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An Experimental Model of Heat Storage in Working Firefighters

Carin M. Van Gelder, MD, L. Alex Pranger, MSE, William P. Wiesmann, MD, Nina Stachenfeld, PhD, Sandy Bogucki, MD, PhD

Abstract

Objective. Develop experimental models to study uncompensable heat stress (UCHS) in working firefighters (FFs). **Methods.** FFs ingested core temperature (Tc) capsules prior to performing sequential tasks in 40°C and personal protective ensemble (PPE), or 18°C and no PPE. Both trials were conducted in an environmental chamber with FFs using self-contained breathing apparatus (SCBA). **Results.** FFs exercising in heat and PPE reproduced UCHS conditions. For every FF in both trials for whom the capsules worked, Tc was elevated, and Tc_{max} occurred after completion of study protocol. Trials with PPE resulted in a mean maximum temperature of 38.94°C (± 0.37°C); Tc_{max} reached 40.4°C. Without PPE, maximum Tc averaged 37.79°C (± 0.07°C). Heat storage values ranged from 131 to 1205 kJ, averaging 578 kJ (± 151.47kJ) with PPE and 210.83 kJ (± 21.77kJ) without PPE. **Conclusions.** An experimental model has been developed that simulates the initial phases of an interior fire attack to study the physiology of UCHS in FF. The hot environment and PPE increase maximum Tc and heat storage over that due to the exertion required to perform the tasks and may decrease time to volitional fatigue. This model will permit controlled studies to optimize work-rest cycles, rehab conditions, and physical conditioning of FFs. **Key words:** uncompensable heat stress; heat storage; occupational health; firefighters; core temperature; personal protective ensemble.

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Introduction

Firefighters (FFs) depend on their protective clothing, or personal protective ensemble (PPE), to allow them to function in temperatures approaching 700°F.[1] The outer shell, moisture barrier, and thermal barrier of the PPE prevent most of the evaporative cooling that should result from sweating. High sweat rates actually increase the weight of the PPE and resultant work performed by the FF.[2] Interior structural firefighting involves heavy work; aerobic activity and working muscles compound metabolic heat production, while the most important physiologic cooling mechanisms are significantly impeded by the PPE. Rapid temperature elevations in exercising FFs[3,4] confirm that the capacity of the normal thermoregulatory system is exceeded under such conditions, causing uncompensable heat stress (UCHS).[5] Heart rates in working FFs have been well studied and are known to remain at or near maximal levels for prolonged periods of time. Heart-rate monitoring does not predict energy expenditure.[6,7] Part of the increase in heart rate is due to work demand, but much more is due to thermal stress.[2] Increased cardiovascular work and thermal stress are thought to contribute to the substantial cardiovascular morbidity and mortality associated with fire suppression.[4,8]

Roughly 100 FFs die and 50,000–100,000 are injured in the line of duty in the United States each year.[9] Although fire suppression constitutes less than 5% of the national fire service emergency call volume, one-third of the line-of-duty deaths and half of the injuries occur on the fire ground.[8,10] Specifically, myocardial ischemia, heat stress, or other conditions related to the physiological stresses of fire fighting are responsible for 24% of the injuries and 50% percent of the line-of-duty deaths in FFs.[11–13] There is no existing experimental method to reliably study UCHS in working FFs.

This preliminary report describes the development of experimental models to study the dynamic effects of PPE and thermal environments on core temperatures (Tc) and heat storage (HS) in working FFs. In addition, both the time period necessary to complete a sequence of firefighting tasks and the time period to volitional fatigue while performing these tasks were compared with and without external heat and PPE.

Methods

Subjects

Local career and volunteer FFs aged 18–50 were eligible for inclusion if they were medically cleared for structural firefighting according to NFPA 1582, *Standard on Comprehensive Occupational Medical Program for Fire Departments*,[14] by the fire department's occupational medical provider within one year of participation in the study. The subjects were off-duty FFs who volunteered

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to participate and were remunerated upon completion of the protocol. Their duty status or responsibilities during the 24-hour period prior to study days did not affect study eligibility.

FFs over the age of 35 or FFs with any cardiac history required normal electrocardiogram (ECG) stress testing within the previous 12 months to participate. Exclusion criteria included current beta-blockers or digoxin therapy. Female volunteers were excluded if a urine pregnancy test was positive. Other exclusion criteria included use of antihistamines or presence of the following symptoms: nausea, vomiting, diarrhea, lightheadedness, difficulty breathing, fever, or pain/stiffness in joints or muscles in the previous 24 hours. Blood alcohol level was tested prior to each study protocol by placing an alcohol test strip (Status Alcohol Strips, Nanogen, Inc., San Diego, CA) under the tongue. A Tc greater than or equal to 37.5°C (99.5°F) or a nonzero blood alcohol level excluded the individual from participation in that day's study.

Institutional Review Board (IRB) Approval

All of these studies were approved by the Yale University School of Medicine Human Investigation Committee (Yale's IRB), and written, informed consent was obtained from each subject prior to participation in each study.

