exertion, and thermal sensation at the end of exercise.
- Heart rate and cardiac output are higher during recovery from exercise in the PPE than in shorts and a T-shirt. These data suggest the heart is working harder following exercise in PPE.
- Blood pressure and stroke volume are lower during recovery from exercise in the PPE than in shorts and a T-shirt. These data suggest the possibility of hypotension in some individuals.
- The SEVR is lower after exercise in the PPE than in shorts and a T-shirt. These data indicate the potential for myocardial ischemia.
- The autonomic control of heart rate is disrupted during recovery from exercise-induced heat stress. The heart rate variability measurements (pNN50, Low and High Frequency) indicate a potential for increased cardiac instability during recovery.

Part Three: Decreasing Cardiovascular Events

Part Three: Decreasing Cardiovascular Events

As described in Part One, firefighting affects every system of the body. This report has focused on the cardiovascular strain associated with firefighting because sudden cardiac events are the leading cause of line-of-duty deaths among firefighters. Furthermore, hundreds of firefighters suffer nonfatal cardiac events each year.

No single research project can describe the complex cardiovascular responses to firefighting or the factors that contribute to the magnitude of the cardiovascular strain. Rather, the Fire Service needs a strong research agenda aimed at fully describing the physiological strain of firefighting.

Further research efforts should be directed to understanding the benefits of different strategies that are used to lessen cardiovascular strain.

As introduced in Part One, in order to minimize the risk of sudden cardiac events in the Fire Service. Every firefighter should:

1. Understand the cardiovascular strain of firefighting;
2. Prepare themselves to meet the cardiovascular strain of firefighting;
3. Take steps to lessen the strain associated with firefighting and to hasten recovery.

Part Three: Decreasing Cardiovascular Events

Understanding the Cardiovascular Strain of Firefighting

Much of this document has been devoted to describing the cardiovascular strain associated with firefighting activity and work in PPE. In short, firefighting work results in significant physiological changes in all components of the cardiovascular system — the heart, the vessels, and the blood. These physiological changes may increase the risk of a sudden cardiac event in individuals with underlying cardiovascular disease.

Firefighting involves strenuous physical work, performed while wearing heavy and restrictive PPE, and conducted in a hot and hostile environment. Thus, firefighting results in activation of the sympathetic nervous and the neuroendocrine systems.

Activation of the sympathetic system in combination with the physical work being performed and the psychological stress experienced are important factor in mediating cardiovascular changes with firefighting.

This study has shown that firefighters' heart rates increase from approximately 71 bpm to 123 bpm just in response to a call for potential structure fire. Heart rate responses to actual firefighting vary dramatically depending upon the individual characteristics of a fire, such as fuel load and ambient temperatures, and the tasks performed by the firefighter. As seen in Figure 38a, understanding the magnitude of the cardiovascular strain associated with firefighting is the first step in motivating individuals to take proactive steps to prepare themselves for the stress of the job.

Figure 38: Understanding and Mitigating the Cardiovascular Strain of Firefighting

Part Three: Decreasing Cardiovascular Events

Preparing for the Cardiovascular Strain of Firefighting

As seen in Figure 38b, there are several proactive steps that firefighters can and should take to prepare themselves for the cardiovascular strain of firefighting and to lessen the risk of cardiac events on the fireground:

1. know and manage the risk factors for cardiovascular disease;
2. receive medical clearance for firefighting;
3. know the signs and symptoms of a heart attack;
4. increase physical fitness.

Know and Manage Risk Factors for Cardiovascular Disease

There are several well-established cardiovascular risk factors that are known to increase the likelihood that a person will suffer a sudden cardiac event. The good news is that many of these cardiovascular risk factors can be improved through lifestyle modifications and through medical management. The bad news is that there is a high prevalence of cardiovascular risk factors among firefighters.

