

Physiologic Monitoring in Extreme Environments: Application of Micro-sensors and Embedded Processors to Predict Heat Stress in Fire Fighters

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ABSTRACT

Interior structural firefighting involves heavy physical exertion under extreme environmental conditions. Personal protective clothing and equipment impose 50 lbs of weight on fire fighters and impede the evaporative cooling mechanisms normally responsible for thermoregulation during exercise. The intense heat of the fire ground further exacerbates the physiological stress on working fire fighters. Occupational morbidity and mortality statistics reflect the impact of such stressors on fire service personnel. Non-invasive physiological monitoring capabilities are needed to more precisely define the cardiovascular responses to the demands of fire fighting and identify markers of impending failure of compensatory mechanisms prior to collapse or onset of irreversible pathology.

A suite of sensors designed to provide continuous remote monitoring of fire fighters has been developed. Oximetry sensors are incorporated into SCBA facemask to allow unencumbered monitoring and analysis of cardiovascular and pulmonary function. The present report also describes a model system for physiological studies of fire fighting. This system comprises a series of timed simulations of fire ground tasks performed by fire fighters in a heated environmental chamber. Preliminary testing confirms the feasibility of reliable oximetry signal acquisition under fire ground conditions.

Keywords Sensors, Remote Physiologic Monitoring, Oximetry, Fire Fighting

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1. INTRODUCTION

Each year in the U.S., roughly 100 fire fighters die and 50-100,000 are injured in the line of duty (1). Half of the line-of-duty deaths and over two thirds of the injuries occur on the fire ground, despite the fact that fire suppression constitutes less than 10% of the national fire service emergency call volume (2). Fifty percent of the deaths and 20% of the injuries are due to myocardial ischemia or other conditions related to the physiological stresses of fire fighting (1).

Despite these statistics, the physiologic stresses associated with interior structural fire fighting are poorly understood. At onset of exercise, healthy adults experience a rapid increase in cardiac output. This is due in part to accelerated heart rate resulting from centrally mediated changes in the equilibrium of parasympathetic-sympathetic stimulation. Stroke volume also increases with augmentation of venous return from the periphery and resulting inotropic enhancement based on Frank-Starling forces governing myocardial contractility. As exercise progresses, blood volume is redistributed to the working muscles to meet oxygen demands and to the skin for dissipation of the heat being produced by the muscles. This is achieved by dilatation of the vasculature in these areas. Vascular redistribution of blood volume together with volume loss due to sweating during ongoing exercise begin to decrease stroke volume, but cardiac output is maintained by compensatory increases in heart rate up to the individual's maximal rate, which is related to age and conditioning. Respirations are both faster and deeper than during rest, but seldom reach maximal during exercise. The combination of increased respiratory rates, evaporative sweat loss and redistribution of blood to capillary beds in the skin provide adequate cooling to maintain body temperature within a degree or so of normal in acclimatized adults during exercise.

Previous studies suggest that cardiovascular compensation, specifically the ability to sustain cardiac output, is also the limiting parameter in work capacity of fire fighters under conditions of uncompensable heat stress (3). Except in the presence of acute or chronic pulmonary pathology, ventilation is able to keep pace with oxygen demand beyond the point at which circulation becomes inadequate. Cardiovascular decompensation, however, is thought to occur much earlier in fire fighting than in other forms of exercise for a number of reasons.

Fire fighting involves heavy exertion with both dynamic, or aerobic, and static, or anaerobic, components. This has been demonstrated through studies measuring heart rates and oxygen demand of fire fighting (3,4). The work activities are performed while wearing thermal and flame resistant protective ensembles that quantitatively prevent evaporative loss of metabolic heat. Furthermore, they are performed in temperatures approaching or transiently exceeding 700°F (5), effectively eliminating even the most remote possibility of dissipating body heat into the environment. The protective ensemble worn by fire fighters includes self-contained breathing apparatus (SCBA). SCBA adds significantly to the weight borne by fire fighters, who routinely wear 50 lb. of personal protective equipment (PPE) and carry an additional 20-65 lb. of equipment as they climb stairs, ladders, or roof inclines. The SCBA is a demand-type positive pressure respirator worn in a backpack-style harness. Both of these features increase work of breathing and decrease total work capacity (6). Finally, fire incidents are unpredictable and require rapid intervention to save lives and property, precluding any possibility of 'warming up' as athletes routinely do before working out. The implications of the foregoing discussion must be viewed in the context of unsatisfactory fitness levels of many fire service personnel. There is great variability in aerobic conditioning of firefighters, especially among volunteers who constitute 75-80% of the fire service. Many are smokers, overweight, or not physically conditioned to safely engage in this level or type of activity. Aerobic capacity is known to be the best predictor of heat tolerance in adults (7).

