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FIREFIGHTER AIR:
THE FIREGROUND, OUR MISSION, AND YOU

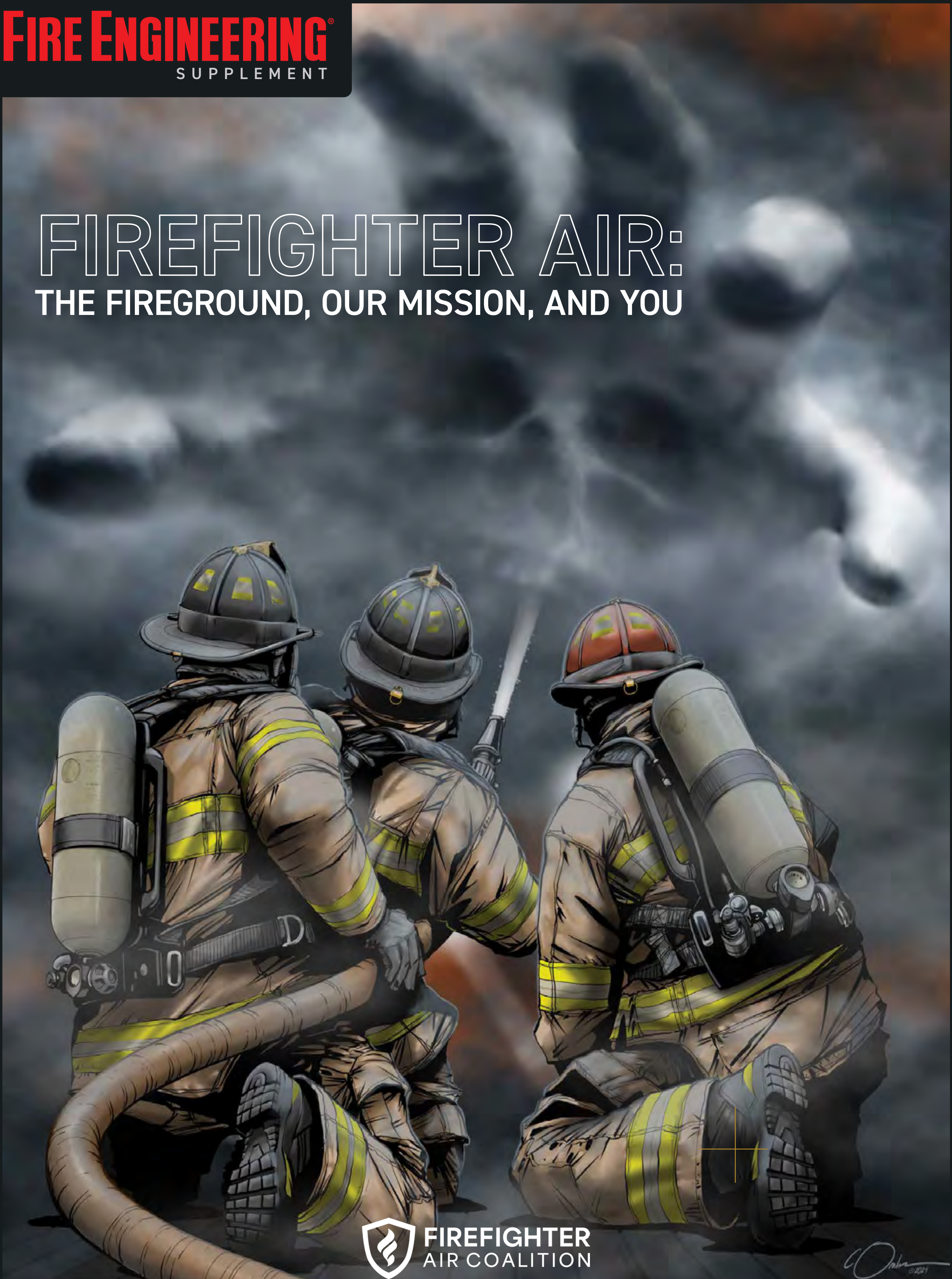


ILLUSTRATION BY PAUL COMBS

Physiological Response to Firefighting: Air Consumption and Work Output

BY RICHARD KESLER, GAVIN HORN, AND DENISE SMITH

THERE'S NO QUESTION that firefighting requires a substantial amount of physical work. The effort needed to perform essential fireground operations is often great and is compounded by the environment you are operating in, the gear you wear, and the demanding nature of the tasks. The physical demands of the job result in rapid increases in air consumption and increased cardiovascular strain to provide for the increased need for oxygen to support the muscular work.