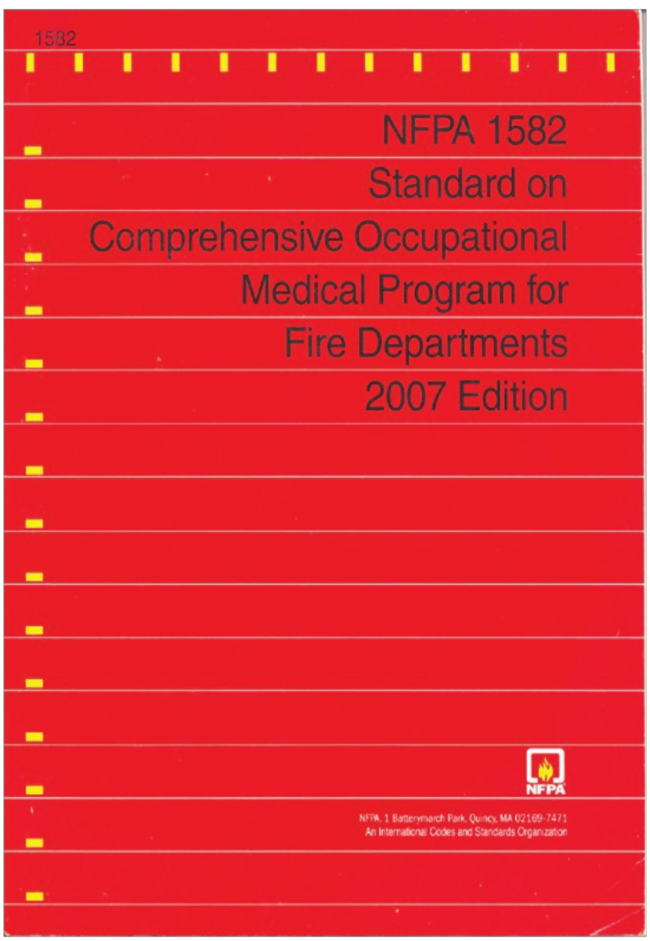
Given the strenuous nature of firefighting work, firefighters should aggressively manage their risk factors. Table 2 identifies the major modifiable risk factors along with desirable levels, a definition of when the values are considered a risk factor, and information on how to manage each risk factor. The table also includes a column for firefighters to record their own values.

Knowing your own value is absolutely necessary to managing cardiovascular health. Just as a firefighter needs to know fire behavior and information about building construction to operate safely at a fire scene, knowing his or her own cardiovascular risk factors, and managing them effectively is critical to being able to safely operate at an emergency scene.

Determining your values for each risk factor can be accomplished through annual medical evaluations (discussed in the next section). Furthermore, your primary care physician can provide you with values for each of the factors listed above. Should these options not be available, there are multiple screening options available in many communities, and you should avail yourself of these opportunities.

Part Three: Decreasing Cardiovascular Events

Many of the variables identified in Table 2 have numerical values that are expressed on a continuum. Thus, if two firefighters had blood cholesterol values of 240 and 280 ml/dL respectively, both would have high cholesterol, but the second firefighter would have a greater risk of cardiac death. A risk assessment tool that takes into account the number of risk factors that an individual has and the severity of the risk factors is the Framingham Heart Score. This simple tool can be accessed at:
http://www.framinghamheartstudy.org/risk/coronary.html



If you have risk factors for coronary artery disease, be sure to discuss them with your physician. It is very important that your physician know that you are a firefighter and that the physician understand the physiological strain of firefighting.

Medical Clearance for Firefighting

As recognized by most major national Fire Service organizations, every firefighter should receive an annual medical evaluation consistent with the National Fire Protection Agency Standard on Comprehensive Occupational Medical Program for Fire Departments (NFPA 1582; 2007). The 1582 Standard enumerates the essential job tasks of firefighting and stipulates components of a medical examination that are appropriate for new and current members of the Fire Service. Briefly, the NFPA standard recommends that all current members of the fire department have an annual medical evaluation that includes: medical history (including personal and family history of cardiovascular disease), physical examination, blood tests (including blood glucose and lipids), urine test, audiology, lung function test, chest X-rays, EKG, and various screening tests.

