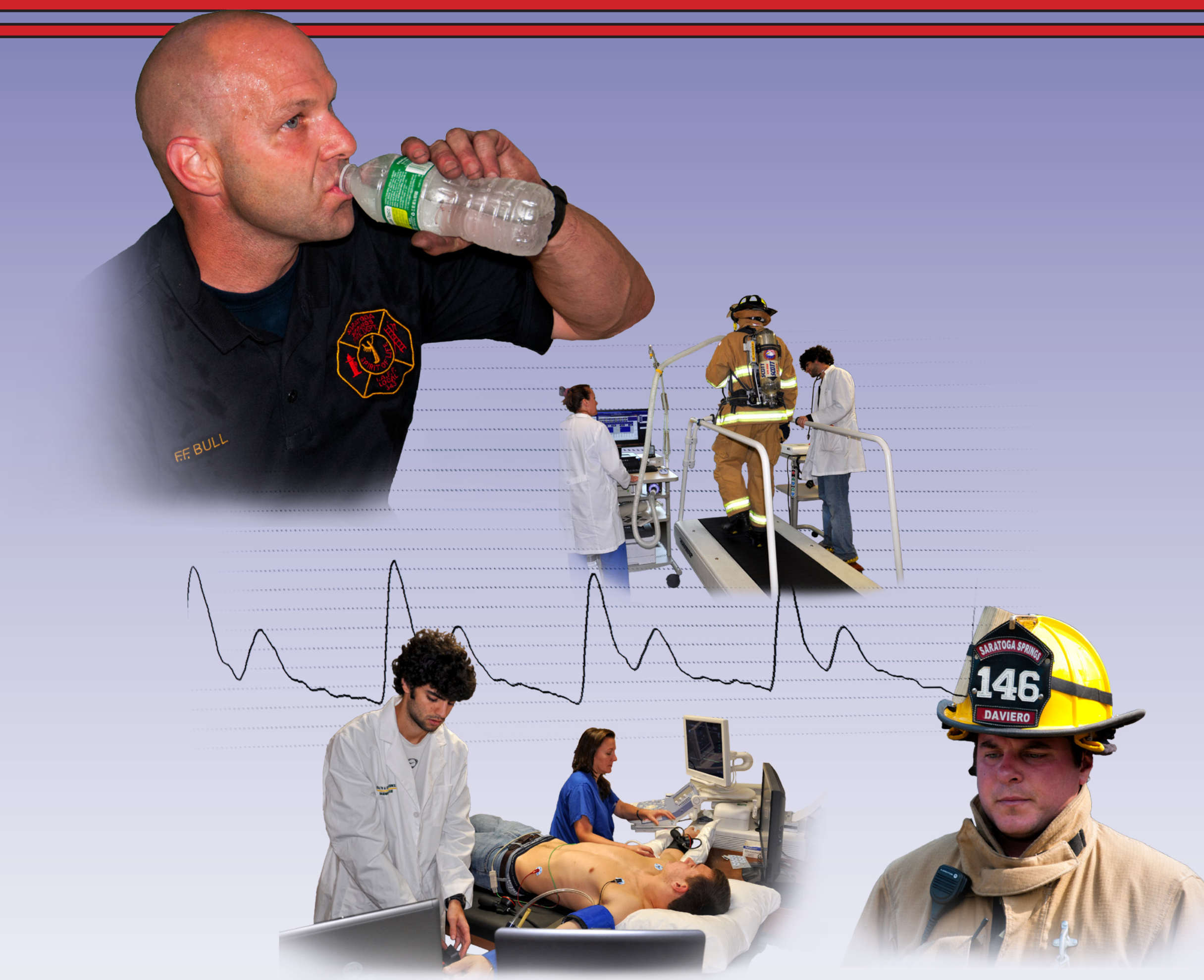
Effect of Heat Stress and Dehydration on Cardiovascular Function



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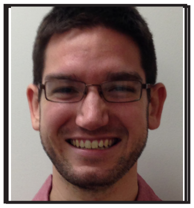

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FP&S grants support projects that enhance the safety of the public and firefighters from fire and related hazards. In the Fiscal year 2005, the U.S. Congress reauthorized funding for FP&S and expanded the eligible uses of funds to include Fire Safety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

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Executive Summary

Firefighters are exposed to numerous life-threatening dangers, including high temperatures, flames, smoke, hazardous chemicals, and unstable structures. Despite these dangers, the physiological strain, specifically cardiovascular strain, associated with firefighting poses the greatest threat to the life and health of a firefighter. The cardiovascular strain associated with firefighting is a major safety concern because it can lead to sudden cardiac events in vulnerable individuals with underlying disease, and because it leads to fatigue and impaired performance in all firefighters.

In order to better understand factors that contribute to cardiovascular strain, we designed a study to investigate the twin challenges of heat stress and dehydration that firefighters face every time they don their gear and answer a call. Heat stress is a universal and well-recognized concern in firefighting. Dehydration has important implications for firefighters because it affects both performance and cardiovascular activity, and it often develops undetected by the firefighter. The purpose of the current research project was to describe, in controlled laboratory conditions, the independent and combined effects of heat stress and dehydration on cardiovascular strain while working/exercising in firefighting PPE.

We had 12 healthy men undergo cardiovascular exercise and testing in 4 conditions: (1) euhydrated-no heat stress; (2) euhydrated-heat stress; (3) dehydrated-no heat stress; and (4) dehydrated-heat stress. Subjects performed a 100-minute intermittent (20 minutes exercise/ 20 minutes rest) treadmill walking protocol. Throughout the intermittent exercise protocol we measured heart rate (HR), blood pressure, and core temperature. Before and after the entire exercise protocol, we performed sophisticated measures of cardiac and vascular function.

We found that HR and core temperature were significantly higher during exercise in the 2 heat stress conditions. Furthermore, both HR and core temperature were significantly higher when dehydration was added to heat stress. There were no negative effects on systolic or diastolic cardiac function at 15 minutes post the exercise challenge in any experimental condition. There were, however, significant increases in the myocardial work demands (~35%) during both heat stress conditions accompanied by significant decreases (25%) in estimates of perfusion to the heart during the heat stress conditions. These results indicate an imbalance in cardiac oxygen demand versus delivery during work in heat stress conditions. Additionally, vascular stiffness increased during the heat stress conditions compared to the no heat stress conditions.

Executive Summary

In conclusion, heat stress (created by wearing PPE and performing work) increases cardiac and thermal strain during work, and this strain is further increased by dehydration. The heat stress conditions caused significant increases in myocardial work and a decrease in markers of perfusion, which may be indicative of ischemia. Furthermore, increased vascular stiffness may contribute to increased cardiac strain. In light of these findings, firefighters should aggressively combat their familiar enemy on the fireground—heat stress. Although firefighters are familiar with heat stress, it has severe consequences. Additionally, while dehydration may not be readily apparent, it nonetheless compounds the problems associated with heat stress, and should be avoided. The detrimental effects of heat stress and dehydration can be mitigated, in part, by proper medical screening; adherence to a physical fitness program; monitoring hydration status; and implementing incident scene rehabilitation.

Chapter One: The Twin Challenges of Heat Stress & Dehydration

Introduction

Firefighting is widely recognized as a dangerous occupation. Firefighters are exposed to numerous life-threatening dangers, including high temperatures, flames, smoke that contains toxic gases and particulates, hazardous chemicals, and unstable structures. Despite these dangers, the physiological strain, specifically the cardiovascular strain, associated with firefighting poses the greatest threat to the life and health of a firefighter. The National Fire Protection Association consistently reports that the leading cause of line-of-duty death (LODD) among firefighters is sudden cardiac death. In fact, even with all of the attention paid to cardiac events, over the past five years, sudden cardiac death has accounted for 42% of LODD (Fahy et al. 2014).

A great deal of work remains to be done to understand the precise mechanisms by which firefighting may lead to a sudden cardiac event. However, it is clear that the combination of physical work, heat stress, and dehydration contributes to high levels of cardiovascular strain (high heart rate, high cardiac output, and enhanced clotting potential), and that cardiovascular strain is likely to play an important role in triggering sudden cardiac events in individuals with underlying cardiovascular disease.

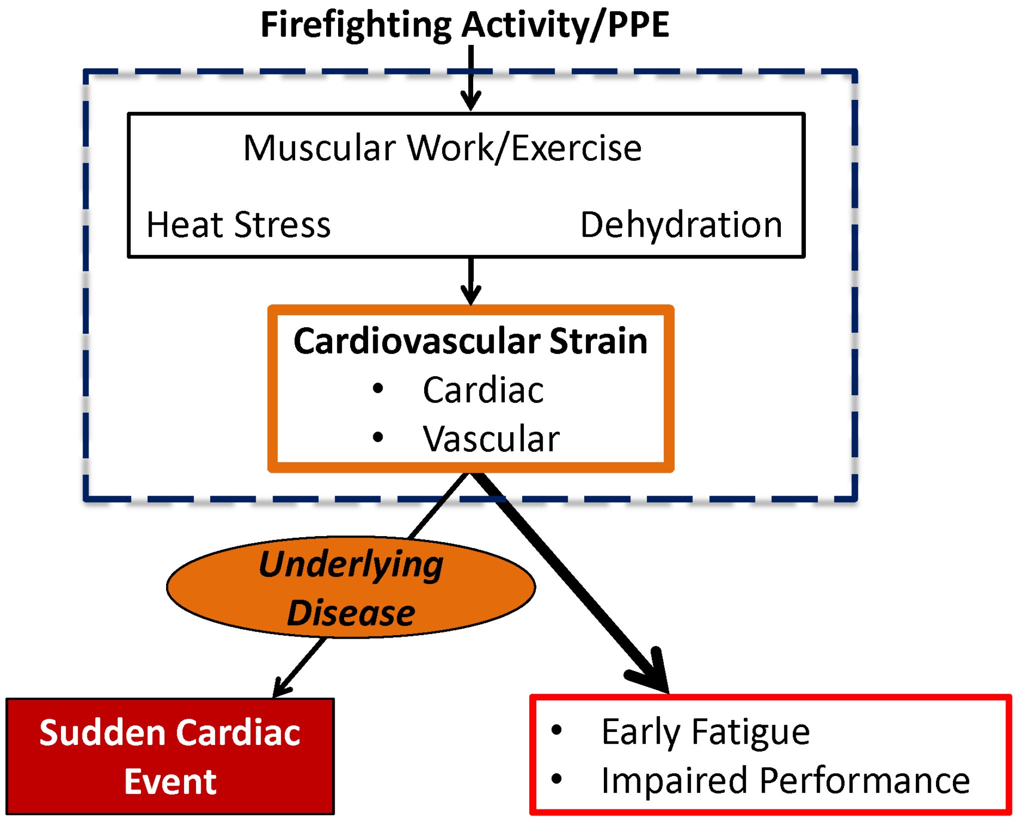

Figure 1: Theoretical model depicting the relationship between firefighting and cardiovascular strain and the relevance to the Fire Service.

Figure 1 illustrates the relationship between factors affecting the cardiovascular strain of firefighting, details their potential to trigger a sudden cardiac event in vulnerable individuals, and indicates that these stressors routinely lead to fatigue and an impaired work capacity.

Figure 1 acknowledges that firefighting involves strenuous work, and that this work is often performed in a hot and hostile environment. Heat stress occurs routinely on the fireground because of the combination of increased muscular work, radiant heat, and impaired heat dissipation induced by personal protective equipment (PPE). High sweat rates caused by heat stress often lead to dehydration. Muscular work, heat stress, and dehydration all contribute to cardiovascular strain. However, relatively little research has been done to document which factors associated with firefighting (heat stress or dehydration) have the greatest effect on cardiovascular function. Cardiovascular strain is critically important to all firefighters because it can lead to the early onset of fatigue and compromise the ability of the firefighter to work at peak function, or even to continue working. Additionally, the cardiovascular strain associated with firefighting is a major safety concern because it can lead to sudden cardiac events in individuals with underlying disease. The remainder of this chapter discusses in greater detail each of the components of the proposed theoretical model.