The firefighting self-contained breathing apparatus (SCBA) allows you to carry a limited volume of air, and you have a limited work capacity based on your physiology. Understanding how firefighting tasks, SCBA size and weight, turnout gear, and physical fitness impact your physiological response, air consumption, and work output can help inform your individual operations and inform officer and incident command level decisions to improve efficiency and safety on the fireground.

Mechanics of the Physiological Response

Performing any type of physical work or exertion requires the human body to convert chemical energy (dietary intake) to mechanical energy (movement). A combination of carbohydrates/fats and oxygen is used to produce adenosine triphosphate, which serves as the energy source for muscular contraction and allows movement. As the speed and intensity of muscular movement increase, so does the oxygen demand from the contracting muscles. When performing physically demanding tasks, such as firefighting, breathing increases to bring more oxygen into the body. At the same time, increases in heart rate and in the force of cardiac muscle contraction transport this additional oxygen to working muscles. Activation of the sympathetic nervous system during firefighting (or other work) helps coordinate the physiological changes needed to meet the increased oxygen demand.

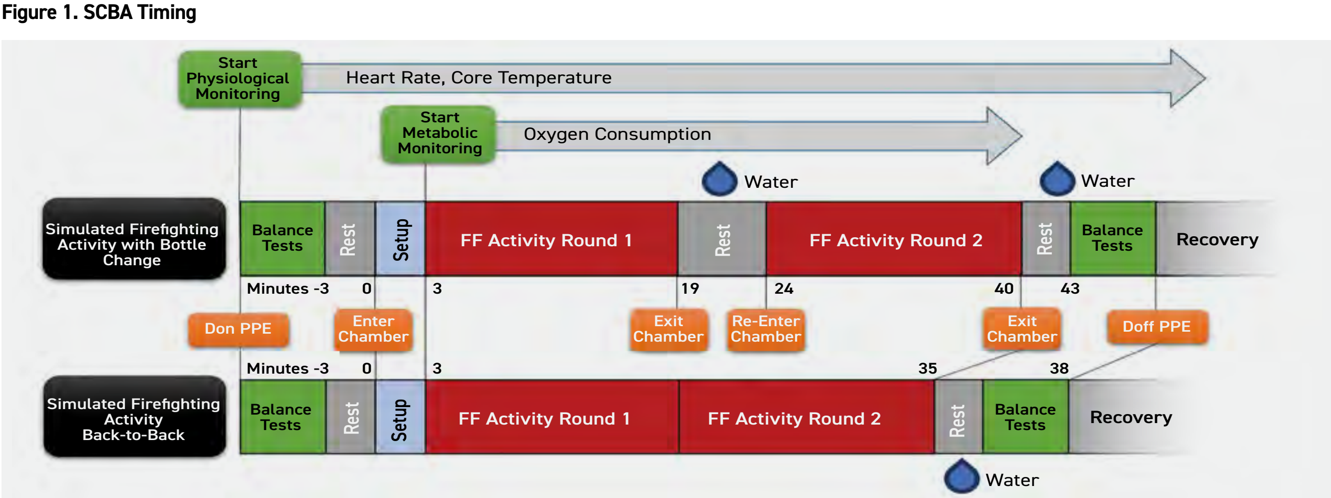
Heart rate and stroke volume both increase with the onset of increased need for oxygen from the muscles—although there is a maximum level to which these can increase. Blood vessels in the contracting muscle groups will dilate to allow for increased blood flow, while vasoconstriction will occur in the nonexercising tissues.

Both the tidal volume (volume of air per breath) and the respiration rate (number of breaths per minute) will increase to provide more available oxygen so that adequate pulmonary diffusion is maintained with the increased blood flow. Minute ventilation (the volume of air entering the lungs each minute) is the product of the tidal volume and the respiration rate, and minute ventilation can easily reach more than 100 L/min in healthy, fit individuals.

With continuing muscular work, core body temperature will begin to rise since heat is a by-product of the metabolic work of the muscles. In an attempt to counteract the increasing body temperature and cool the body, sweating rates will increase and vasodilation of the skin will occur, increasing blood flow to the skin. The increased cardiac output (heart rate × stroke volume) also results in elevated blood pressure.