If you work for a department that does not have annual medical evaluations, then work within your organization to find ways to include medical evaluations and education on risk factor management. You deserve it, and so do your fellow firefighters.

Part Three: Decreasing Cardiovascular Events

Know the Signs and Symptoms of a Sudden Cardiac Event

Given that heart attacks (sudden cardiac events) are the leading cause of line-of-duty deaths among firefighters, it is important that all firefighters know the signs and symptoms of a heart attack. Furthermore, it is imperative that you act quickly and decisively if a heart attack is suspected. An unnecessary delay in seeking treatment may mean the difference between life and death.

COMMON SIGNS AND SYMPTOMS OF A HEART ATTACK

Some heart attacks are sudden and intense but most heart attacks start slowly with mild pain or discomfort. Often affected people aren't sure what's wrong and wait too long before getting help. Here are signs that can mean a heart attack is happening:

- **Chest discomfort**. Most heart attacks involve discomfort in the center of the chest that lasts more than a few minutes or that goes away and comes back. It can feel like uncomfortable pressure, squeezing, fullness, or pain.
- **Discomfort in other areas.** Symptoms can include pain or discomfort in one or both arms, the back, neck, jaw, or stomach.
- **Shortness of breath.** With or without chest discomfort.
- **Nausea or lightheadedness**, anxiety, nervousness, or cold sweaty skin.
- **Paleness or pallor, feeling of impending doom, or "something is wrong".**

If you think you or a fellow firefighter is having a heart attack, call 9-1-1 or your emergency medical system immediately!

Modified from American Heart Association:
http://www.americanheart.org/presenter.jhtml?identifier=4595

Part Three: Decreasing Cardiovascular Events

Physical Fitness

Firefighting is strenuous physical work and places considerable strain on the body. In order to meet the unique physical demands of firefighting, and to perform firefighting in a safe manner, firefighters must be physically fit. Like soldiers and elite athletes, firefighters should be physically prepared to meet the unique physical challenges they face.

Health-related physical fitness includes cardiorespiratory fitness (aerobic capacity), body composition (appropriate percent body fat and percent muscle), and muscular fitness. Each of these components is critically important to firefighters being able to perform safely and effectively during emergency operations. In addition to health-related fitness, there are work-specific fitness components that have the ability to improve a firefighter's performance on the scene, including muscular power, balance, and agility.

Cardiorespiratory endurance refers to the body's ability to take in oxygen through the respiratory system, transport it through the blood stream, and use it in the cells to produce energy. Therefore, cardiorespiratory capacity is a functional measure of the body's ability to perform work. The greater the aerobic capacity, the more work an individual can perform. But, cardiorespiratory fitness is not only a performance measure, it is also an indicator of the health of the cardiovascular system. An individual with a low aerobic fitness level has higher cardiovascular disease risk.

Body composition refers to the percentage of the body that is fat and the percentage that is lean muscle mass. Firefighters benefit from higher-than-average muscle mass because so much of firefighting work requires high force production. On the other hand, excess body fat is detrimental, as it decreases work performance and increases thermal and cardiovascular strain. Furthermore, excess body fat, especially abdominal body fat, is directly linked to an increased risk of cardiovascular events. Unfortunately, a large percentage of the Fire Service is currently overweight.

Indeed, research studies have found that 25 to 40% of firefighters are obese. Losing weight, especially abdominal fat can do a great deal to improve the health of a firefighter. First, as stated previously, losing weight decreases the risk of heart disease and improves performance. Additionally, a reduction in weight is associated with a decrease in blood lipids and a reduction in blood pressure.

Because of the physiological demands of firefighting, it is important to adopt a healthy lifestyle that includes maintaining a high level of muscular strength and cardiovascular (aerobic) fitness. As seen in Figure 39, there are many benefits to a well-designed fitness program that address specific concerns of firefighters:

- improved strength and performance;
- increased plasma volume;
- improved thermoregulation;
- improved cardiovascular risk profile.

A physically fit firefighter will experience less cardiac strain while performing the same amount of work as a less fit firefighter. A fit firefighter will be stronger, lighter, and able to perform more work than a less fit firefighter. This means he or she will be better able to perform his or her duties and will be less likely to suffer a sudden cardiac event.