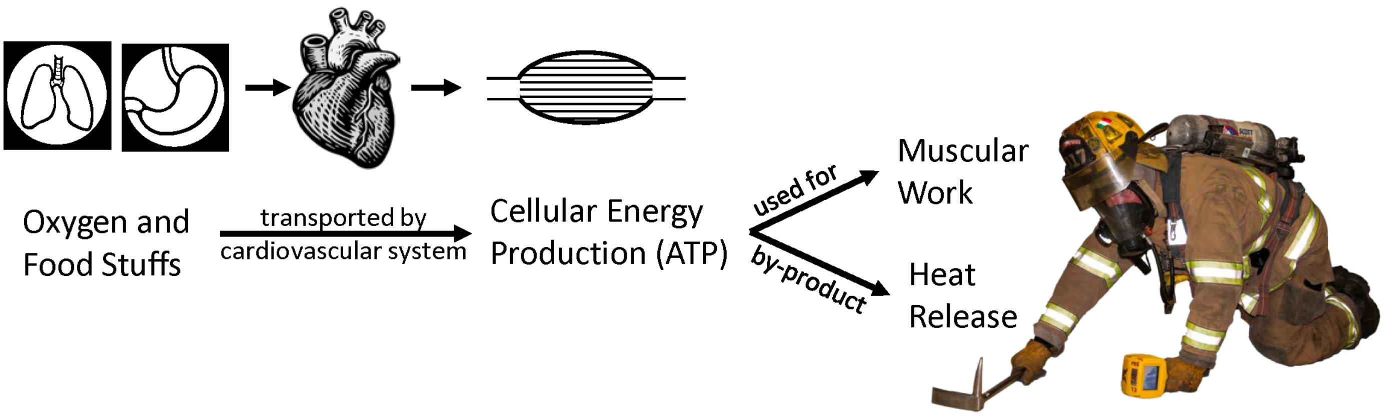

Figure 2: The relationship between energy production and work and heat production.

Physical Work

Relationship Between Muscular Work and Metabolic Heat Production

To perform work, muscle cells must produce energy to power muscle contractions. As illustrated in Figure 2, oxygen is consumed through the respiratory system and transported to muscle cells by the cardiovascular system. As the muscle cells use oxygen and foodstuff to produce cellular energy (ATP) for muscular work, a large amount of heat is released.

Cells need oxygen to produce energy. Hence, during strenuous work (e.g., firefighting), oxygen demand in skeletal muscle increases dramatically. Simply put, the more work that is performed, the greater the oxygen consumed.

Table 1. Cardiovascular and metabolic responses during strenuous firefighting.

Variable	Rest	Firefighting
Heart rate (bpm)	70	192
Stroke volume (mL/beat)	85	130
Cardiac output (L/min)	5.7	25
Oxygen consumption (mL/kg/min)	3.5	45.5

When muscles use energy to perform work, heat is released as a by-product. In fact, during heavy exercise, approximately 70–80% of the energy expended is released as heat, which can result in considerable heat stress. The heat produced is stored in body tissues and will result in an increase in body temperature unless heat loss occurs at a rate equal to heat gain.

To meet the increased demand for oxygen delivery to the muscles during strenuous work, cardiac output is increased and blood flow is directed from inactive organs (such as the gut) to active skeletal muscles. Table 1 shows representative values for heart rate, stroke volume, cardiac output, and oxygen consumption at rest and following strenuous firefighting activity.

The responses described in the paragraph above reflect the impressive ability of the cardiovascular system to respond to work and to increase energy production to support work. These cardiovascular responses also demonstrate that strenuous physical work places considerable strain on the cardiovascular system.

Physical Demands of Firefighting

Firefighters regularly perform strenuous activities such as stair and ladder climbing, forcible entry, victim search and rescue, building ventilation, and fire attack and suppression (Figure 3). This work must often be performed quickly and may be sustained for prolonged periods. Additionally, firefighters must perform work from unusual postural positions that increase energy requirements.

Furthermore, firefighting tasks are performed while wearing PPE, which contributes to increased work in several ways. Firefighting PPE, including self-contained breathing apparatus (SCBA), weighs approximately 50 lbs. Additionally, firefighters carry tools and equipment that may weigh 40 lbs or more. The increased weight that a firefighter must carry adds considerably to the muscular work performed during firefighting. Furthermore, turnout gear consists of multiple layers, which makes the gear bulky. This bulkiness restricts movement and alters gait, which results in a "hobbling" effect that is less efficient than walking and increases the amount of energy required to do work.

Because of the strenuous physical demands of firefighting, firefighters need to possess a high aerobic capacity, a high anaerobic capacity (the ability to do short bouts of intense work), and high levels of muscular strength and endurance. Although different firefighting tasks require different levels of energy expenditure, the consensus is that firefighters should have a maximal aerobic capacity of at least 42 mL/kg/min to safely perform the essential tasks of firefighting (NFPA 2013).

Figure 3: Firefighting is physically demanding.

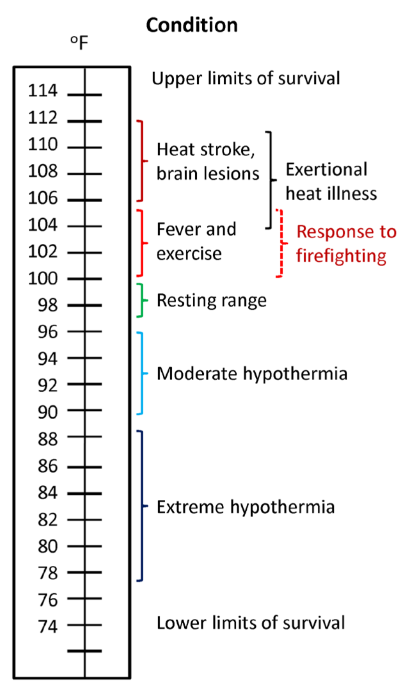

Figure 4: Human thermoregulation. Adapted from Plowman and Smith 2014.

Heat Stress

Thermoregulation

Thermoregulation is the process by which the body maintains its temperature. Normally, the body regulates its internal body temperature within a narrow range close to 98.6°F, despite wide variations in environmental temperatures. It is important to maintain temperature within approximately 1.5°F of 98.6°F because greater changes in body temperature can lead to severe dysfunction, even death (Figure 4).

Although the body seeks to maintain a relatively stable internal temperature, the equilibrium between heat gain and heat loss is constantly changing (Figure 5). Heat can be gained from the environment (when the air temperature is higher than the body temperature); however, heat produced by the body as a result of metabolism and muscular work is the primary source of heat gain. Heat is dissipated from the body through four processes:

- Radiation - transfer between objects without contact;
- Conduction - transfer through direct physical contact with an object;
- Convection - exchange with surrounding air; and
- Evaporation - conversion of sweat to vapor.

During rest, body temperature is easily maintained within a narrow range as heat loss and heat gain are balanced (Figure 5A). During exercise, muscular activity results in the generation of heat, but the increase in heat production is largely offset (only a small temperature increase) by a large increase in heat loss through evaporative cooling (Figure 5B). Thus, body temperature only increases slightly during exercise in moderate environments. In extreme conditions, such as those encountered during firefighting, muscular activity generates a high heat load and the clothing properties of PPE

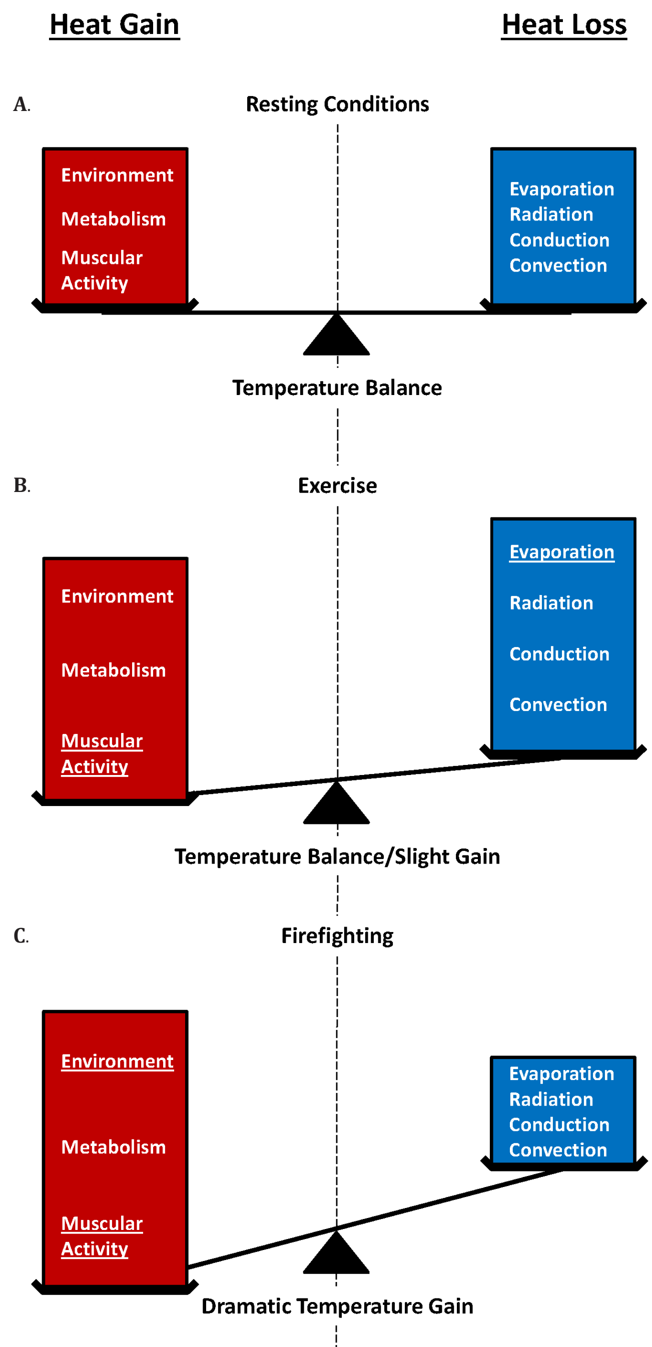

Figure 5: Temperature balance at rest, during exercise, and during firefighting.

severely restrict heat loss; therefore, thermal equilibrium is disrupted and body temperature increases more dramatically (Figure 5C).

The magnitude of heat gain or loss through radiation, conduction, convection, and evaporation depends on the following environmental conditions:

- Ambient temperature (temperature difference between objects affect radiation; heat moves from the hotter to the cooler object);
- Relative humidity (high humidity reduces evaporation); and
- Wind speed (low wind speed decreases convection).

Figure 6A shows typical values for heat exchange mechanisms during exercise. In hot conditions, evaporation contributes to the greatest heat loss (55%). During exercise, heat is lost from the body through radiation because body temperature is lower than the air temperature.

Heat exchange is dramatically influenced by clothing. Thick, multilayered clothing with a low permeability, such as firefighting turnout gear, can severely limit heat loss. Figure 6B details the process of heat exchange during firefighting and shows how PPE influences heat exchange mechanisms. In contrast to exercise, environmental heat contributes significantly to heat load on the body. Furthermore, heat loss through evaporation, convection, conduction, and radiation is dramatically decreased. Although a firefighter may sweat profusely, the sweat does not evaporate effectively because PPE essentially creates a microenvironment in the air layer between the skin and PPE that has 100% humidity. Although PPE contains a vapor barrier, the air layer between the skin and PPE has little air movement and heat loss via convection is limited.