In addition to the added static workload and defeat of evaporative cooling mechanisms imposed by fire fighting PPE, the cardio-accelerator compensation that normally maintains cardiac output during exercise is also lost to working fire fighters. This is because heart rates achieve maximal or near-maximal levels in fire fighters before they ever reach the incident scene (8,9). This is thought to be due to a combination of adrenergic stimulation associated with receiving the alarm, the lights-and-siren trip to the fire, and the initial exercise required to don the full protective ensemble. Its theoretical net effect, however, is an almost immediate decrement in cardiac output with initiation of exertion and sweating on the fire ground. This

initiates a cascade of sequential failure of compensatory mechanisms. Decreasing cardiac output leads to a constriction of the peripheral vasculature to maintain systolic blood pressure. This results in a rapid rise in core temperature, which is sustained even after exercise ceases (3,10). Clearly, if this plausible sequence consistently occurs, it is easy to understand the excess cardiovascular morbidity associated with fire suppression. One study (11) has used estimation of aortic valve area by ultrasonography to estimate cardiac output before and immediately after simulated fire fighting activities in PPE and did observe an early decrease in apparent cardiac output. Further work is needed, however to confirm the hypothetical physiology of fire fighting, and to identify physiological parameters that indicate the achievement of near-maximal work capacity prior to cardiovascular collapse, symptomatic heat illness or other adverse clinical outcomes. Such parameters must be amenable to noninvasive monitoring on the fire ground.

Remote, non-invasive, medical monitoring of fire fighters could greatly reduce fire ground morbidity and mortality in the future. However, remote surveillance of physiologic data from individuals engaged in heavy exertion under conditions of extreme life safety hazard in real time offers significant technical challenges. The sensor system must support rapid data collection, processing and effective transmission over sufficient distances to monitor personnel operating on a fire ground. Sensors require access to fire fighter biological signals, but cannot be applied as additional steps in donning PPE; as this would compromise response times. Placement and integration of sensors into the protective ensemble might be a workable solution, but must not compromise fit, comfort or airtight seals, and must provide accurate readings from all wearers. The full system of sensors, transmitters and power supplies must not add significant weight, external tethering or "cube" that could encumber a fire fighter or decrease essential mobility or dexterity during fire ground operations. Both hardware and software must be hardened to the severe environmental and functional conditions associated with fire suppression activities. Robust signals and processed output are essential before information can be relied upon for decisions involving life safety. This includes freedom from radio frequency interference on the electromagnetically complex fireground. Affordability for fire departments is another important consideration. Commercial, off the shelf (COTS) components may be the most cost-effective solution for development and testing of fire fighter monitoring systems.

Equally challenging is development and validation of a fire fighting simulation model through which to test the physiologic hypotheses and evaluate instrumentation. Hardening experimental prototypes to withstand full fireground conditions prior to confirming their clinical utility would be fiscally impractical. Furthermore, each emergency incident is different from any other, so accumulating statistically significant data for multiple subjects on multiple occasions would also be impossible. It is difficult to emulate the physiological stresses associated with the fire ground in the laboratory. Most investigators in the past have opted for either limited information that can be obtained by cardiac telemetry on the fire ground (3,8,9) or more extensive monitoring during highly variable combinations of heat exposure, PPE use, and exercise protocols (4,12).

2. MONITORING PARAMETERS

The SCBA-based oximetry system described in this preliminary report is incorporated into PPE to provide unencumbered monitoring through face piece-mounted sensors, radiotelemetry and processing software. This allows for continuous, remote measurement of heart rate and oxygen saturation of both pulsatile and non-pulsatile tissue compartments. From these parameters, we also derive heart rate variability.

2.1 Oximetry

Pulse oximetry is a well-established, noninvasive medical monitoring modality. Pulse oximetry detects alterations in hemoglobin oxygen saturation, measuring arterial oxygen saturation based on spectrophotometric principles (13). EMS providers in the pre-hospital setting use it, and its hardware has proven rugged enough to support this application. It was selected as one component of the sensor suite for fire fighter physiologic monitoring not only because of its proven toughness, but also because the sensors can be easily integrated into the SCBA face piece where oximetry is performed in reflectance mode. Most

importantly, however, oximetry was selected as the basis for the system because of the nature and amount of physiologic information that can be derived from it.