Sensors

Orally ingestible CorTemp® telemetric temperature sensors (HQ, Inc., Palmetto, FL), or capsules, were calibrated to ± 0.10°C accuracy. Data were transmitted every 15 seconds to a monitor (BCTM3; FitSense Technology, Inc., Southborough, MA) worn by subjects, then downloaded to a computer after each trial. Measuring Tc using such telemetry capsules has been validated during rest and exercise, and under various environmental conditions.[15]

The ingestible sensors were stored, with a small magnet attached to keep the battery turned off, in vacuum-sealed plastic bags. Sensor activation via magnet dislodgement would deplete the capsule's internal battery and result in eventual inactivation. Therefore, they were separated from each other by at least 2 cm of sculpted styrofoam and from any metal (e.g., shelf, etc) to prevent inactivation. The capsules had been precalibrated and were confirmed to be operational prior to ingestion by a FF prior to each trial. An investigator confirmed pill absence with the BCTM3 receiver when the second capsule was dispensed. Each capsule had a unique serial number and calibration code supplied by the manufacturer. These were entered into the spreadsheet on the laptop computer used for data collection and served as the unique identifier for each experimental trial.

Manufacturer instructions state that capsules should be ingested at least two hours prior to data collection.[16] For the first trial (UCHS), FFs were asked to take the capsules three hours before trial time. Because temperature fluctuation was observed, FFs were asked to ingest the sensors, or pills, at least eight hours prior to the second trial. Time of pill ingestion was recorded: Pills were ingested approximately three hours prior to the UCHS trials (mean, 221 minutes; range, 190–263) and approximately eight hours prior to the CHS trials (mean, 477 minutes; range, 317–665).

PPE/SCBA

FFs brought their own PPE to the trials, which included helmet (Cairns & Brother, Clifton, NJ), hood and gloves (Nomex™; W. L. Gore & Associates, Elkton, MD), coat and bunker pants (Globe Manufacturing, Pittsfield, NH), and leather or rubber boots, depending on FFs' personal preference. Each full set satisfied NFPA 1971, *Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting*.[17] For all trials, FFs breathed air via self-contained breathing apparatus (SCBA). These were NFPA-1981 compliant[18] Interspiro Spiromatic S-2 model units (Interspiro, Branfort, CT) with 30-minute carbon-fiber air cylinders filled to 4000 pounds per square inch (psi). Coat and bunker pants are composite materials (i.e., outer shell, moisture barrier, and thermal barrier); PPE used for this study was NFPA-compliant.[17]

Environmental Conditions

FFs performed simulated fire-ground tasks, as described in detail below, in an environmental chamber located in the John B. Pierce Laboratories at Yale University (New Haven, CT). The chamber provides roughly 1680 ft^3 of uniform, precisely controlled temperature and humidity conditions. The apparatus and equipment required to complete the simulations were arranged within the chamber to facilitate sequential completion of the tasks. Two investigators, one monitoring data acquisition and one prompting the FF through the protocol while observing for hazards or signs of clinical decompensation such as confusion or ataxia, were present inside the chamber throughout each experiment.

For the first trial (UCHS), participants wore full PPE over gym shorts and T-shirt and SCBA. The environmental chamber temperature was set at 40°C (UCHS conditions). Although far below the thermal extremes of the fire environment, a maximal ambient temperature of 40°C was chosen, since subjects would not be cooled by passive transfer of metabolic heat through the skin into the environment.

One week later, all participants performed identical tasks wearing gym shorts, T-shirt, and SCBA with the chamber temperature at 18°C for the second sequential task trial (CHS conditions). Chamber humidity was maintained at 45% for both temperatures, and air velocity in the chamber was maintained at 0.05 m/s.

Sequential Task Protocol (STP)

The sequence of simulated firefighting tasks was designed to simulate the power and endurance required during interior fire-suppression operations and was based as nearly as possible on the Fire Service Candidate Physical Ability Test (CPAT). This is a rigorous screening test for fire service applicants that has been validated to correlate with actual critical job functions in the United States and Canada.[19] The CPAT was modified so that 1) all tasks could be performed within an environmental chamber under tightly controlled conditions of heat and humidity, 2) the subjects would use SCBA because the increased work of breathing adds to the physiologic demands of firefighting, and 3) brief rest periods were built into the task transitions to better simulate structural fire suppression. The series of simulated fire ground tasks was designed to be roughly equivalent to the work that would be performed during the initial attack on a structure fire. Each FF went through the protocol twice, as described above. Total exercise times as well as times to volitional fatigue on the final task were recorded.

The protocol consisted of:

1. A loud alarm sounds to initiate the trial.
2. The subject dons full firefighting turnout gear, including SCBA as rapidly as possible, according to established practice.
3. The subject shoulders a harnessed 75-lb high-rise hose pack, enters the environmental chamber, and walks at 4 mph on a treadmill (Sportcraft TX 350; Budd Lake, NJ) at 2% grade for two minutes.
4. The subject dismounts the treadmill and drops the hose pack.
5. One-minute rest period (FF stands or walks within chamber)
6. The subject then works at a steady pace on a stair-stepper apparatus for an additional two minutes, simulating climbing to the fire floor in a multiple-storied occupancy.
7. One-minute rest period
8. The subject goes to a designated corner of the chamber, at which time the lights in the chamber are turned off. The subject performs a right-handed search around the periphery of the darkened chamber while pulling a nozzle attached to a 50-ft length of 1 3/4 in hose line, bundled and tied for safety;
9. When the subject finds the sand-filled, rescue manikin ″victim,″' located diagonally across the chamber from the search starting point, the nozzle is dropped. With the chamber still dark, the subject drags or carries the 120-lb rescue manikin back around the periphery of the chamber, keeping contact with the wall, until the door is reached.
10. The subject pulls the manikin out of the chamber, drops it, and spends two minutes resting outside the chamber, simulating air-cylinder change on the fire ground.
11. The subject then re-enters the chamber and repeats the stair climb in number 5 above.
12. One-minute rest period
13. The subject works to volitional fatigue on a weighted breach and pull simulation using a pike pole that is worked from mid-chest level to just over the top of the head (see Fig. 1).
14. The individual exits the chamber, removes all PPE, rehydrates *ad lib*, and continues to have all clinical parameters monitored.