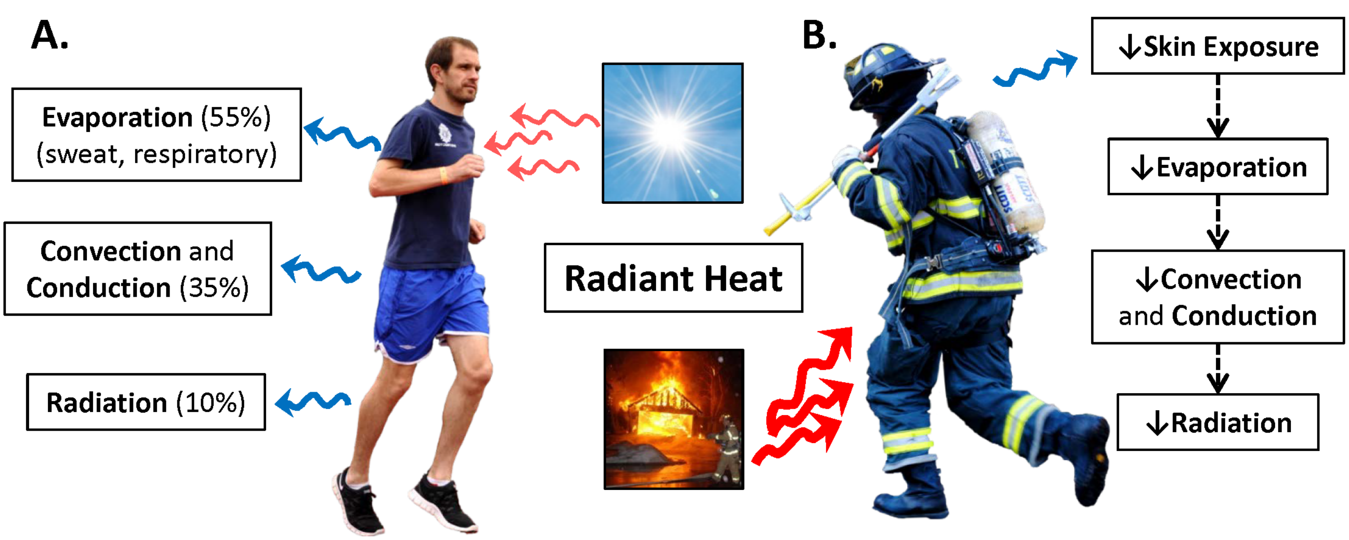

Figure 6: Heat loss and heat gain during exercise (A) versus firefighting work in PPE (B). Adapted from Plowman and Smith 2014.

Red = heat gain
Blue = heat loss

Heat Stress/Heat Strain

Heat stress refers to the overall heat load placed on an individual as a result of the combined effects of metabolic heat, environmental conditions, and clothing requirements. Heat strain results from the body's response to heat stress. The physiological mechanisms that dissipate heat are sweating and increased blood flow to the skin. Increased sweat rate enhances the potential for heat loss due to evaporative cooling. During work in warm environments, evaporative cooling is the primary mechanism by which the body cools itself, as long as humidity is low enough to allow for the evaporation of sweat. Additionally, heat produced in the muscles is transported by the blood, and vasodilation of the cutaneous skin vessels allows warm blood to be brought near to the body's surface where heat can be transferred to the environment through radiation, conduction, and convection.

When the body is in thermal balance, heat gain equals heat loss and body temperature remains constant. However, when heat gain (produced from muscular work and absorbed from the environment) exceeds heat loss, body temperature increases. Uncompensable heat stress is a condition in which the evaporative cooling requirements of the body are greater than the cooling capacity of the environment. In such situations, core temperature increases considerably. An increase in core temperature is a concern because it hastens fatigue, may lead to heat illnesses, and exacerbates cardiovascular strain. Heat illness includes a spectrum of disorders ranging from heat rash to life-threatening heat stroke.

Heat stress is a serious concern for firefighters because it can seriously compromise cardiovascular function in multiple ways:

- Sweating leads to a decrease in plasma volume, which increases blood viscosity, and decreases stroke volume and potentially cardiac output;
- Vasodilation in cutaneous vessels decreases venous return, leading to a decrease in stroke volume and potentially cardiac output; and
- Widespread vasodilation challenges the ability of the body to maintain blood pressure and perfuse the vital organs, such as the brain, kidneys, and liver.

Heat Stress With Firefighting

Heat stress is perhaps the most recognizable form of physiological stress during firefighting (Figure 7). Because firefighters perform strenuous work in hot environments while wearing PPE, it is not surprising that heat stress is a common concern among firefighters.

Figure 7: Firefighting results in heat stress.

Firefighting leads to heat stress because of:

- High levels of muscular work that produce heat as a by-product;
- High environmental temperatures due to fire or exposure to high ambient temperatures and direct sun exposure (especially during summer months in hot climates); and
- Heavy and encapsulating PPE.

Many workers encounter heat stress (e.g., miners, steel plant workers), but no other occupational group is routinely exposed to the extreme environmental conditions that firefighters encounter. Furthermore, the environmental conditions experienced by firefighters may change dramatically. These environmental conditions are a major factor in heat stress. Firefighters are routinely subject to high levels of radiant heat from fires (Figure 8). The effects of radiant heat and the length of time the human body can withstand such conditions depends on the heat source and the duration of exposure. While PPE provides protection against extreme environmental conditions, the turnout gear absorbs heat during exposure and this heat energy will be transferred to the firefighter.

Figure 8: Firefighters face multiple hazards, including high radiant heat levels.

Because of its weight and insulative properties, PPE can contribute significantly to heat stress even when work is performed in moderate environments. The PPE provides a great deal of protection from the environmental heat load, but it also imposes a physiological burden. The weight of the PPE (approximately 50 lbs including SCBA) greatly increases metabolic heat production during physical work. Furthermore, multiple layers of turnout gear result in high insulative properties that severely limit heat dissipation. Essentially, the PPE that is designed to limit heat from passing from the environment to the firefighter also works to keep the heat generated by the firefighter from being dissipated to the environment. Moreover, during exposure to environmental heat, the turnout gear absorbs heat which is subsequently transferred down the thermal gradient to the firefighter.

Heat stress is a major concern for firefighters because it:

- Causes diminished work capacity and fatigue;
- Results in impaired cognitive function;
- May progress to life-threatening heat stroke; and
- Exacerbates cardiovascular strain.

Given the concern about heat stress among firefighters, it is surprising that there have been relatively few research studies that have measured core temperature during firefighting activities. This dearth of research can be explained, in part, because it is difficult to accurately measure core temperature. Oral temperature measurements are often misleading because they tend to underestimate core temperature, and temperature in the oral cavity is affected by heavy breathing and fluid ingestion. Tympanic thermometers are convenient (and are often used), but they are not accurate or reliable in conditions in which temperature is changing (such as during exercise or firefighting), and they can be heavily influenced by environmental conditions (Casa and Armstrong 2003).

In order to accurately measure core temperature during firefighting activities, firefighters ingest a vitamin-sized radio telemetry pill that measures temperature in the gastrointestinal tract. The pill must be taken several hours before the research so that the temperature of the pill is not affected by fluid ingestion.

Several studies have reported an increase in core temperature of approximately 1.3°F (0.7°C) after short bouts of live-fire drills (Smith et al. 2011; Horn et al. 2011; Colburn et al. 2011; Burgess et al. 2012). It is important to note that these studies required firefighters to engage in firefighting activities for 20 minutes or less. In actual emergencies, firefighters would continue to work in PPE during overhaul and clean-up activities and core temperature would likely continue to rise. A recent study investigated core temperature responses during repeated evolutions, as typically occurs in training, that may be more representative of a prolonged operation (Figure 9). Importantly, core temperature rose more quickly and reached higher levels (>102°F) following repeated bouts of firefighting activity (Horn et al. 2013).

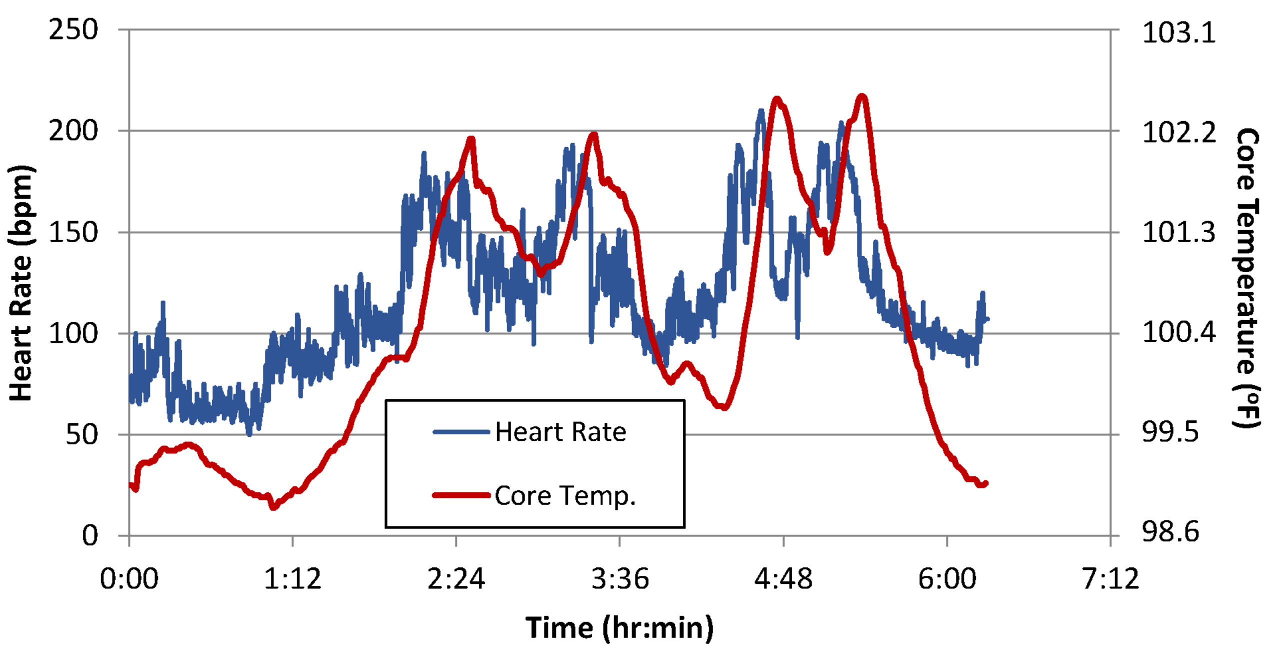

Figure 9: Heart rate and core temperature during repeated bouts of firefighting activity.

Dehydration

Body Fluid Balance

It is remarkable that approximately 60% of the human body is comprised of water, representing about 88 lbs (or 40 L) for a man weighing 154 lbs (Figure 10). Body water is distributed between intracellular fluid (fluid within cells) and extracellular fluid (fluid surrounding the cells).

Intracellular fluid represents about 62.5% of the total fluid in the human body. Extracellular fluid, ~37.5% of total body water, surrounds the cells (as interstitial fluid) or is circulated in the blood vessels as blood plasma. Water constantly moves among these fluid compartments to ensure that cells are properly hydrated. The balance of body water is vitally important for biological function. Loss of intracellular fluid (cellular dehydration) is detrimental to cell function. Decreased plasma volume negatively affects cardiac function. Because water is constantly lost from the body as a result of urine production, breathing, and sweating, it is critical that humans replace fluid loss by eating and drinking.

The amount of water intake required to maintain fluid balance varies widely from person to person and is highly influenced by physical activity/work. Figure 11A shows typical daily fluid intake and output (2500 mL) in sedentary adults. However, if an individual engages in strenuous exercise or work and sweats profusely, sweat output may increase 10-fold. Under such conditions, if fluid intake is not increased sufficiently, a fluid imbalance will occur. A state

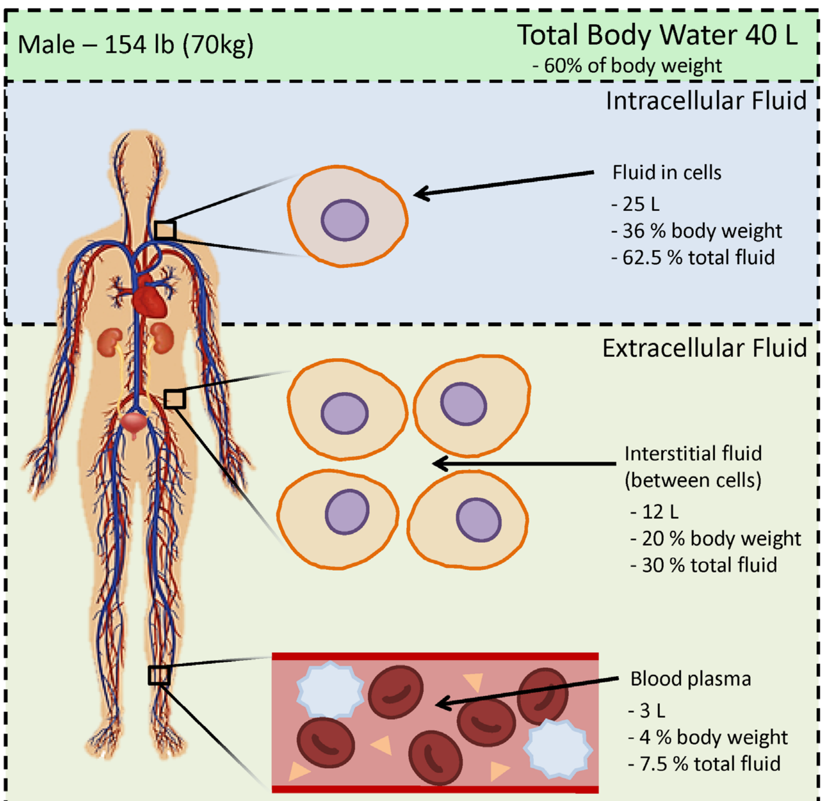

Figure 10: Body water distribution in a representative man.

of mild dehydration results when fluid intake is insufficient to compensate for fluid loss (Figure 11B). Dehydration can develop when fluid intake is severely restricted or when fluid loss is excessive, as in the case of diarrhea or excessive sweating (Figure 11C).