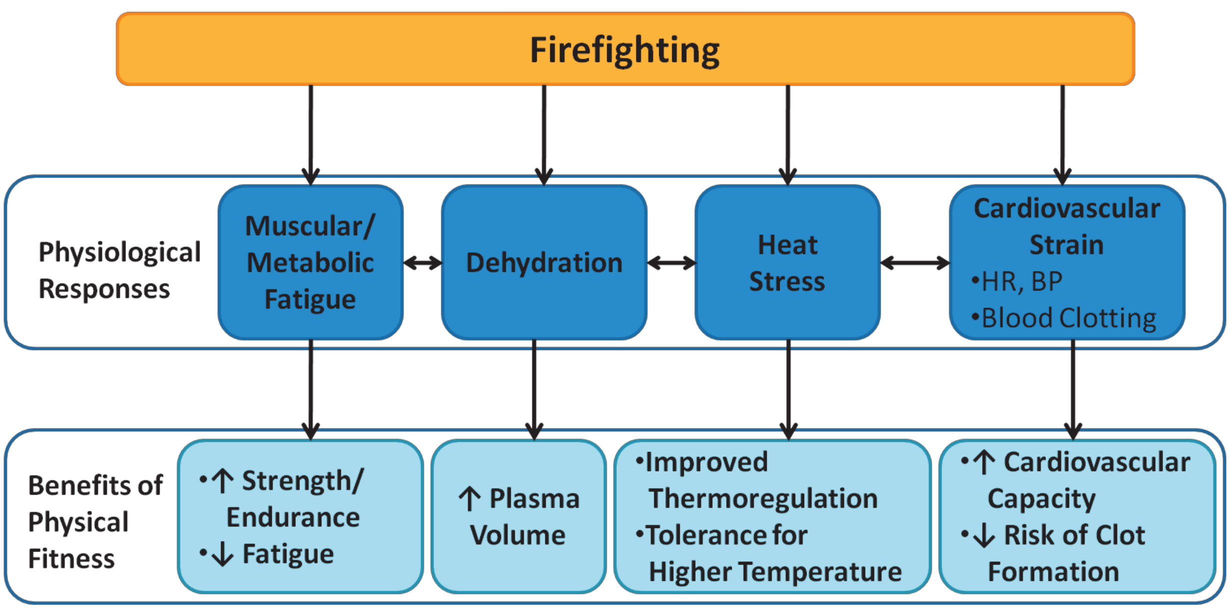


Figure 39: Physiological Responses of Firefighting and the Benefits of Physical Fitness

Part Three: Decreasing Cardiovascular Events

Hastening Physiological Recovery from Firefighting

As seen in Figure 38c, appreciating the magnitude of the cardiovascular strain associated with firefighting activity can serve as a powerful motivator to taking appropriate steps on-scene and following firefighting activity to hasten physiological recovery. Perhaps the most important steps that can be taken are adopting and implementing incident rehabilitation.

Incident Rehabilitation

Incident rehabilitation is an intervention to mitigate the physical, physiological, and emotional stress of firefighting in order to improve performance and decrease the likelihood of injury or death. Firefighting is strenuous work, and firefighters frequently suffer exhaustion, heat stress, and dehydration on the fireground. These stressors can impair performance and may increase the risk of injuries. Firefighting also causes significant cardiovascular strain, and less frequently but even more seriously, firefighting

can trigger a sudden cardiac event in individuals with underlying cardiovascular disease. Incident rehabilitation can also help identify medical problems early and may prevent serious consequences.

According to the National Fire Protection Agency (NFPA) standards for incident rehabilitation (NFPA 1584), the primary goal of rehabilitation is to ensure that the physical and mental condition of members operating at the scene of an emergency or a training exercise do not deteriorate to a point that affects the safety of each member or that jeopardizes the safety and integrity of the operation.