The breach and pull task (Fig. 1) simulates the overhaul phase of fighting a structure fire. After entrance (tasks 3–6), initial knockdown of the free-burning phase and search of the occupancy for victims (tasks 8–10), FFs focus on overhaul (task 13). Overhaul on the fire ground consists of "breaching and pulling" down ceilings and walls, exposing areas within a building where unapparent heat and fire may reignite or still be smoldering. As in the standardized CPAT,[19] this was the final task in the STP. The breach-and-pull apparatus was built by the authors with the assistance of its original inventors. The counterweights used in the Molitor Machine® (Phoenix, AZ) were validated with strain-gauge analysis of the force required to penetrate and dislodge standard gypsum board walls and ceilings with a pike pole.[19]

The modified version is smaller than the 8-ft-high steel Molitor Machine® used in the CPAT,[19] due to the height constraints of the environmental chamber. The shorter apparatus required the subjects to perform the pike pole work on their knees, as if they were working in crawl spaces (not a rare occurrence in fire suppression). This modification of the machine likely served to eliminate much of the usual contribution of the lower extremities to the breach-and-pull task, making it mostly an upper-body exercise. Upper-body exertion has been shown to result in disproportionate cardiovascular stress.[20] It is notable that the heavy exertion necessary to break through walls and ceilings to look for smoldering fire is required when the FF may already be fatigued and dehydrated.

Subjects were encouraged to rehydrate with fluids immediately after exit from the chamber, replicating field firefighting. They were instructed to discontinue protocols if chest pain, difficulty breathing, or other symptoms of clinical decompensation developed.

Data and Analysis

Physical characteristics of FFs were recorded; weights were recorded in shorts. Body mass index (BMI) and