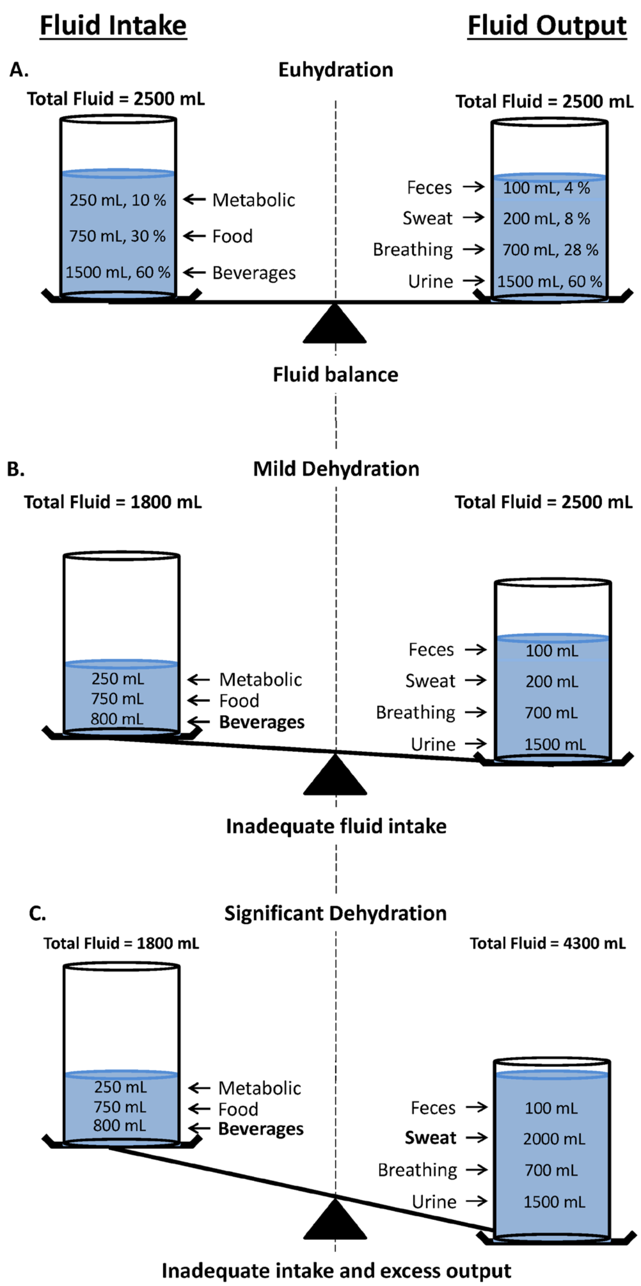

Figure 11: Fluid balance at rest, with slight dehydration, and with significant dehydration.

The evaporation of sweat is a major mechanism by which humans thermoregulate. Sweat rate varies among people, is influenced by fitness level, and is dramatically affected by work intensity and environmental conditions.

During moderate-to-hard intensity exercise or work in a hot and humid environment, as is routinely encountered during firefighting, humans can lose between 1–2 liters (1 L = 1.06 quarts) of sweat per hour (Figure 12). High sweat rates during prolonged operations can lead to severe dehydration.

A high sweat rate is often considered a positive adaptation—for instance, well-trained athletes have very high sweat rates. Because sweat evaporation cools the body, athletes can work at high exercise intensities without overheating. However, because firefighters wear heavy, impermeable gear that does not permit sweat to evaporate, the effectiveness of cooling is greatly diminished.

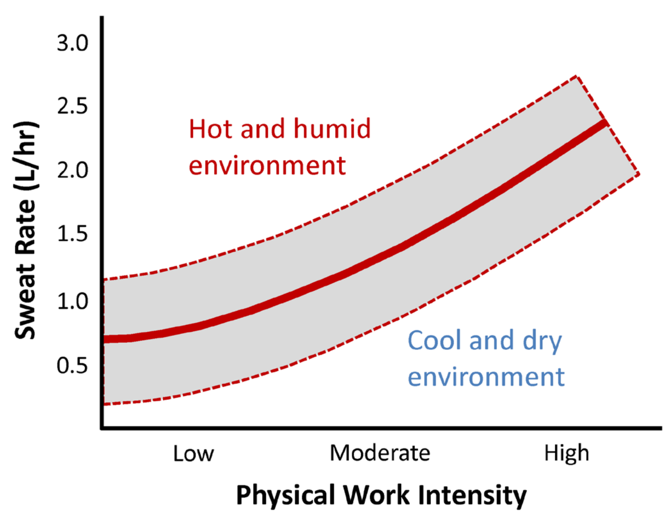

Figure 12: Relationship between sweat rate and intensity of physical work in different environmental conditions. Adapted from Plowman and Smith 2014.

Dehydration in the Fire Service

Dehydration is not as obvious a challenge as heat stress. But dehydration is a significant concern for firefighters. Importantly, dehydration often develops before firefighting begins, and it becomes worse because of sweat loss during firefighting.

Dehydration has important implications for firefighters because it affects both performance and cardiovascular activity. Dehydration is associated with:

- Reduced maximal aerobic power (Sawka and Coyle 1999), reduced muscular endurance (Bosco et al. 1974), reduced physical work capacity (Craig and Cummings 1966), and decreased attention and vigilance (Hancock and Vasmatzidis 2003);
- Increased perception of difficulty of exertion (Montain and Coyle 1992);
- Decreased plasma volume (Smith et al. 2001a), and decreased stroke volume (Smith et al. 2001b; Fernhall et al. 2012); and
- Increased heart rate and cardiac work, and decreased blood pressure (particularly post firefighting)(Horn et al. 2011; Fahs et al. 2011).

Several major research reports indicate that a high percentage of firefighters report to work (or training) in a dehydrated state (Horn et al. 2011; Espinoza and Contreras 2007). One study (Horn et al. 2012) reported that prior to the start of training:

- 31% were seriously dehydrated;
- 46% were significantly dehydrated;
- 14% were minimally dehydrated; and
- 9% were well-hydrated.

Starting work in a dehydrated state puts a firefighter at increased risk for heat injuries and increased thermal and cardiovascular strain.

Figure 13: Firefighting activity often results in profuse sweating.

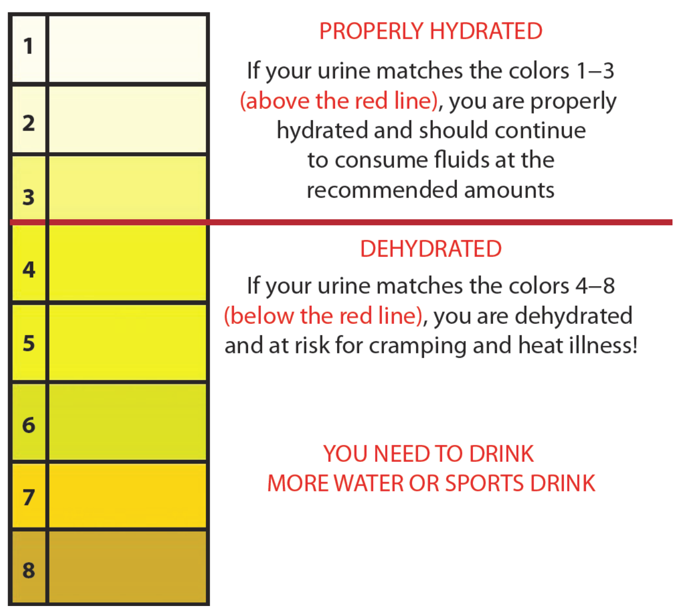

Figure 14: Urine color and hydration status.

Performing strenuous work in a hot environment while wearing PPE leads to profuse sweating as the body attempts to regulate temperature (Figure 13). During firefighting simulations, sweat rates of firefighters have been reported to be greater than 2 liters per hour (Barr et al. 2008; Horn et al. 2011). Even during training activities that include rest/debrief periods and encouragement to drink, fluid ingestion may not match fluid loss during firefighting. For example, one study reported that firefighters lost 1.1% of their body weight (moderate dehydration) during 3 hours of firefighting training despite aggressive rehabilitation efforts (Fernhall et al. 2012).

Although thirst is a driving force for fluid intake, it is an inadequate mechanism to ensure proper hydration. Given the detrimental effects of dehydration and because many firefighters are dehydrated when they begin work, it is important to monitor hydration status. The easiest way to detect dehydration is to use a simple urine chart (Figure 14). These charts can easily be placed in rest rooms to serve as a reminder to firefighters that urine should be a light color and should not have a strong odor. It is wise for firefighters to follow a hydration program that ensures that they are well-hydrated. Monitoring urine color helps ensure proper hydration. The firefighter should also be regularly reminded to consume fluid to ensure the production of a light urine or a urine color that is representative of a well-hydrated state.

In addition to being well-hydrated before beginning a shift or training drills, firefighters need to be vigilant about consuming water (and sports drinks) before and during emergency operations. Fluid ingested should primarily be water or a low-calorie sports replacement beverage. Caffeinated beverages such as coffee, tea, and soda can serve as a diuretic and increase water loss—exacerbating rather than offsetting dehydration. An additional concern is that many drinks, including soda and sweetened tea, contain a lot of sugar which is often associated with excess body weight (another factor that increases heat stress). Overall, firefighters should consume adequate amounts of fluids to replace what is lost on a daily basis during fluid turnover and sweating.

One of the goals of incident rehabilitation is to ensure that firefighters are able to rest and to rehydrate in a quiet place away from emergency operations (Figure 15). It is best to begin rehydration before dehydration becomes severe. Many departments provide firefighters with a bottle of water when their first air bottle is changed. More fluids are then provided during rehabilitation.

Figure 15: Incident rehabilitation provides opportunity for rest and rehydration.

Cardiovascular Strain of Firefighting

Research has consistently reported what firefighters already know—that firefighting is strenuous work that leads to significant cardiovascular strain. Researchers have documented many changes in the cardiovascular system during firefighting, many of which may be mechanistically linked to sudden cardiac events in vulnerable individuals with underlying cardiovascular disease. Furthermore, cardiovascular strain is a concern for all firefighters because it can lead to the early onset of fatigue and may impair the ability of firefighters to continue working. Research studies have demonstrated that firefighting results in considerable cardiovascular strain. Figure 16 summarizes some of the cardiovascular responses to firefighting. This figure shows that the cardiovascular responses to firefighting are the result of multiple factors, including activation of the sympathetic nervous system, performance of muscular work, extreme environmental conditions, and heat stress and dehydration.

A firefighter's response to firefighting is also mediated by individual characteristics, including age and fitness status. Importantly, health status, especially underlying cardiovascular disease, is a critical factor in determining the magnitude of cardiovascular strain during firefighting and whether cardiovascular strain will trigger a cardiac event.