There is a limit to each person's physiological response. Maximal oxygen consumption ($\dot{V}O_{2,Max}$) represents the maximum amount of oxygen that can be consumed and used by the body during maximal work and is measured in milliliters of oxygen consumed per minute per kilogram of body mass (ml/min/kg) or as a metabolic equivalent of task (MET). One MET is equivalent to 3.5 ml/min/kg of oxygen consumption. Firefighters typically do not work at maximal oxygen consumption levels, as this level of work can only be sustained for seconds. Rather, firefighters typically work at

Figure 1. SCBA Timing



Schematic of studies used to assess physiological response to firefighting operations. Firefighting activity consisted of four activities: Stair Climb, Hose Advance, Search, and Overhaul. In some trials, rest was provided to simulate a bottle change, while in others Round 1 and Round 2 were completed back-to-back with no break in between. *(Figure courtesy of authors.)*

submaximal workloads—higher-intensity work (>80% of $\dot{V}O_{2,Max}$) can only be sustained for a few minutes but lower-intensity work can be sustained for longer periods. Individuals with a higher cardiorespiratory fitness level (higher $\dot{V}O_{2,Max}$) can do more work at a given percentage of their $\dot{V}O_{2,Max}$, and they can work at a higher intensity for a longer time than unfit individuals.

The fatigue experienced by firefighters is a result of heavy muscular work, heat stress, and physiological disruption during firefighting. The strenuous nature of firefighting operations and the thermal and ergonomic constraints of working in turnout gear combine during firefighting operations to create a strain on our cardiovascular, muscular, and respiratory systems. The added weight and restrictive burden of the personal protective equipment increase the metabolic work required to perform the same tasks relative to what's required when wearing only station clothes or typical exercise clothing. In contrast to traditional exercise clothing, turnout gear that encapsulates the firefighter limits air movement for convective cooling and evaporative cooling of the sweat—leading to a condition where the body's cooling mechanisms are not effective.

While firefighters' fitness levels will not be discussed in detail in this article, it is important to note that improved fitness can help modulate the physiological response including increasing thermotolerance, improving musculoskeletal efficiency; increasing cardiovascular efficiency, allowing for greater oxygen consumption; and allowing for longer working times with higher work output.

Figure 2. Firefighting Activities

Simulated firefighting activities represent operations commonly performed on the fireground. *(Figure courtesy of authors.)*

Initial Response to Firefighting Operations

Numerous research studies have documented physiological changes while performing firefighting activities. In one study conducted at the Illinois Fire Service Institute, firefighters performed simulated fireground activities, including a stair climb, hose advance, search, and overhaul tasks, over the course of 14 minutes in a heated chamber (116°F, 47°C).[1] Each activity was two minutes long, with two-minute breaks between each session, simulating an emergency response. Firefighters' heart rates reached near maximal values (between 180 and 185 bpm) and core temperature rates of change were 0.08°F/min (0.045°C/min)—resulting in an increase in core temperature of more than 1°F (0.6°C). These changes occurred with only 14 minutes of intermittent firefighting activities.

Minute ventilation and oxygen consumption increased during the firefighting activities, resulting in more air being consumed from the SCBA and more oxygen used by the body than would have been at rest. This finding is not surprising but hard to quantify in the field. To collect this data while the firefighters were on air, we developed a system to integrate metabolic monitoring equipment with the SCBA face piece.[2] With this new tool, we found that peak oxygen consumption values during a single bout of activity were the highest during the stair climb (8.1 METs), slightly lower during the hose advance and search (6.7 to 7.2 METs), and lowest during overhaul (5.5 METs). The hose advance and search activities resulted in the highest peak minute ventilation [90 L/min (liters/minute)], followed by the overhaul task. The stair climb had the lowest minute ventilation (74 L/min).

The standard 30-minute SCBA cylinder holds approximately 1,275 liters of air. If peak ventilation rates were sustained, the entire cylinder would be consumed within approximately 14 to 17 minutes. Under these conditions, the working time until the end-of-service-time indicator or low-air alarm alert (when 33% of the air supply remains and firefighters should be out of the structure) would be approximately 9 to 11 minutes. With a 45-minute cylinder, which is typically filled with approximately 1,900 liters of air, the entire cylinder would be consumed in 20 to 24 minutes. The reported data are peak ventilation rates. This sustained rate would be unlikely due to the inverse relationship between the physiological limits of work output intensity and duration but may occur in an extreme situation where maximal work output is required over an extended period. Average minute ventilation throughout the study was lower than the peak rates as firefighters rested between activities, reflecting the intermittent nature of firefighting tasks at most incidents. It is also important to recognize that minute ventilation rates on the fireground could vary considerably, based on job assignment, fire conditions, or psychological stress levels.