Vital signs such as heart rate, blood pressure and arterial oxygen saturation are relatively late indicators of compromised tissue perfusion in patients being monitored for severe medical or surgical conditions. Increased heart rate is a nonspecific sign that is associated with fever, emotional state, endocrine abnormalities and many other factors. When used as an indicator of volume depletion, tachycardia is relatively insensitive, requiring loss of 15-25% of total intravascular volume. This translates to 7-10 liters of fluid from a 70 kg adult. Loss of blood pressure is even less sensitive, and arterial oxygen saturation is maintained until full cardiovascular collapse occurs. Pulse oximetry would therefore appear to have minimal value in detecting sub-clinical fluid depletion or cardiovascular inadequacy for work demands in fire fighters.

In the critical care setting, more subtle alterations in tissue perfusion are inferred by monitoring indirect indicators such as lactic acid production, biochemical markers of end organ injury and oxygen saturation in mixed venous blood. The latter parameter, while perhaps most sensitive, requires cannulation of the pulmonary artery and performance of co-oximetry on intermittently obtained blood samples. Once again, these markers would not appear amenable to real-time monitoring of working fire fighters.

Historically, non-invasive oximetry became clinically useful for monitoring respiratory status in the 1970's when it was recognized that regularly intermittent changes in the length of the oximeter's light path as it was transmitted through tissue beds resulted from arterial pulsations (13). Pulse oximeters now measure light absorption through living tissue via an alternating current (AC), or pulsatile, component and a direct current (DC) component. The percentage of oxygenated hemoglobin in the arterial compartment is reported after processing that essentially subtracts the static background absorption from the pulsatile component. The DC signal used by oximetry processors, but not reported by the device, represents static tissue absorption primarily due to hemoglobin in the venous and capillary beds. The earliest metabolic changes of hypoperfusion, may, therefore, be detectable by measurement of changes in the DC signal. Transcutaneous oxygen and carbon dioxide monitors were recently used as part of a non-invasive suite that also included pulse oximetry and estimation of cardiac output by thoracic bioimpedance. Data from this suite was found to correlate well with hemodynamic measurements by conventional, invasive devices in ICU patients (14). Analysis of the plethysmographic waveform generated by pulse oximeters was also found to correlate with volume status in mechanically ventilated patients under general anesthesia (15). These findings suggest that both the AC and DC components should be monitored by the oximetry system integrated into SCBA face pieces.

Studies in the 1960's suggested that beat-to-beat changes in heart rate, or heart rate variability (HRV) may have prognostic significance, and new technologies are facilitating increased use in clinical settings. Both short and long term oscillations of heart rate result from the complex interactions of efferent and afferent autonomic pathways. Reduced HRV has been shown with aging and with disease states such as diabetes, spinal cord injury and sepsis. It is associated with increased mortality in ICU populations and following myocardial infarction. Moderate exercise training, however, increases HRV in adults. HRV is currently analyzed by various signal processing manipulations including time domain statistics, frequency domain techniques based on spectral estimation, and methods derived from nonlinear dynamics and statistical physics. Higher frequency (0.15 - 0.5 Hz) components primarily reflect parasympathetic tone, while lower frequency components (0.05 - 0.15 Hz) are associated with a combination of sympathetic and parasympathetic tone. At present, essentially all HRV analysis for medical applications uses ECG waveform data. The utility of pulse oximetry waveforms for HRV analysis under strenuous working conditions is examined in the present study using established criteria (16-18).

2.2 Core Temperature

It is not anticipated that core temperature monitoring will be part of a practical, fieldable sensor suite for real time monitoring of fire service personnel engaged in structural fire fighting. It is not feasible to either apply or insert thermometry probes during an emergency response. Since the occurrence of incidents is

unpredictable, it is not possible to ingest capsules like those used in these studies, as they must be given time to traverse beyond the proximal small bowel before their readings reflect body core temperature.

This does not diminish the importance of including core temperature monitoring in studies to elucidate the physiology of fire fighting and evaluate the predictive value of alternative parameters. 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. As such, it is essential to correlate this critical indicator with other test parameters.