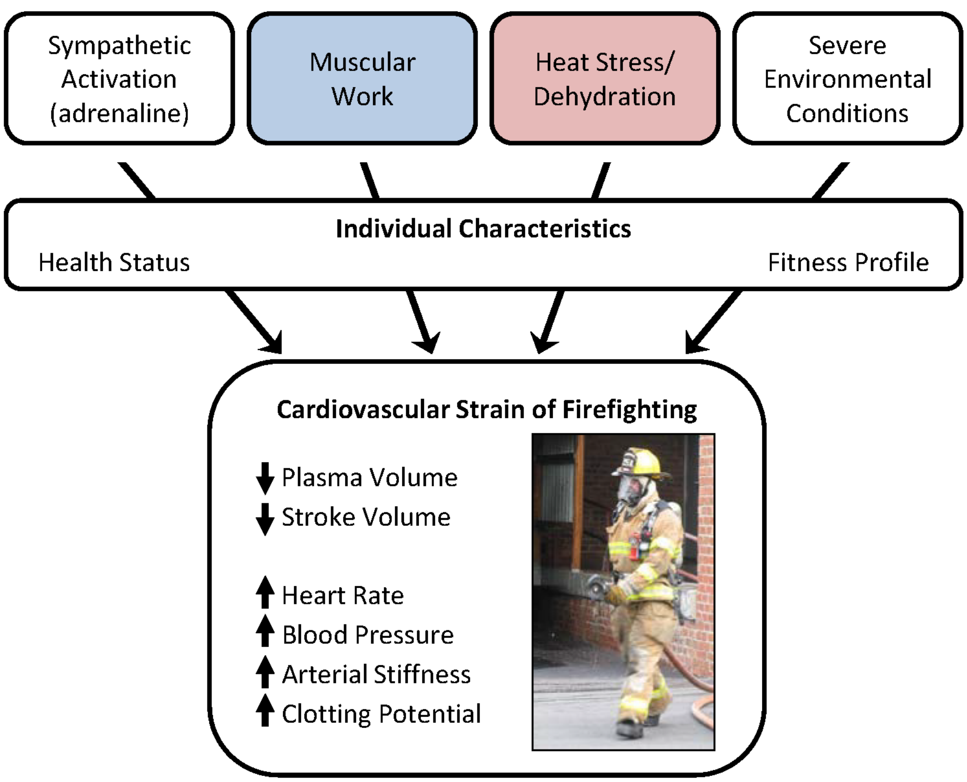

Figure 16: Factors affecting the cardiovascular strain associated with firefighting. Adapted from Smith et al. 2014 in press.

Remaining Research Questions

Numerous field studies have shown that firefighting leads to increased cardiovascular strain, and heat stress and dehydration are recognized as important contributors to cardiovascular strain. Although these field studies provide valuable information, they are not designed to determine the independent effect of heat stress or dehydration on cardiovascular strain. A better understanding of the independent contributions of heat stress and dehydration to firefighter welfare may allow the Fire Service to develop targeted policies to prevent and reduce detrimental changes in cardiovascular function.

As described in the next chapter, we performed a controlled laboratory experiment using conditions that are relevant to firefighting. The study used an intermittent work protocol to model alternating work/rehab cycles during firefighting operations. Exercise intensity was selected to elicit heart rate and core temperature responses similar to those observed during firefighting activity. The study held the type and intensity of work and the amount of weight carried constant, and then manipulated heat stress and dehydration to determine their independent effects on both cardiac strain and vascular function (Figure 17).

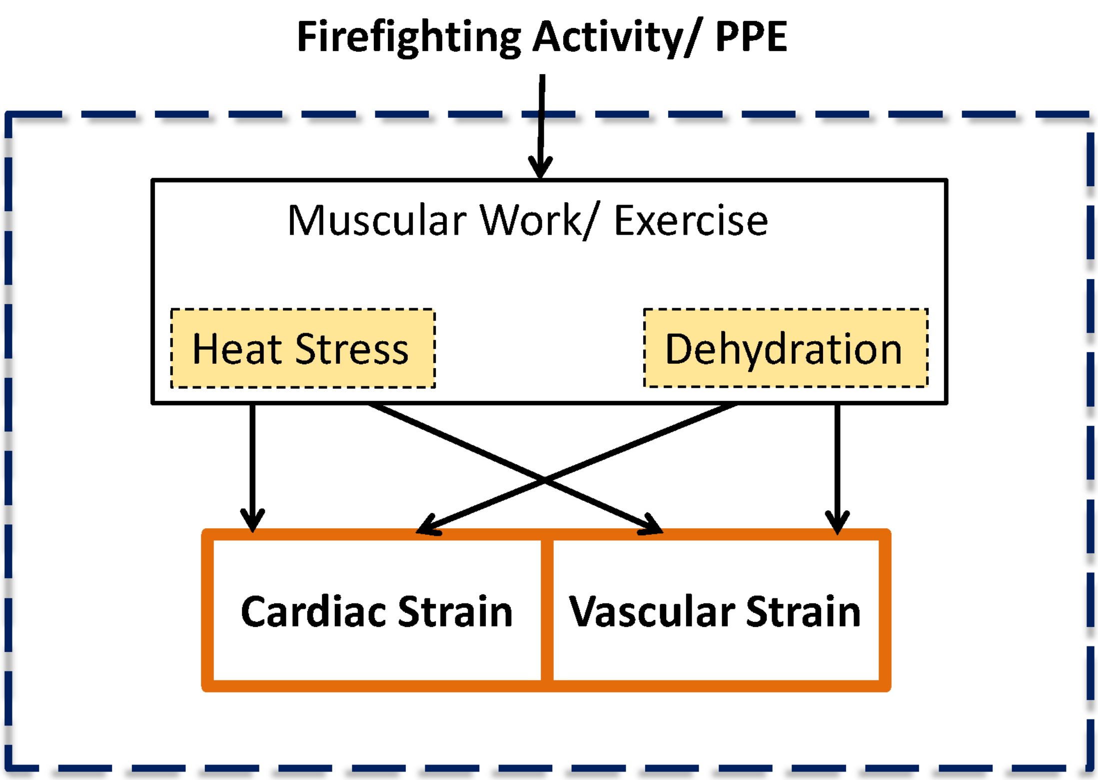

Figure 17: Overview of laboratory study.

Chapter Two: Research Project

Introduction

Heat stress and dehydration are twin challenges that frequently occur on the fireground and are known to collectively exacerbate the cardiovascular strain of firefighting. However, the independent effects of heat stress and dehydration on cardiovascular function during strenuous work in PPE are unknown.

Investigating the effects of heat stress and dehydration on cardiovascular function is important and will allow us to better understand the mechanisms by which heat stress and dehydration lead to fatigue and an increased risk of sudden cardiac events.

Therefore, we designed and conducted a carefully controlled laboratory study that allowed us to investigate the cardiac and vascular responses to a standardized amount of work (on a treadmill while wearing PPE) when heat stress and dehydration were manipulated. Specifically, the goals of this study were to investigate:

1. The independent and combined effects of moderate heat stress and dehydration on heart rate (HR) and core temperature responses during intermittent work in PPE; and
2. The effects of heat stress on sophisticated measures of cardiac and vascular function after intermittent work in PPE.

Methods

Study Design

To complete Goal 1, we measured HR and core temperature during a standardized exercise protocol (Figure 18A). To complete Goal 2, we assessed cardiac and vascular function before and after the exercise protocol (Figure 18B). Each participant completed four experimental trials, each on a different day. Each trial involved the same 100-min intermittent exercise/work protocol but the degree of heat stress and dehydration were varied by clothing and fluid manipulations (Figure 19) to create four experimental conditions:

- Euhydrated-no heat stress (Figure 19A);
- Euhydrated-heat stress (Figure 19B);
- Dehydrated-no heat stress (Figure 19C); and
- Dehydrated-heat stress (Figure 19D).

Exercise Protocol

The amount of work performed during each trial was kept constant to allow us to isolate the effects of heat stress and dehydration. A 100-minute intermittent exercise protocol involving 20 minutes of treadmill walking in PPE or a weighted vest and 20 minutes of rest, for a total of three exercise/work periods, was used to approximate work cycles encountered by firefighters (Figure 18). Participants walked on a treadmill at a 5% grade. Treadmill speed was adjusted so that each participant walked at about 75% of maximal HR during the heat stress trials. For each participant, treadmill speed and grade were constant for all four trials.

While the laboratory study did not include every physical and psychological strain encountered during actual firefighting activities, it allowed highly controlled levels of work to be performed under standardized conditions. This

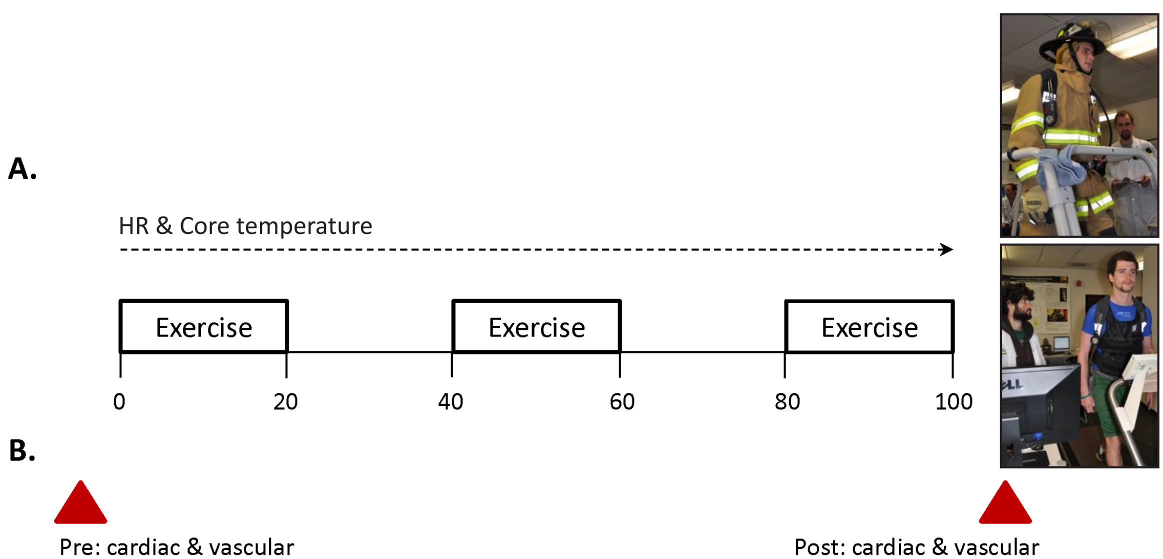

Figure 18: Measurements obtained during the experimental trials.

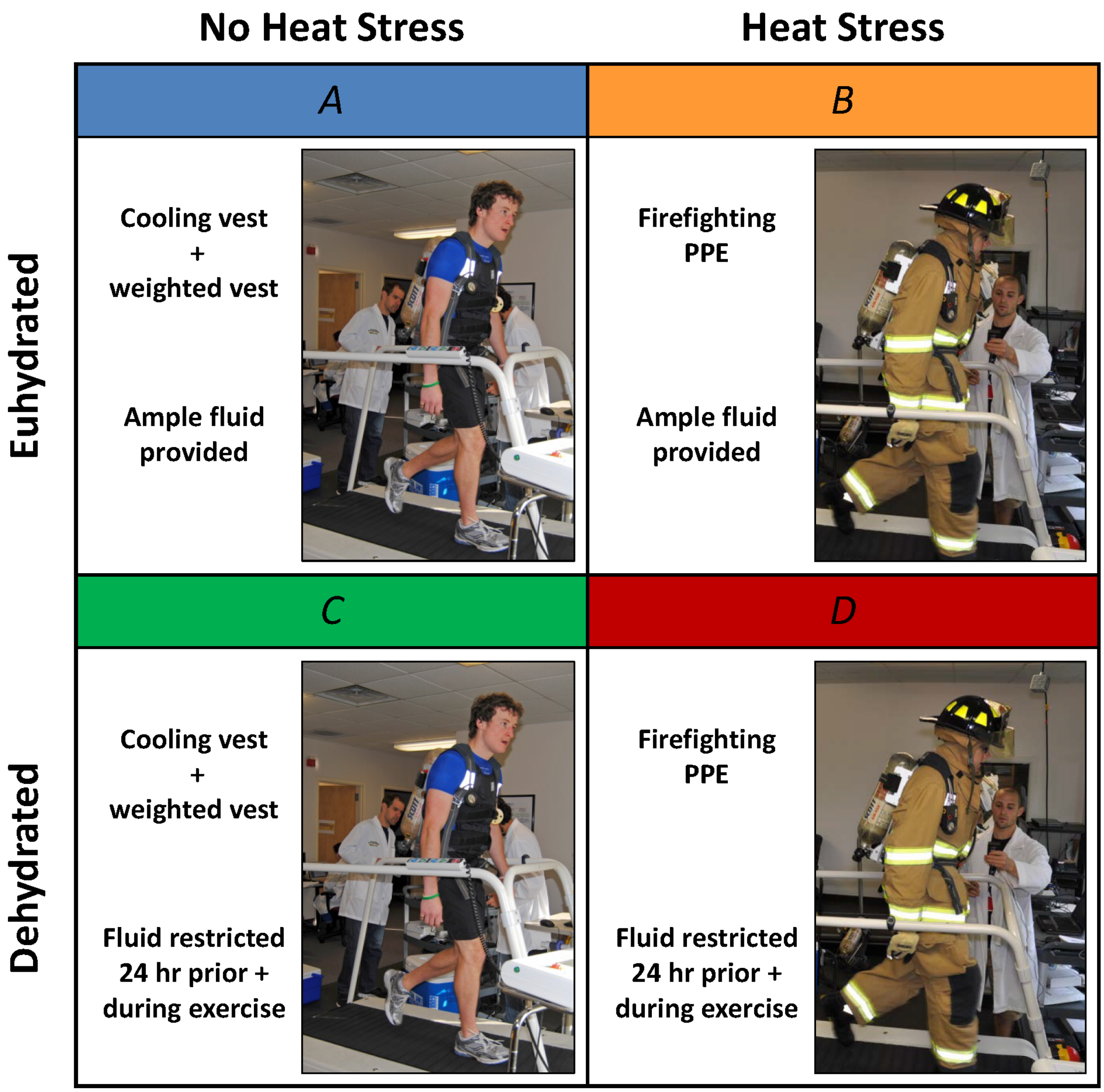

Figure 19: Experimental design and conditions.