After completing the firefighting activities in the above study, firefighters completed an obstacle course designed to simulate exiting the structure and walking on the fireground. The course consisted of challenges requiring the firefighter to step over an obstacle, duck under a crossbar, maneuver through the stud space in a wall, and climb up and down a small set of stairs. There were important changes in gait mechanics and body movements as firefighters stepped over the obstacles and stair treads.[3,4] These changes are indicative of fatigued muscles and could potentially lead to increased risk of trips and falls—one of the leading causes of fireground injuries each year.[5]

Repeated Bouts and Extended-Duration Operations

Although many fires are contained and suppressed while using only one bottle of air, it is not uncommon to respond to larger incidents requiring multiple bottles of air or conduct overhaul operations for extended periods of time after suppression. Our team sought to better understand the physiological implications of these longer operations in a research setting. To do so, and to allow comparability with previous research, we conducted studies in which the firefighters completed a second round of simulated firefighting activities in the same heated chamber. After the first round, they repeated the same four activities (stair climb, hose advance, search, and overhaul). In some cases, the firefighters took a short five-minute break to change SCBA bottles, hydrate, and cool off before returning to work. In other experiments, the firefighters continued working straight into a second round, simulating the use of an extended duration SCBA (45- or 60-minute cylinder). In the second round, heart rates were higher than the first round and reached most firefighters' age-predicted maximum (185-190 bpm). Core temperatures continued to rise.

During the second round of activities, oxygen consumption was significantly lower for all activities. When firefighters had a five-minute break between rounds, peak oxygen consumption decreased from 8.2 METs in the first round to 7.0 METs in the second round on the stairs (-15.0%), from 6.8 to 5.5 METs on the hose advance (-20.1%), from 7.0 to 5.1 METs for the search (-27.0%), and from 5.3 to 4.2 METs for the overhaul task (-21.1%). This decrease in oxygen consumption clearly shows that the firefighter cannot sustain the same work intensity during longer-duration incidents—and it demonstrates that approaching $\dot{V}O_{2,Max}$ is not what causes fatigue but rather that oxygen consumption decreases because the work level cannot be sustained. While oxygen consumption was significantly lower for all activities in the second round (relative to the first round), minute ventilation was the same for all activities when rounds were completed back-to-back and slightly reduced when firefighters had the five-minute rest between rounds. These findings suggest that in the second round of activity, the firefighters had a reduced respiratory efficiency—they were consuming less oxygen from a similar volume of air from their SCBA. This is consistent with the muscles being able to produce less force and generate less work output as they become fatigued.

On average, peak minute ventilation was approximately 79 L/min, which is almost twice the standard 40 L/min consumption rate NIOSH used to estimate service time for the SCBA cylinder. Our highest observed minute ventilation was less than the 103 L/min ventilation rate used in the NFPA 1981 tests.

Physiological responses are dependent on the intensity and duration of activity. Throughout these studies, firefighters were instructed to operate at a "fireground pace." This meant working as hard (intensity) and as fast (pace) as they would on the fireground and completing as many repetitions of each activity as possible while ensuring tasks were completed as instructed and safely. Each bout of firefighting activity was intermittent and designed to last 14 minutes, reflecting a "typical" response and the approximate duration of work before exiting due to air supply limitations. During the second round of activities at this self-selected intensity and pace, firefighters had a lower work output compared to the first round (measured as the number of repetitions of each task that was completed). On average, there was a 20% decrease in work output in the second round: –10.4% on the stair climb, –22.4% for hose advance, –26.8% for search, and –18.3% during overhaul. The decrease in work output was even more substantial when the rounds of activity were completed back-to-back without a break. The percentage changes in work output were consistent with the previously discussed percent changes in oxygen consumption, indicating that muscular fatigue limits the firefighter's ability to sustain continued activity.

The instruction to work at a "fireground pace" also included stopping the simulated activity to rest as needed and ending the simulated activities protocol when they would normally call for a relief crew and exit the structure at a real event. All the firefighters were able to complete the first round of activity, but 11 of the 30 were unable to complete the second round of activity in all three of the tested conditions. The group unable to complete all the tasks had higher body mass indexes (BMI) and overall lower fitness (lower $\dot{V}O_{2,Max}$). The average BMI for those able to complete all trials was approximately the same as the threshold between normal and overweight (BMI = 25 kg/m^2), while the average BMI for those unable to complete at least one of the trials was near the threshold between overweight and obese (BMI = 30 kg/m^2). The average maximal oxygen consumption ($\dot{V}O_{2,Max}$) of those who did not complete all of the trials was $\dot{V}O_{2,Max}$ of 40.3 ml/min/kg, which is below the suggested minimum recommended level of 42 ml/min/kg in the 2022 edition of NFPA 1582. The group who successfully completed all

Figure 3. Data Summary

Parameter	Change During First Round (from rest)	Change During Second Round (compared to first round with 5-min rest)	Change During Second Round (compared to first round with back-to-back)
Heart Rate	↑	↑	↑
Core Temperature	↑	↑	↑
Minute Ventilation (Breathing Rate × Tidal Volume)	↑	↓	— (same as first)
Oxygen Consumption	↑	↓	↓
Work Output	↑	↓	↓

Summary of physiological responses to performing simulated firefighting activities in the heat. Larger arrows represent a greater change. *(Figure courtesy of authors.)*

trials had an average $\dot{V}O_{2,Max}$ of 45.7 ml/min/kg, above the threshold in NFPA 1582.