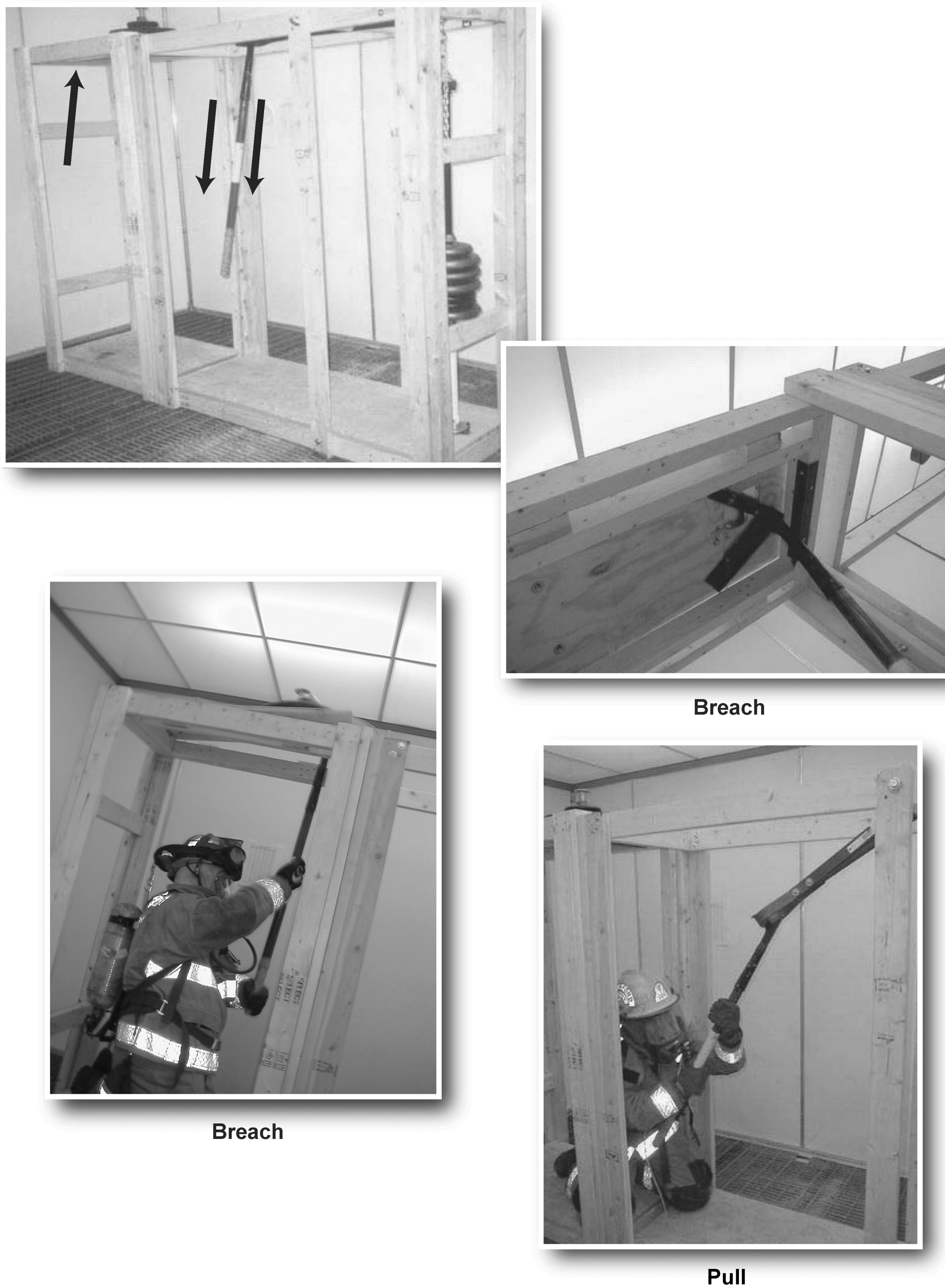

FIGURE 1. Breach and pull task.

body surface area (BSA, by the Dubois method) were calculated.[21] Tc and Tc_{max} were measured. Tc data were obtained every 15 seconds and averaged to provide mean values for each minute throughout the protocol. Time to Tc_{max} was determined.

Tc crude data were filtered to exclude artifact from analysis. Readings that were $\geq 2°C$ different from previous or following time points and those exceeding 42°C were excluded from determination of mean one-minute values. Excluded artifact represented $< 0.01\%$

TABLE 1. Subject Population Characteristics

	Mean n = 9	(Range)
Age (years)	30.9	(21–35)
Sex(no. male)	9	
Weight (kg)	98.6	(84–118)
Height (cm)	180.3	(175–188)
BMI[a] (kg/m^2)	30.5	(23.8–37.4)
BSA[b] (m^2)	2.18	(2.07–2.34)
Firefighter experience (years)	13	(6–17)

[a]Body mass index.
[b]Body surface area.

of data collected, and all one-minute mean readings were based on at least two data points.

Heat storage values in kJ were determined for each participant, as shown in the following equation:

$$[(\Delta Tc) \cdot (\text{wt in kg}) \cdot (3.49\ kJ/^\circ C.\ kg)]$$

where ΔTc is the net change in Tc during protocol, and 3.49 kJ/°C·kg is the average specific heat of body tissues.[15,22] Times at the start and completion of the breach-and-pull task as well as the duration of the full protocol were recorded.

Quantitation and correlations were performed using Excel (Microsoft; Redmond, WA). Paired *t*-tests were calculated using GraphPad (GraphPad Software, San Diego, CA, www.graphpad.com) with statistical significance established at $p \leq 0.05$.

RESULTS

Sequential Task Protocol

All 10 recruited subjects met inclusion criteria. One reported symptoms of gastroenteritis the night before the first trial and was excluded; no other FFs were excluded. All subjects were experienced FFs and familiar with the simulated tasks. Years of experience and physical characteristics are shown in Table 1. They were not acclimatized to hot working (environmental) conditions, as the study took place in New England during winter.

Nine FFs completed two trials each. One Tc sensor failed, leaving 17/18 complete data sets. One FF (of nine) fatigued prior to completion of the full list of tasks under UCHS conditions.

All trials under both conditions resulted in increased Tc. The highest Tc_{max} reached was 40.4°C (UCHS). Under CHS conditions, Tc_{max} averaged 37.79°C (range, 37.46–38.12), whereas trials under UCHS conditions resulted in a mean $Tc_{max}$of 38.94°C (range, 37.78–40.44) ($p = 0.03$). See Table 2 for Tc increase data; a > 1.5°C increase was seen under UCHS conditions. Figure 3 shows time of Tc_{max} and time of task completion for CHS and UCHS conditions where each FF serves as his control. Data are shown in Table 3. Figure 2 summarizes the Tc increase data; all FFs in both trials reached their Tc_{max} after the conclusion of the exercise.

TABLE 2. Sequential Task Protocol, Mean Tc^a_{max}, Tc^b, and Heat Storage

	CHS[c] trial (SD)	UCHS[d] (SD)	p-value
Tc_{max}(°C)	37.79 (± 0.1)	38.94 (± 0.4)	0.0298*
Tc increase (°C)	0.63 (± 0.1)	1.64 (± 0.4)	0.056
Heat Storage (kJ)	211 (± 21.8)	578 (± 151.5)	0.055

[a]Maximum core temperature.
[b]Core temperature.
*Significant.

Table 3 shows the duration of total exercise, breach-and-pull times, and time to Tc_{max}. UCHS conditions did not influence times for completion of these tasks significantly. The average length of time FFs performed the STP was <16 minutes; no FF worked longer than 21 minutes. Average exercise times are shown in Figure 2. The end of the breach-and-pull task was the end of the total exercise, as shown by the second red (UCHS) or blue (CHS) dashed line. FFs tended to take longer to reach the breach-and-pull task in UCHS, and then fatigued more rapidly, for slightly shorter total exercise duration.