level of control allowed us to measure the effects of heat stress and dehydration.

Manipulated Variables

We induced moderate heat stress (core temperature <101.3°F) by having participants wear full PPE. We induced moderate dehydration (3%) by restricting fluid intake 24 hours before testing and limiting water intake during the exercise test. These levels of heat stress and dehydration were selected to correspond with levels reported during firefighting activities.

Heat Stress. To induce heat stress, participants wore structural firefighting PPE while walking on a treadmill (Figure 19B,D). Firefighting PPE consisted of boots, turnout pants and coat, gloves, thermal hood, helmet, and SCBA.

No Heat Stress. To minimize heat stress, participants wore a cooling shirt while walking on a treadmill (Figure 19A,C). The cooling shirt circulated cool water next to the body and was used to limit body temperature increases due to exercise. In this trial, participants also wore a weighted vest. The weighted vest was worn so that the weight carried (and hence the work done) was the same as during the trial in which PPE was worn.

Euhydrated. For the euhydrated trials, participants started the testing fully hydrated and we replaced fluid lost through sweating during the exercise test (Figure 19A,B). Participants were given 2–3 L (30 mL water/kg body weight) to drink 24 hours prior to testing, and water and Gatorade were provided during testing to match fluid loss (as determined by changes in nude body weight during a familiarization trial).

Dehydrated. For the dehydrated trials, participants began in a mildly dehydrated state (1–2% body weight loss) because this level of dehydration has been reported to be common among firefighters (Figure 19C,D). Mild dehydration was induced by restricting participants to 1–1.5 L (15 mL water/kg body weight) during the 24 hours prior to testing. We also provided minimal fluids (about 1 cup [200 mL]) during the testing protocol.

Participants

Twelve healthy, physically active college-aged men participated in this study. We followed all ethical guidelines for human subject testing. The study was approved by the Institutional Review Board of Skidmore College, and participants provided written informed consent prior to testing. Medical evaluations were performed before testing. Individuals who smoked or had known cardiovascular, metabolic, or orthopedic conditions were excluded from the study.

Standardization

Because physiological variables, such as HR and vascular measures, are influenced by several factors, we carefully standardized our study to allow better comparisons among conditions. For each individual, testing was performed at the same time of day, separated by at least 24 hours, and was completed within a 4-week period. Participants did not consume alcoholic beverages or perform strenuous exercise for 24 hours prior to experimental trials. Caffeine was not consumed within 8 hours of testing. All participants consumed a standardized meal (GNC protein bar; 390 kcal, 12g fat, 49g carbohydrates, 30g protein) 30 min before testing.

Measurements

To achieve Goal 1, physiological and perceptual measures were collected throughout the 100-minute intermittent exercise protocol (Figure 18A). Specifically, HR and core temperature were measured every 2 minutes, and rate of perceived exertion (RPE) and thermal sensation (TS) were collected every 5 minutes throughout

Figure 20: Cardiac function measured using cardiac ultrasound.

the 100-minute intermittent exercise protocol. We used a telemetric pill to measure core temperature.

To achieve Goal 2, we measured cardiac function (Figure 20) and vascular function (Figure 21) before and after the exercise testing protocol. These sophisticated measures cannot be obtained during exercise in PPE, but by measuring them after the exercise protocol, we were able to determine the cumulative effects of heat stress and dehydration. Table 2 outlines the physiological parameters, how they were assessed, and the variables derived.

Figure 21: Brachial artery diameter, used to assess vasodilation, was measured using ultrasound.

Table 2: Physiological measurements obtained for Goal 2 of the study.

Physiological Parameter	Definition	Assessment Technique	Variables
Cardiac Function			
Systolic Function	The contractile ability of the heart	Cardiac Ultrasound	Ejection Fraction, Fractional Shortening
Diastolic Function	The ability of the heart to relax and fill with blood	Cardiac Ultrasound	Mitral valve blood flow during early diastole (Mitral E) and after atrial contraction (Mitral A)
Myocardial Oxygen Demand	An estimate of cardiac oxygen consumption	Calculated from HR and systolic blood pressure (SBP)	Rate Pressure Product (RPP) = HR x SBP
Myocardial Oxygen Supply	An estimate of oxygen delivery to the heart	Applanation Tonometry, pulse wave analysis	Subendodcardial Viability Ratio (SEVR) - pressure-time index in diastole/pressure-time index in systole
Vascular Function			
Vasodilation	The ability of blood vessels to expand circumferentially	Brachial artery diameter, Ultrasound	Vessel Diameter
Arterial Stiffness	A measure of arterial rigidity	Carotid Ultrasound, wave intensity analysis	β stiffness

Results

Descriptive Characteristics

Participants were young (age = 22 yr), highly fit (maximal oxygen consumption = 60 mL/kg/min) and lean (body fat = 15%) men.

Although our participants were younger and fitter (and likely healthier) than the general population of firefighters, it was necessary to conduct the first study in a homogenous group of healthy participants as age and disease are known to affect the variables measured in this study. Future testing should include older individuals, women, less fit participants, and those with cardiovascular risk profiles similar to firefighters.

The euhydrated protocols were designed to minimize body weight loss, whereas the dehydrated protocols sought to achieve a 3% body weight loss. Figure 22 shows that the criteria were met: body weight remained fairly constant (within 0.4%) for euhydrated conditions

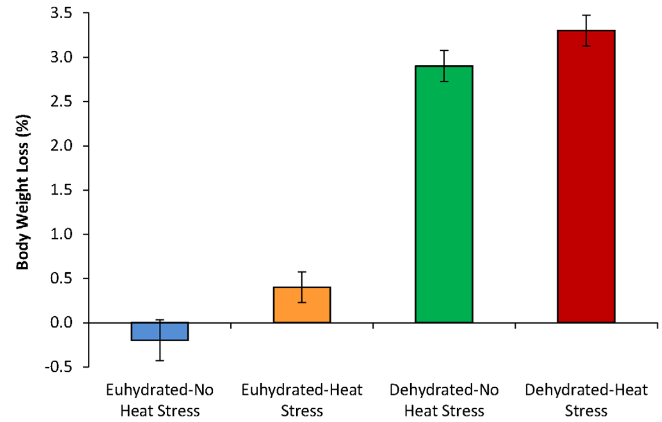

Figure 22: Body weight loss in the four experimental conditions.

and body weight loss was approximately 3% for both dehydrated conditions.

Goal 1 Results

As expected, HR increased during exercise and returned toward baseline during rest for all four conditions. Figure 23 clearly illustrates the marked differences in HR between heat stress and no heat stress conditions. In the no heat stress conditions, HR reached 105–108 bpm at the end of the exercise protocol. In the euhydrat-

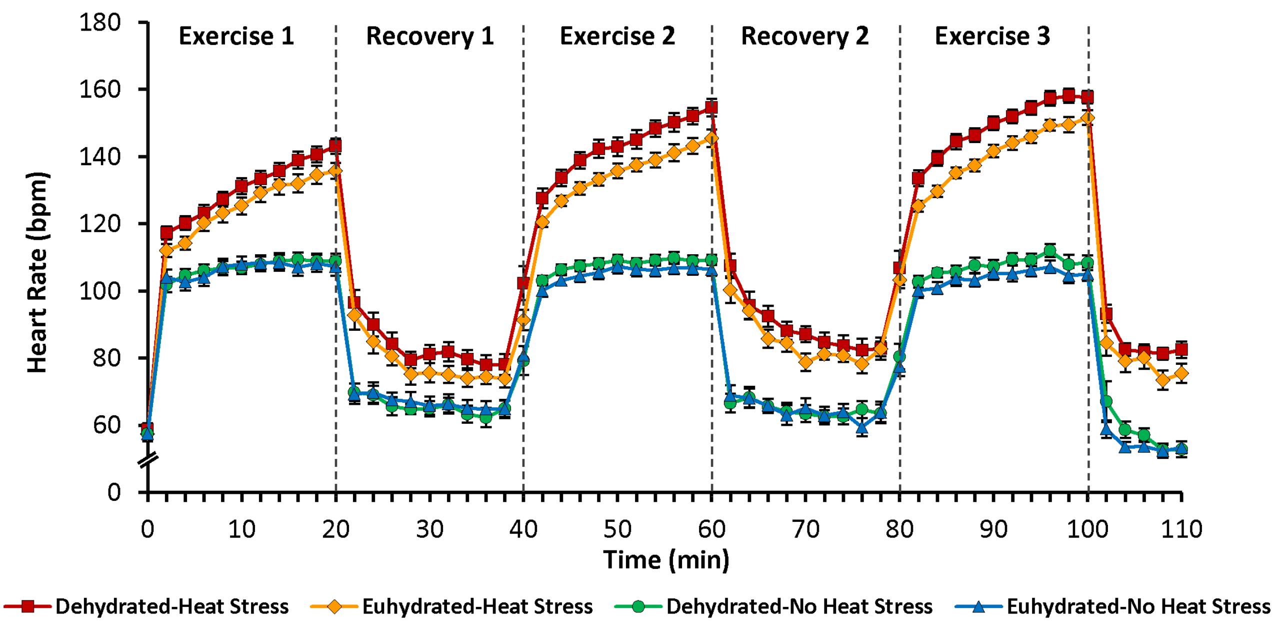

Figure 23: Heart rate (HR) during intermittent exercise in different experimental conditions.