The NFPA standard identifies specific purposes of incident rehabilitation, including:

- provide medical monitoring and treatment;
- establish standards for food and fluid replacement;
- provide relief from climatic conditions;
- provide for rest and recovery;
- provide for member accountability.

These goals address the cardiovascular strain of firefighting and are an important component of an overall strategy to improve firefighter performance and decrease cardiovascular injuries and fatalities.

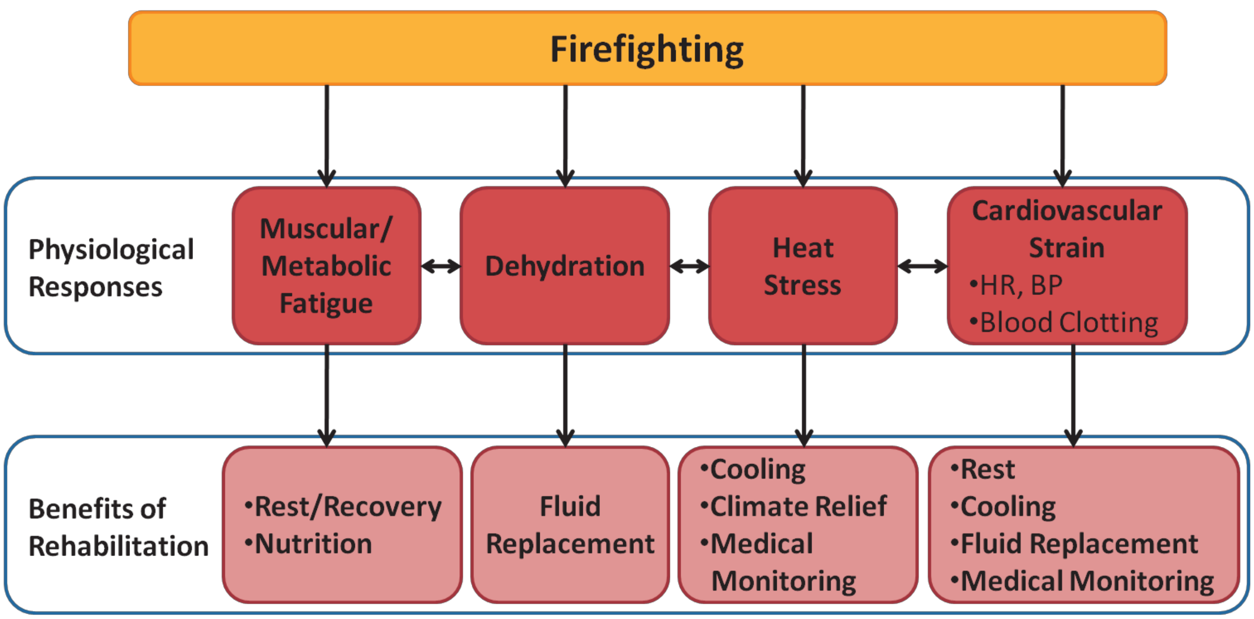


Figure 40: Benefits of Rehabilitation in Mitigating Physiological Strain of Firefighting

Glossary of Terms

Aerobically trained- in Study 1, subjects who participated in at least 3 days of planned aerobic activity each week that lasted a minimum of 30 minutes were considered aerobically trained.

Adrenocorticotrophic hormone- stimulates the synthesis of epinephrine precursors.

Arrhythmia- abnormal heart rhythm (slow, fast, irregular, early).

Arterial stiffness- reduced elasticity of arterial walls; associated with increased risk of cardiovascular disease.

Autonomic nervous system- portion of nervous system responsible for involuntary bodily functions such as heart rate, digestion, and perspiration.

Buckberg Index- also call subendocardial viability ratio (SEVR). It is the ratio of the area of the diastolic phase to the systolic phase of a heart beat; closely correlated with blood supply to the subendocardium.

Calls- in Study 1, a call that was recorded by a firefighter.

Cardiac output- the volume of blood a heart pumps in one minute.

Cardiac ultrasound- also known as echocardiogram; creates two-dimensional images of the heart, can also assess the velocity of blood flow and heart muscle contraction.