A wide range of heat-storage values was observed throughout the study (131–1205 kJ). The average heat storage was 578 kJ (range, 211.33–1205.25) in UCHS conditions and 210.83 kJ (range, 131.43–327.75) in CHS conditions (Table 2). A subset of subjects demonstrated an increase in Tc (UCHS) ≥ 2.5°C and thus showed a very significant rise in heat storage (mean, 1073 kJ; $p < 0.001$) compared to the other FFs performing work under UCHS conditions. In CHS conditions, they did not show a significant change in heat storage compared to the others ($p = 0.106$). These three FFs had a significantly faster rate of Tc increase under UCHS conditions than the others (Table 4). Most of this rapid rise in Tc occurred after completion of the study protocol (Figure 2).

The subjects' mass ranged from normal (BMI < 25 kg/m^2) to obese (BMI ≥ 30–39 kg/m^2).[23] The correlation between BMI and HS as well as time to complete tasks was examined. The top graph in Figure 4 shows the correlation for FFs' BMI and HS in both environmental conditions ($r^2 = .1111$ in UCHS conditions,

TABLE 3. Sequential Task Protocol, Mean Exercise Times, and Time to Tc^a_{max}

	CHS[b] mean (SD)	UCHS[c] mean (SD)	p-value
Breach and pull (minutes)	3.3 (± 0.82 min)	1.9 (± 0.33 min)	0.202
Total exercise (minutes)	15.8 (± 2.6 min)	15.0 (± 1.3 min)	0.518
Time of Tc_{max} (min)	19.8 (±2.5 min)	20.38 (± 1.4 min)	0.412

[a]Maximum core temperature.
[b]Compensable heat stress.
[c]Uncompensable heat stress.

TABLE 4. Sequential Task Protocol and Mean Core Temperature Increase/Time (°C/minute)

	CHS	UCHS	p-value
Hyperthermic FF[a] subset (n = 3)	0.023	0.147	0.013*
Other FFs (n = 6)	0.035	0.040	0.218
Total (n = 9)	0.031	0.085	0.070

[a] Firefighter.
*Significant.

TABLE 5. Industrial Standards for Shift Workers in Heat[33]

Maximum heat storage (acclimatized workforce)	389 kJ
Maximum heat storage (unacclimatized workforce)	324 kJ
Maximum core temperature	38.5°C
Maximum increase in core temperature	1.0°C

while in CHS conditions, r^2 was −.2179). The next graph plots BMI and time to complete STP. UCHS trial r^2 was 0.1066, while CHS r^2 was 0.0136; again, no correlation was seen.

DISCUSSION

The experimental model developed here simulates the initial phases of an interior fire attack, allowing study of the physiology of heat stress in experienced FFs using sensor technology. Of the typical tasks associated with the fire rescue services, interior structural firefighting while wearing SCBA demands the most energy of FFs.[24] Environmental temperatures may reach very high levels within structural fires.[1] Much of FFs' work on the fireground involves intermittent anaerobic work[8,25,26]; however, most studies of heat stress have evaluated subjects performing only continuous aerobic work.[2,27,28] Previous methodologies used to study FFs in heat have had limitations, such as using SCBA or PPE but not both,[29] measuring only heart rate,[24] and inadequate representation of volunteer FFs in the subject pool.[30]

One of the few studies of intermittent exercise in heat involved healthy male subjects age 19–43 years, and found that this type of exercise leads to higher core body temperatures than continuous work under similar conditions.[29] In addition, a study looking at cardiovascular effects of repeated, strenuous live-fire drills found significant reduction in stroke volume after 20 minutes of performing such drills.[31] Since heart rate is sustained at or near maximum throughout a fire response,[2,6,7,32] any decrease in stroke volume immediately translates to decreased cardiac output, further compromising FFs' ability to physiologically compensate for the heat stress.

The core temperature data clearly show that the STP, when performed in heat and PPE, induced uncompensable heat stress (UCHS) in experienced FFs. Several subjects reached significantly higher Tc ($p < 0.03$) under these conditions than they did working in CHS conditions. This occurred during their very short work times prior to onset of volitional fatigue. Tc and, therefore, HS were markedly increased for half of the UCHS subjects, and the values recorded exceeded industrial standards for working shifts in hot environments (up to 1205 kJ) (Table 5).[33] In general, HS values correlate well with the time in hot environments that is tolerated by workers.[26,34] The standards mentioned above pertain to protracted exposure to heat (e.g., workers in industrial settings involving eight-hour shifts in smelting facilities). FFs that perform short, but intense, work cycles in heat may not develop the thermal tolerance of workers who acclimate to their hot environments over weeks or years.