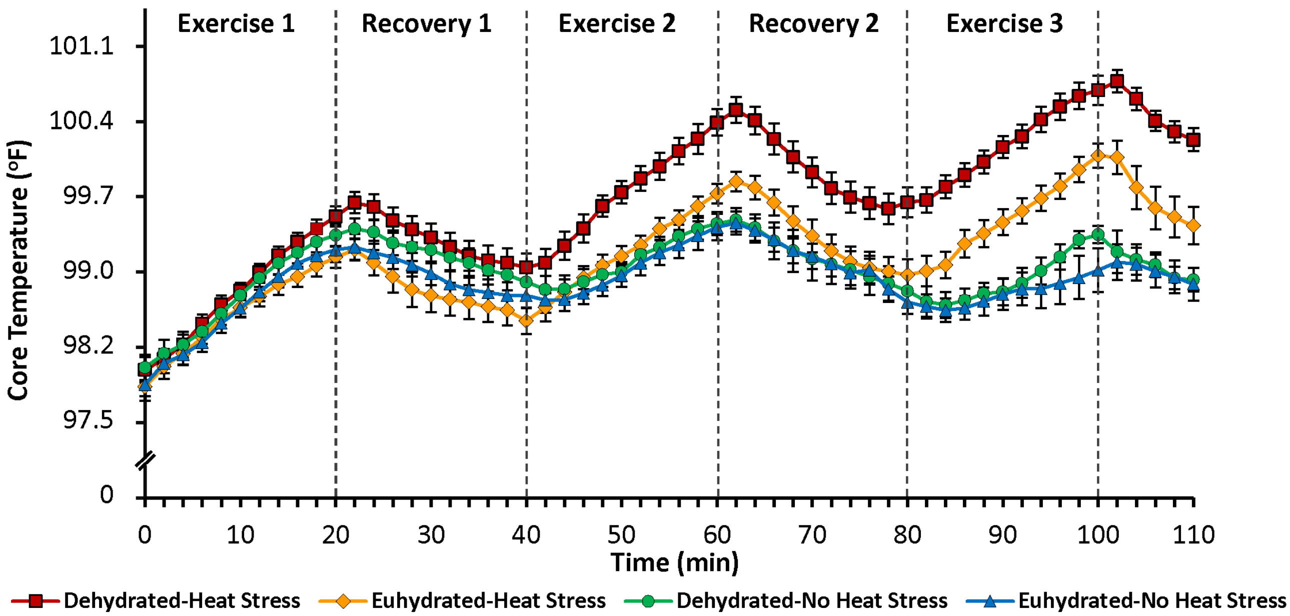

Figure 24: Core temperature during intermittent exercise in different experimental conditions.

ed-heat stress condition, HR rose to 152 bpm. When dehydration was superimposed on heat stress, HR increased further to 158 bpm. These results indicate what firefighters know well—that PPE imposes substantial cardiac strain during work. Additionally, dehydration further exacerbates cardiac strain during work.

Core temperature rose throughout exercise bouts and dropped during rest periods in all four conditions (Figure 24). At the end of exercise, the heat stress conditions resulted in higher core temperatures than in the no heat stress conditions. With heat stress, euhydrated core temperature rose by 2.2°F, whereas dehydrated core temperature rose by 2.6°F. This clearly demonstrates that dehydration increases thermal strain even when the work performed is identical. The difference in core temperature became evident by the end of the first exercise bout and increased as the protocol continued.

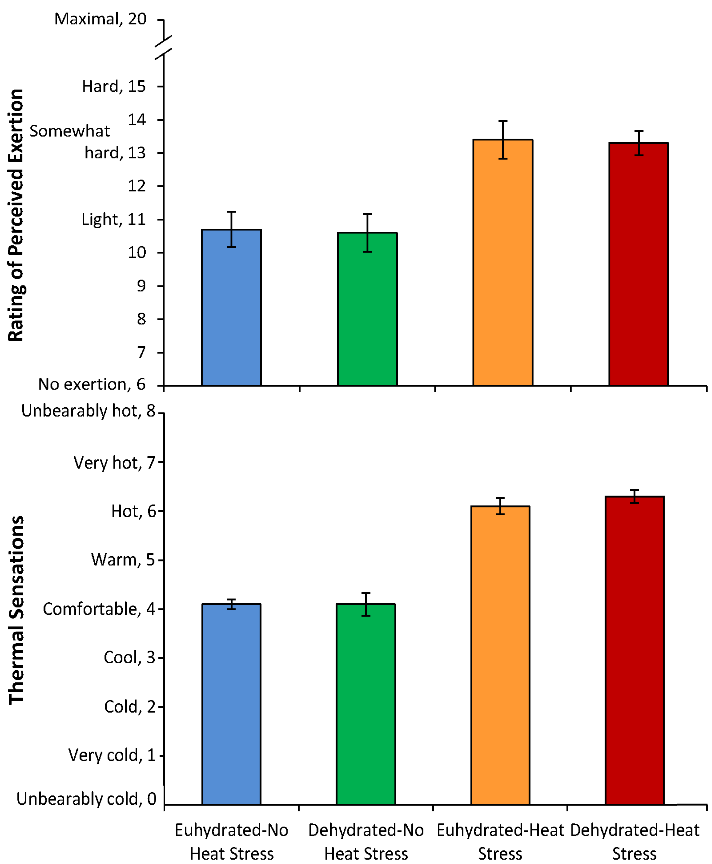

Figure 25: Perceptual measures during exercise in different experimental conditions.

Participants' perceptions of how hard they were working and how hot they felt during the exercise trials mirrored differences in HR and core temperature (Figure 25). Exercise in the heat stress conditions resulted in higher ratings of exertion than in the no heat stress conditions. As expected, the heat stress conditions resulted in higher TS than in the no heat stress conditions. Dehydration did not influence RPE or TS.

Goal 2 Results

Cardiac Function

We did not find any negative effect on systolic (ejection fraction, fractional shortening) or diastolic (mitral E, mitral A) cardiac function after exercise combined with moderate heat stress, dehydration, or a combination of both. When compared to pre-exercise values, left ventricular contractility (ejection fraction and fractional shortening) remained unchanged. Similarly, ventricular diastolic function remained stable. Thus, despite recurrent elevations in core temperature and increased cardiac work during exercise, as happens during firefighting activity, there was no evidence of impaired cardiac function following work in this group of young, fit men. This finding needs to be further studied because some indices of cardiac function have been shown to be impaired by firefighting activity (Fernhall et al. 2012).

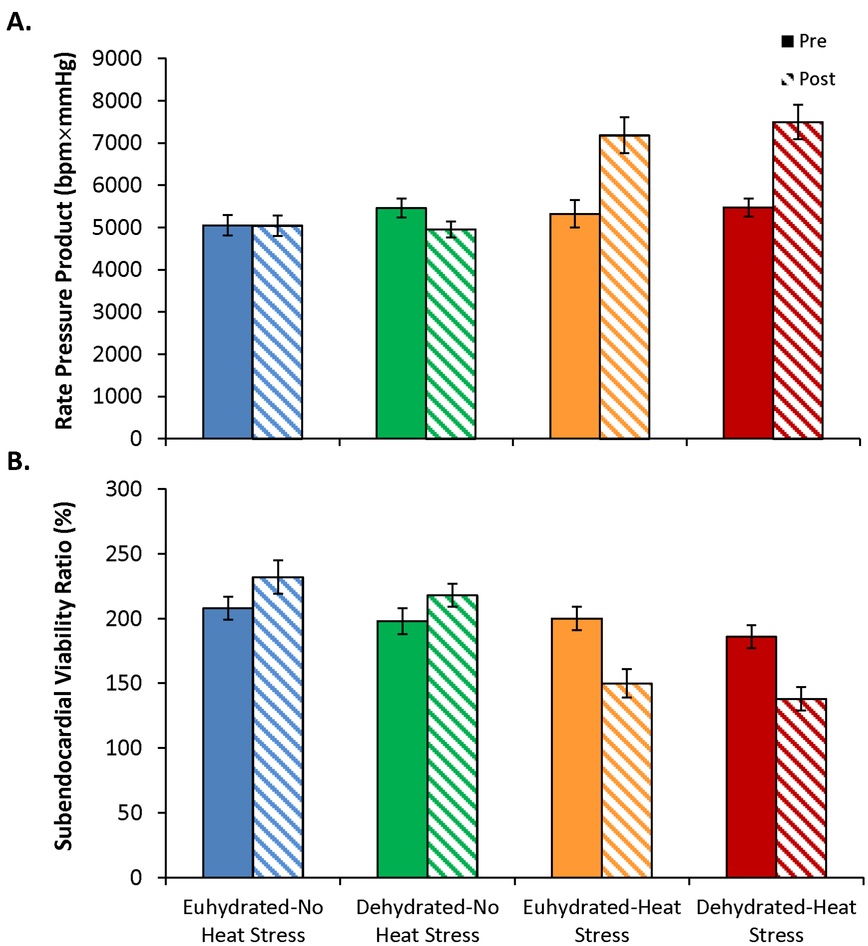

Figure 26: Rate pressure product (RPP; A) and subendocardial viability ratio (SEVR; B) pre- and post-exercise in different experimental conditions.

Myocardial Work

The rate pressure product is an indicator of myocardial work, or the stress put on the heart. Following exercise in the heat stress conditions, the rate pressure product increased by ~35% (Figure 26A). In contrast, the rate pressure product did not change after exercise in the no heat stress conditions. Dehydration had no significant effect on estimates of myocardial work. The higher rate pressure product following exercise with heat stress indicates that metabolic demand on the heart was higher. This is likely due to the much higher HR reached during exercise in the heat stress conditions, and consequently, the higher HR during recovery. The higher cardiac work (rate pressure product) reported in this study is similar to findings reported in studies involving firefighters (Horn et al. 2011).

Myocardial Oxygen Perfusion

The subendocardial viability ratio (SEVR), is an indicator of myocardial (heart muscle) oxygen perfusion. The lower the SEVR value, the less oxygen delivered to the heart.

Myocardial oxygen perfusion (SEVR) remained statistically unchanged (~10% increase) in the no heat stress conditions, but was decreased by 25% following exercise in the heat stress trials (Figure 26B). The lower SEVR suggests that oxygen delivery to the myocardium may be compromised following exercise-induced heat stress. Dehydration did not affect myocardial oxygen delivery.

The mismatch between myocardial work and myocardial oxygen supply following exercise-induced heat stress could reflect ischemia which may render the heart more susceptible to arrhythmias. This finding may help explain the triggering of sudden cardiac events in vulnerable individuals. The decrease in myocardial oxygen supply (estimated by SEVR) has also been reported following firefighting activity and has been shown to persist for 80–120 minutes after firefighting (Horn et al. 2011).

Vascular Function

Blood vessel diameter increased following exercise in the heat stress conditions, whereas blood vessel diameter remained unchanged in the no heat stress conditions (Figure 27). Dehydration had no significant effect on blood vessel diameter. The increased vessel diameter observed following the heat stress trials may result from the body's attempt to off-load heat through the skin. We are unaware of any published reports on blood vessel diameter but a study that measured blood flow reported a significant increase after firefighting (Fahs et al. 2011), reflecting increased vasodilation.

Arterial Stiffness

Healthy arteries are elastic vessels that swell when blood enters them, and they are also slightly rigid (stiff) as they propel blood forward throughout the body.

In this study, exercise in the heat stress conditions caused central arterial stiffness (β stiffness) to increase. In contrast, there was no significant change in β stiffness in the no heat stress trials (Figure 28). Dehydration has no statistically significant effect on arterial stiffness. The increase in stiffness seen in the heat stress conditions is consistent with findings of increased arterial stiffness following firefighting activity. In a published study investigating the effect of firefighting, the increase in β stiffness was not statistically significant, although other measures of arterial stiffness did increase significantly (Fahs et al. 2011). The authors hypothesized that a combination of thermal, metabolic, and psychological stress may contribute to increased stiffness of the central arterial system. We have shown that heat stress is likely a major contributor.

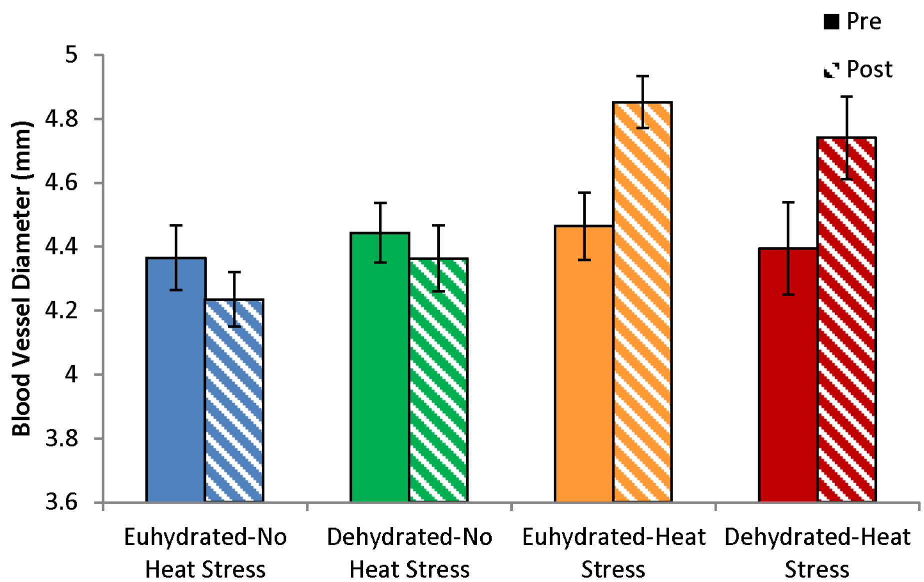

Figure 27: Blood vessel diameter pre- and post-exercise in different experimental conditions.