Complete blood count (CBC)- a full analysis of the particles contained in a subject's blood including red blood cells, white blood cells, and platelet count.

Cortisol- a steroid hormone released in response to stress; suppresses immune system function and aids in digestion.

Cross-fit- in Study 1**,** participants who are both aerobically and strength-trained.

Dehydration- loss of body fluid.

Dual energy x-ray absorptiometry- a technique that measures total body composition and bone mineral density via x-ray analysis.

Ejection fraction- the difference between the end-diastolic volume (volume of blood remaining in a heart right before a beat) and end-systolic volume (volume of blood remaining in a heart following a beat).

Endothelial function- associated with blood vessels' abilities to constrict or dilate; early indicator of cardiovascular disease and atherosclerosis.

Epinephrine- also known as adrenaline; initiates the fight-or-flight response.

Fraction shortening- measurement of left ventricle performance based on a ratio of the diameter of the left ventricle when contracted vs. relaxed.

Heart attack- also known as myocardial infarction; occurs when blood vessels become blocked preventing the blood supply from reaching the heart.

Heart rate variability (HRV)- a measurement technique that records the time interval between heart beats or interbeat intervals (IBI); reduced HRV is a predictor of cardiovascular death.

Glossary of Terms

Hemoconcentration- an increase in the concentration of red blood cells as a result of a decrease in plasma volume or increased red blood cells.

High frequency (HF)- a frequency domain measure of heart rate variability; an indicator of parasympathetic nerve control.

Hyperthermia- elevated body temperature.

Interventricular septal thickness- thickness of the wall separating the right and left ventricles.

Left ventricular internal diameter- diameter of the left ventricle.

Left ventricular posterial wall thickness- thickness of the posterior wall of the left ventricle.

Leukocytosis- an increase in the concentration of white blood cells.

Low frequency (LF)- a frequency domain measure of heart rate variability; an indicator of both sympathetic and parasympathetic nervous activity.

Low-fit- in Study 1, participants that did not meet the criteria for aerobic, strength, or cross-fit categories.

Mean arterial pressure- the average pressure within an artery over a complete cycle of a heart beat.

Metabolic strain- increased levels of oxygen cost (energy use).

Modifiable risk factors- risk factors for chronic heart disease that can be managed by an individual; modifiable risk factors include hypertension, elevated blood cholesterol, smoking, insufficient physical activity, poor nutrition, and obesity.

Norepinephrine- also known as noradrenaline; assists in the fight-or-flight response.

Observations- in Study 1, the number of firefighters that responded to a call.

Physiological Status Monitor (PSM)- a fully integrated system that measures heart rate, respiration rate, and activity (QinetiQ North America); in the Field Study, the system was embedded in a T-shirt.

Plasma volume- the total volume of plasma in the body.

pNN50- a time domain measure of heart rate variability; the fraction of consecutive NN (normal beats) intervals that differ by more than 50 ms divided by the total number of NNs. Expressed as a percentage.

Pulse wave analysis- measure of arterial stiffness; evaluates the shape and amplitude of the aortic pulse wave.

Pulse wave velocity- measure of arterial stiffness; stiffer arteries will increase pulse wave velocity.

Rate pressure product- measure of oxygen demand of the heart; heart rate multiplied by systolic blood pressure.

Reactive hyperemia- an increase in blood flow following a temporary occlusion.

Strength-trained- in Study 1, subjects who participated in at least 3 days of planned weight lifting workouts each week for the last 3 months.

Stroke volume (SV)- the volume of blood the heart pumps each beat.

Sudden cardiac event- an unexpected cardiovascular event (stroke, heart attack, heart arrhythmia) that occurs suddenly in a person with or without diagnosed cardiovascular disease. These events may or may not result in death.

Thermal strain- a response to exercise indicated by increased skin and core temperatures and profuse sweating.

Total peripheral resistance- overall resistance to blood flow through the entire vascular system.

Venous occlusive plethysmography- measures changes in volume to determine circulatory capacity.

Vulnerable individuals- those at risk for cardiac events.

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Notes

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