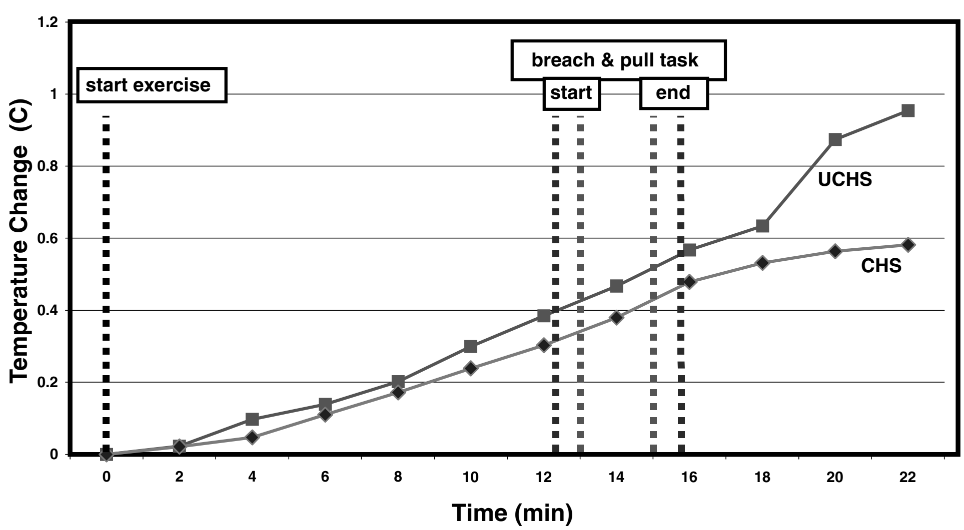

FIGURE 2. Exercise times for firefighters and mean temperature change in UCHS and CHS conditions.

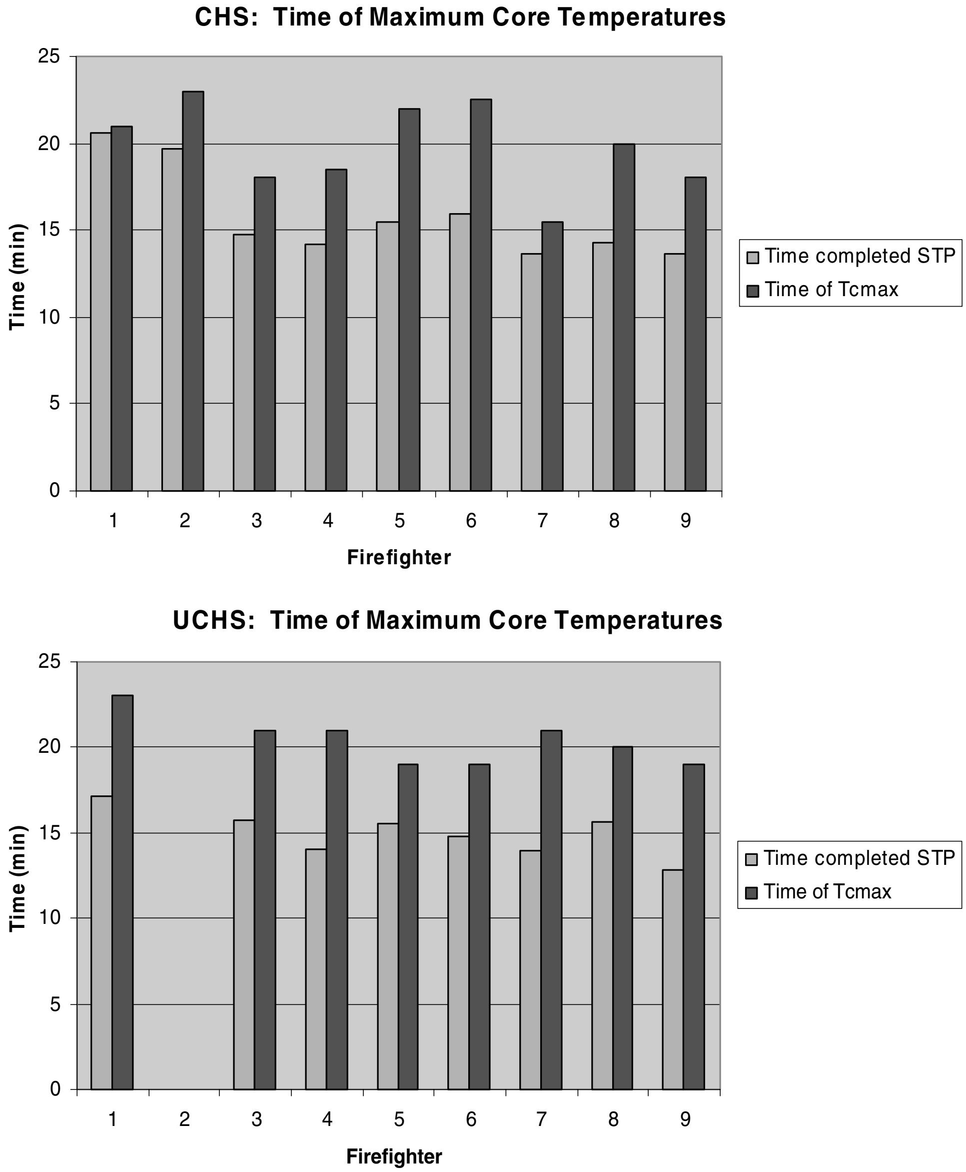

FIGURE 3. Time of maximum core temperatures and task completion for CHS and UCHS conditions.