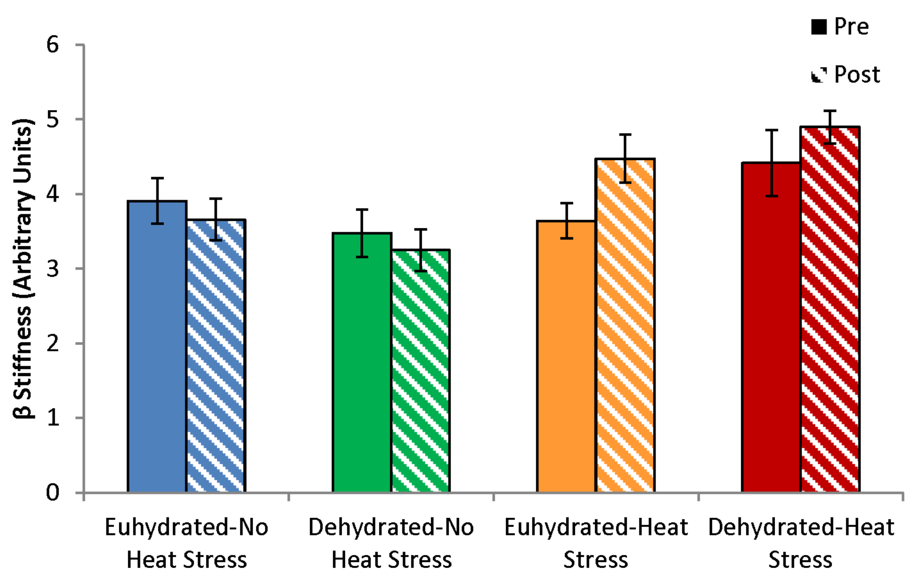

Figure 28: Arterial stiffness pre- and post-exercise in different experimental conditions.

Summary

The purpose of this study was to document the effects of heat stress and dehydration on measures of cardiac and vascular function. Using an exercise protocol that models fireground operations, participants completed a 100-minute exercise/rest walking task under four different conditions: euhydrated-no heat stress (control), euhydrated-heat stress, dehydrated-no heat stress, and dehydrated-heat stress.

The participants in this study were young, fit, healthy men. We conducted this study using a group with similar physical characteristics because the variables measured during the study are affected by many factors, including age, fitness, and disease. Using a small, homogeneous group allowed us to better isolate the effects of heat stress and dehydration and minimize differences in results that could be attributed to various physical characteristics. We found that exercise-induced heat stress affected several measures of vascular function. Future studies are needed to investigate the effects of heat stress on women and individuals who are older, less fit, and have a cardiovascular risk profile more similar to firefighters. Table 3 provides a summary of our results.

Table 3: Summary of results.

Physiological Parameter	Variable(s)	Response
Goal 1 (measured during exercise)		
Heart Rate	HR	~50 bpm higher in heat stress conditions ~6 bpm higher in dehydrated-heat stress than euhydrated-heat stress condition
Core Temperature	Core Temperature	~1.1°F higher in heat stress conditions ~0.4°F higher in dehydrated condition ~0.6°F higher in dehydrated-heat stress than euhydrated-heat stress condition
Goal 2 (measured before and after exercise)		
Cardiac Function		
Systolic Function	Ejection Fraction Fractional Shortening	No effect of heat stress or hydration status
Diastolic Function	Mitral E Mitral A	No effect of heat stress or hydration status
Myocardial Oxygen Demand	Rate Pressure Product (RPP)	~35% increase post-exercise in heat stress conditions Little or no effect of hydration status
Myocardial Oxygen Supply	Subendocardial Viability Ratio (SEVR)	~25% decrease post-exercise in heat stress conditions ~10% increase post-exercise in no heat stress conditions Little or no effect of hydration status
Vascular Function		
Vasodilation	Vessel Diameter	~8% increase post-exercise in heat stress conditions Little or no effect of hydration status
Arterial Stiffness	β Stiffness	~20% increase post-exercise in heat stress conditions ~7% decrease post-exercise with dehydration

Chapter Three: Mitigating Heat Stress & Dehydration in the Fire Service

Overview

As described in Chapter 1, firefighting involves muscular work and results in heat stress and dehydration. While most firefighters are keenly aware of having experienced heat stress on the fireground, they may have only a small appreciation for how it affects their performance and little or no understanding of how it affects their cardiovascular system. Simply put, familiarity with heat stress may lead firefighters to misjudge how dangerous heat stress can be. Furthermore, while most firefighters have heard about the dangers of dehydration, they may be unaware of how it contributes to thermal and cardiovascular strain.

This study convincingly documented that heat stress has a profound effect on cardiovascular strain, and that dehydration further exacerbated cardiovascular strain during intermittent work. Heat stress also resulted in changes in cardiac and vascular function that may be particularly troublesome in individuals with underlying cardiovascular disease.

Summary of Major Findings

1. Heat stress had a profound effect on heart rate during work in PPE (50 bpm higher). Thus, although heat stress is a familiar enemy, it needs to be combatted as aggressively as possible on the fireground.
2. Dehydration added to cardiac strain during work when superimposed on heat stress (6 bpm higher) – as typically occurs with firefighting.
3. Dehydration resulted in increased thermal strain during work.
4. Heat stress resulted in little or no change in traditional measures of systolic function (such as ejection fraction).
5. Heat stress resulted in greater myocardial work and less oxygen perfusion following exercise in the heat stress conditions. The mismatch in oxygen demand/oxygen supply to the heart may lead to ischemia.
6. Heat stress resulted in vasodilation – an expected response associated with increased blood flow to muscle and skin.
7. Heat stress resulted in an increase in central arterial stiffness as measured by carotid ultrasound. Increased arterial stiffness may increase cardiac work.
8. Dehydration had little effect on cardiac or vascular function. However, dehydration had an additive effect on cardiac strain during work and dehydration resulted in increased core temperature.

Summary of Major Recommendations

In order to mitigate heat stress and dehydration – and the resultant cardiovascular strain – firefighters should:

1. Receive an annual medical evaluation consistent with NFPA 1582 guidelines (NFPA 2013) and performed by a physician familiar with the physiological demands of firefighting.
2. Engage in regular physical exercise to improve thermoregulation, enhance cardiovascular function, improve work performance, and provide cardioprotection.
3. Ensure that they are properly hydrated before emergency operations.
4. Adopt NFPA 1584 and ensure that incident rehabilitation is established for emergency incidents and training drills (NFPA 2008).

Medical Evaluations

Based on the documented effects of heat stress and dehydration, the evidence compiled on the cardiovascular strain imposed by firefighting, and the statistics that document sudden cardiac events as the leading cause of LODD, it is imperative that all firefighters receive proper medical evaluations when they join a Fire Department and that they annually receive medical evaluations thereafter. The National Fire Protection Association 1582 Standard outlines the components of a proper medical evaluation for firefighters.

Medical evaluations should include an assessment of cardiovascular risk factors and screening for cardiovascular disease. One important, but often underappreciated, aspect of the medical evaluation is the information it provides firefighters, information they can use to manage their own health. The findings of the medical evaluation should not just be used to clear a firefighter for duty, they should also be used to aggressively manage risk factors. For example, firefighters who are cleared for duty with mildly elevated blood pressure (prehypertension) should aggressively pursue lifestyle changes to reduce blood pressure.

Physical Fitness

Given the strenuous nature of firefighting, and the resultant cardiovascular strain of firefighting, it is essential that firefighters engage in routine physical fitness programs (Figure 29). There are multiple benefits to fitness, many of which directly offset the detrimental effects of heat stress and dehydration.

Physical fitness is beneficial in mediating the effects of heat stress and dehydration - and cardiac strain - for many reasons; it:

- Enhances the body's ability to dissipate heat (improved thermoregulation);
- Increases the body's tolerance for increases in body temperature (increased thermotolerance);
- Increases blood volume;
- Increases cardiac efficiency;
- Increases work capacity;
- Improves clotting profile; and
- Lessens the risk of fatal arrhythmias.

Figure 29: Physical fitness is imperative for firefighting performance and heat tolerance.

Ensure Proper Hydration

Evidence suggests that most Americans are under-hydrated. As a result, general public health recommendations aim at encouraging more water consumption. The need for firefighters to be properly hydrated is even more compelling (Figure 30). Evidence shows that over 70% of firefighters are dehydrated when they arrive at work. This situation is compounded by fluid loss during firefighting drills or emergency operations. To improve thermoregulaton and lessen cardiovascular strain, firefighters should:

- Drink plenty of water or other non-sugary, non-caffeinated, low-calorie fluids. 2-3 Liters per day replaces normal fluid lost through urine production, feces, and breathing.
- Consume enough water to replace fluid lost during exercise, which often exceeds 1.5 Liters per hour of exercise.
- Avoid alcohol or other diuretics the night before being on-duty or engaging in training drills.

Figure 30: Adequate hydration can improve thermoregulation.

- Monitor hydration levels by examining urine color. Urine should be pale or light yellow. Dark yellow urine is an indicator of dehydration.

Incident Rehabilitation for Rehydration and Cooling

Incident Rehabilitation is an intervention designed to mitigate the effects of the physical, psychological, and emotional stress of firefighting (Figure 31). Incident rehabilitation seeks to improve performance and decrease the likelihood of on-scene injury or death (Smith and Haigh 2006; Bledsoe et al. 2009; USFA 2008). The NFPA 1584 Standard on Incident Rehabilitation provides guidance on establishing and implementing Incident Rehabilitation (NFPA 2008). Incident Rehabilitation provides an opportunity for firefighters to rest and recover away from the emergency scene. Rehabilitation also provides an opportunity for the administration of fluids and electrolytes to replace those lost during emergency operations. It also encourages cooling by doffing gear and providing active cooling (forearm immersion, misting fan, cooling tools) on hot and humid days when the body is less effective at dissipating heat.

Because of the cardiovascular and thermal strain of firefighting, Incident Rehabilitation provides for the monitoring of vital signs and careful observation of firefighters for signs suggestive of the need for medical care.

Given the significant dehydration that can result from emergency operations, it is important for firefighters to continue to rehydrate once they are released from the emergency scene and are back in quarters. Continued rehydration will help to ensure that firefighters are properly hydrated and are ready for the next emergency call.

Figure 31: Incident rehabilitation is a critical time to cool the body and hydrate.

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Glossary of Terms

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

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.

Cardiovascular strain – the physiological response of the cardiovascular system to exercise or physical work.

Dehydration – excessive loss of body fluid. Serious dehydration is classified by a > 5% reduction in body weight, significant dehydration by a 3 to 5% decrease in body weight, minimal dehydration by a 1 to 3% decrease in body weight, and well hydrated by a +1 to -1% change in body weight.

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

Euhydration – normally hydrated.

Exercise-induced heat stress – heat stres caused by performing muscular work/exercise; typically associated with work/exercise in excessive heat or in encapsulating gear.

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

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

Heat exchange – in normal thermoregulations, the movement of heat between the environment and the body.

Heat strain – how the body responds to heat stress.

Heat stress – the overall heat load placed on an individual from the combination of metabolic heat, environmental conditions, and clothing.

Hyperthermia – elevated body temperature.

Physiological strain – how the body responds to exercise or physical work.

Glossary of Terms

Plasma volume – the total volume of plasma in the body (not including blood particles).

Rate pressure product – measure of oxygen demand of the heart; reflects total work of the heart. Calculated by multiplying heart rate and systolic blood pressure (HR x SBP).

Subendocardial viability ratio (SEVR) – 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.

Stroke volume – the volume of blood a heart pumps during 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 – how the body responds to heat stress (see heat strain).

Thermoregulation – a process by which the body maintains its temperature.

Uncompensable heat stress – a condition in which the evaporative cooling requirements of the body are greater than the cooling capacity of the environment, such as in a firefighter wearing PPE.

Vulnerable individuals – those at risk for cardiac events.

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