The weight of the SCBA the firefighter wears can also influence the ability to complete multiple bouts of firefighting activity. We examined the impact of SCBA weight (35, 40, and 45 pounds) by having firefighters complete the same activities in the environmental chamber in two 14-minute-long rounds of activity (or until they were fatigued to the point that they would call for a relief company and exit the structure).[6] There was a trend toward decreased time until needing to exit and calling for relief as the weight of the SCBA they used increased. Average time until exit was 35.9, 35.7, and 31.2 minutes for SCBA weighing 35, 40, and 45 pounds, respectively. These weights represented the current maximum allowable weight under the 2019 edition of NFPA 1981, plus the addition of 5 and 10 pounds. This range of differences in working time between SCBA of different weights could be critical to fireground operations. A difference of more than four minutes between the lighter 35-pound SCBA and the heaviest 45-pound SCBA would significantly affect the amount of work a company would be able to complete during fireground operations.

Considerations for Fireground Operations

When firefighters are operating on the fireground—especially when activity continues beyond approximately 15 minutes of hard work and into a second air bottle—they will experience significant thermal burden (increased core temperature), which will lead to near-maximal cardiovascular strain despite being unable to sustain high oxygen consumption rates. The initial activation of the sympathetic nervous system results in elevated heart rates, stroke volume, and minute ventilation. As firefighters continue to work through the second bottle of air, core temperature continues to rise (at a greater rate of increase), heart rate continues to rise, minute ventilation remains relatively constant, but oxygen consumption and work output decrease. Effectively, the firefighter will consume nearly the same amount of air as the first round of activity but will use less of the available oxygen and be able to complete less fireground work.

NFPA 1584 suggests that firefighters should report to rehab after completing two bottles worth of work with a 30-minute cylinder or a single bout with a 60-minute cylinder. Our data suggest that significant rest and recovery should be provided after the first bout of work if operationally feasible. If this is not possible, it should be understood that overall work output will likely decrease while physiological strain will increase during a second bout. Further, firefighters with higher BMI and poorer overall fitness may reach their physiological limit prior to reaching the limit of the second bottle.

It can be challenging to quantitatively assess firefighters' fatigue level and operational readiness for additional work on the fireground. While monitoring heart rate on the fireground can give some indication of physiological status, it does not give the full picture. Heart rate may quickly start to recover to baseline after work stops, while other metrics such as core temperature and the metabolic state of the muscles will take substantially longer. Questioning how the individual feels may also not be a good indicator of status to return to work. In our studies, on average, firefighters reported feeling "fairly good" before starting the second round of activity but still had substantial declines in work output. It is also important to consider that we've recorded many of the same physiological changes in heart rate and core temperature when the firefighter isn't on air but is working on the fireground in full PPE.[7] Crews performing operations off air and then tasked to go on air (due to changing conditions or assignment) may have decreased work output similar to those who have already worked through a first bottle.

Officers, incident commanders, EMS, and other supporting groups should consider these physiological changes associated with firefighting operations when assigning tasks and evaluating firefighters. They should recognize that firefighters who are sent back to live fire activities—after a quick air bottle change for a second 30-minute cylinder or who are continuously working through a larger cylinder—may not have the same operational capabilities as those who are just beginning their work. ■

ENDNOTES

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DENISE SMITH is a professor of health and human physiology at Skidmore College. Her primary area of research is cardiovascular health, with a specific focus on the relationship between heat stress and cardiovascular function. A significant portion of her research focuses on the cardiovascular strain associated with firefighting activity. She has led several government-funded studies to investigate strategies to minimize the physiological strain associated with firefighting. She has also conducted several laboratory studies designed to identify specific components of firefighting activity (work performed, heat stress, sympathetic nervous stimulation) that are responsible for specific physiological responses to the combined stress of firefighting. Smith has coauthored several textbooks and has published more than 60 scientific papers, primarily on firefighter cardiovascular health.