Whether the temperature elevation seen in our subpopulation of FFs means that they are at increased risk for occupational heat stress, or represents a benign observation, including equipment artifact, should be evaluated in a larger study. HS values are valuable for studying the degree of heat stress experienced by subjects because they consider an individual's body mass as well as the change in core temperature. Heavy work loads together with high temperatures have been shown to result in HS rates that greatly exceed what would be expected if the two factors were simply additive,[2,25] suggesting that HS may be a particularly good marker of UCHS in FFs.

No significant difference in time to complete the last task (breach and pull) or the entire protocol was observed between the UCHS and CHS conditions. Despite this, FFs subjectively reported greater ability to continue the breach-and-pull exercise under CHS conditions. This is consistent with previous studies showing decreased Ratings of Perceived Exertion (RPEs) while working under mild ambient conditions and wearing fewer protective garments.[2,3]

Tc for all FFs continued to rise after exercises under both protocols. Others have shown similar results after completion of exercise.[7,27,29,33–35] The cumulative evidence underscores the need for rehabilitation areas at fire scenes and incorporation of cooling periods in rest cycles, as advocated by others,[2,7,27] and perhaps to preemptively evaluate FFs for their ability to tolerate heat stress.[35] Results of the present study indicate that temperatures continue to rise for as much as seven minutes

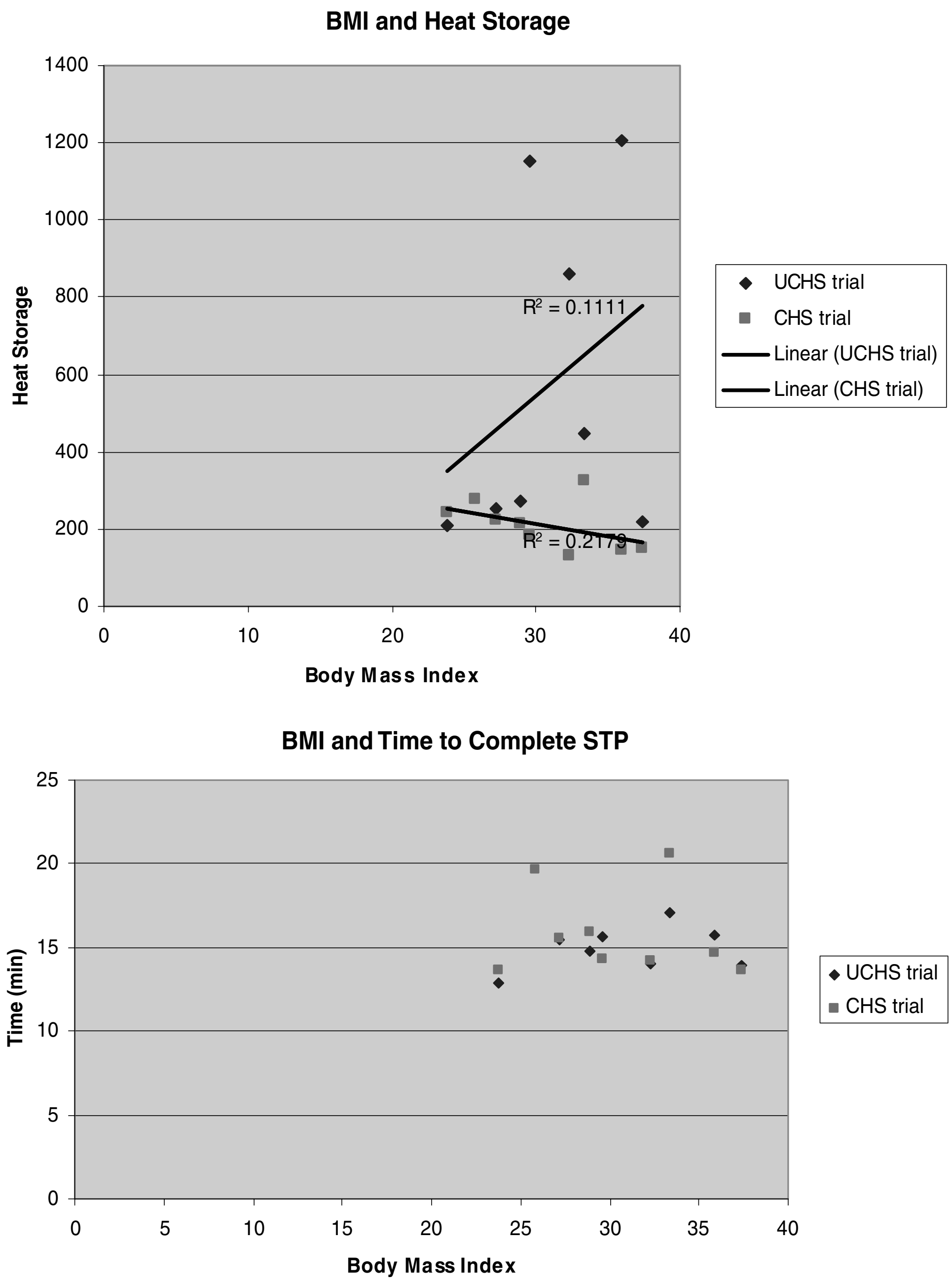

FIGURE 4. Body mass index and correlations with heat storage, time to complete task (UCHS and CHS).

after initial postexposure cooling and rehydration have begun.

No correlation between subjects' BMI and HS or time to complete STP was seen. In general, subjects with a larger BMI (increased mass in relation to surface area) do have greater heat storage and decreased heat tolerance to aerobic activity.[36] However, increased fat-free mass does not contribute to decreased heat tolerance. An increased mass may protect the individual from rapid rises in Tc, but the increase in cardiovascular strain with this same increase in mass may result in an overall increase in morbidity. Since FFs with higher BMIs may have increased muscle mass, it is difficult to establish a direct relationship between BMI and overall capacity to perform FF tasks.[23] FFs require a combination of strength and aerobic fitness, and optimizing both of these fitness levels likely should increase their heat tolerance.

FFs in the current study worked for less than 20 minutes. This is likely because the STP (intermittent work) was more physiologically demanding than typical aerobic exercises, such as walking or running. Increased working time may be seen with lighter equipment, more permeable clothing, and with the establishment of work-rest cycles.[2] The short duration of exercise in these studies calls into question the recommended "two-bottle rule" traditionally used by fire departments[37] as a convenient marker for the end of the first work cycle and initiation of rehabilitation. If FFs use 15–20 minutes of air from a 30-minute cylinder, they may be completing 30–40 minutes of work under conditions of UCHS. This equation is even worse with the use of 45- or 60-minute SCBA air cylinders. While mock fire exercises increase heart rate by 25% over resting, live-fire exercises induce increased cardiovascular stress when compared to mock fire exercises.[38] Heart rates increased by up to approximately 40% in live-fire exercises.

Obtaining accurate, continuous Tc as a marker of UCHS was of prime importance. Use of ingestible capsules allowed the measurement of Tc while FFs performed strenuous work. In some subjects, there were marked fluctuations in the raw Tc data. These were blunted, but still present, when the interval between ingestion time and exercise was increased (CHS trial). Other authors also have observed rapid changes in core temperatures,[33,39] suggesting that intermittent rectal temperatures may miss rapid, transient elevations in Tc (potentially underestimating Tc_{max}). The data-filtration techniques developed for this work revealed clear trends in Tc and were similar to methods used by others.[22,39]

With significant pressure (which may also be partially self-induced) to rescue lives and save property, FFs may not heed internal cues warning of impending exhaustion. Despite developments of training standards and new technology, FF line-of-duty deaths due to stress or overexertion have not decreased appreciably in recent years. FFs performing interior structural fire suppression may need objective data or limits to know when to exit. A significant rise in core temperature is a reliable indicator that an individual has exceeded the capacity of his or her thermoregulatory and cardiovascular compensatory mechanisms. The information may be used to guide work-rest cycles and to identify appropriate clinical parameters that should be monitored during work and rehabilitation.

Limitations

This study was designed to compare how environmental factors (heat and PPE vs. temperate conditions without PPE) affect Tc in FFs performing structural firefighting activities. It is possible that earlier activities affected FFs. FFs were requested to be off (not working as a FF) on trial days, but other restrictions on work activities were not possible. Previous days' activities were not documented. In reality, FFs are not able to restrict duties before duty days and often perform other jobs requiring strenuous activity. In addition, hydration status was not controlled for, other than general encouragement to FFs to drink fluids prior to trials. Hypohydration may reduce exercise tolerance time.[40] During the STP, all subjects completed the protocol in heat and PPE first and, at least a week later, repeated the protocol without heat or PPE. Future, larger studies should consider randomizing which protocol each FF completes first to minimize the introduction of systematic bias related to familiarity with the apparatus and protocol. This would complicate study logistics, as it takes several hours to change and stabilize the temperature in the chamber.

Skin temperatures were not measured. They are not a reliable measure of Tc, but such measurements do add information to the individual's dynamic state of heat stress.[35,41] Wide variations in stomach temperatures and increased temperatures seen near the liver and working (abdominal) muscles may account for increased data fluctuation seen with shorter time intervals between ingestion of the capsule and initiation of exercise in this study.[15] As has been noted by others,[39] extending the interval between capsule ingestion and protocol performance increases the likelihood of "pill failure" that occurs in some subjects due to rapid passage through the gastrointestinal tract. It is also possible that an early generation of capsules increased the failure rate. Overall, these pills are feasible for study but not for occupational use where hazardous environments occur unpredictably, and pill transit time throughout the GI tract cannot be controlled.

The small number of subjects in this study limits significant findings to 1) higher Tc_{max} were measured for FFs working in UCHS conditions and 2) Tc_{max} and the apparent rate of Tc increase were significantly higher in a subset of the FF subjects. An increased sample size would allow further evaluation of trends seen for Tc increase and heat storage. Studying additional variables, such as lactate production and oxygen consumption, may reveal additional insights into the physiology of UCHS associated with live structural firefighting.

CONCLUSIONS

An experimental model that simulates the initial phases of an interior fire attack to study the physiology of UCHS in FFs has been developed. As expected, performance of FF tasks in PPE and a hot environment result in substantial increases in Tc and HS compared with performance of the same tasks without heat and PPE. A subset of subjects showed an exaggerated Tc response to exercise in UCHS conditions. This is preliminary work; ideally, FFs should be studied in their working environment, live fire. Further study with larger numbers of subjects will be required to confirm the observations seen here and correlate the increase in Tc with other parameters.

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