3. SENSOR SUITE

3.1 Core Temperature

CorTemp[®] capsules, originally developed by the Applied Physics Lab at Johns Hopkins University in collaboration with the NASA Goddard Space Flight Center, are now marketed by Human Technologies, Inc. Each ingestible, 2 cm, silicone coated capsule remains in the human digestive tract for about 3 days and contains a quartz thermo sensor, micro battery and telemetry system. The vibration frequency of the quartz correlates directly with ambient temperature. The resulting magnetic flux transmits a signal to the integrated triaxial antenna, which in turn sends it to a recording device. The capsule is FDA-approved, and is accurate to 0.1°C. The FitSense[®] monitoring system includes a wristwatch sized radio repeater to boost the telemetry signal received from the capsule, and a pager-sized receiver/recorder worn on the belt. It can be directly linked to a computer for real time monitoring and includes an 8-bit micro controller. Both components of the core temperature monitoring system are commercially available and were purchased for these studies.

3.2 Oximetry

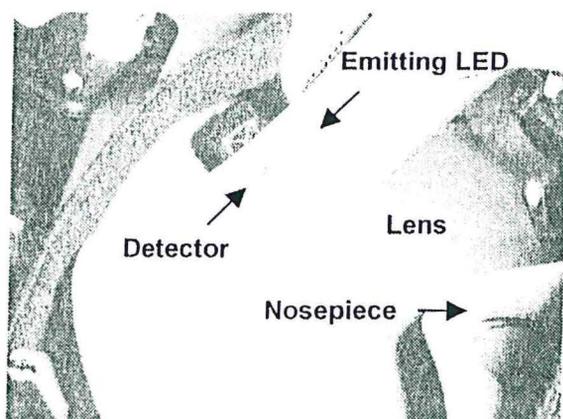


Figure 1. View from inside mask. Emitter and detector elements integrated into forehead portion of SCBA face piece. Arrows point to two embedded sensors in the face seal that cover the forehead.

Spirotroniq[®] S model SCBA face masks were kindly provided by Interspiro, Inc of Branford, CT. BCI, Inc. (Waukesha, WI) reflectance mode pulse oximetry sensors were added to the reflected rubber lining of the face piece that forms the seal with the wearer's forehead by BCI factory technicians (Figure 1). They were mounted to the opposite side of the lining with heat stable glue and similar rubber backing. The space between the forehead reflection and the clear shield attachment to the face piece provides a channel to accommodate the bulk of the LED emitter and detector components as well as the wiring. The wiring exits near the attachment of the low-pressure air line so that it can be easily added to the wiring bundle already prototyped by Interspiro, Inc and designed to run with the low pressure line back to an electronics box attached to the base of the SCBA harness.

Previous testing (19) has indicated that the forehead is a suitable location for placing pulse oximetry sensors. The airtight seal required by the National Institute for Occupational Safety and Health (NIOSH) ensures continuous contact with the integrated sensors. The series of head straps designed to secure the seal with the face also reduces the incidence of motion artifact, a common problem with ambulatory pulse oximetry. Some variability had been noted among different wearers in reliability of signal acquisition during previous work with SCBA-mounted oximeters (unpublished observation). This was suspected to be due to the placement of the emitting and detecting components of the oximetry sensors in the face pieces. Prior to sending the masks for modification, the optimal distance between the LED emitters and detectors at the particular angle imposed by the contour of the mask fitting the forehead (Figure 2) was empirically determined using volunteer subjects with differing face shapes and skin characteristics. There was no

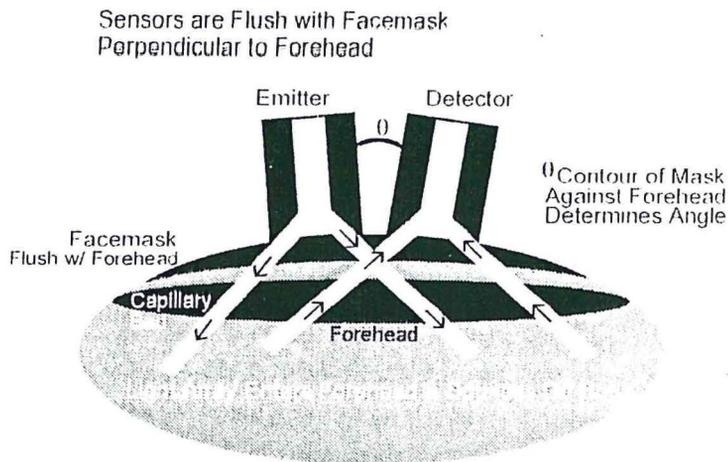


Figure 2. Diagrammatic representation of reflectance mode oximetry and location of the emitting and detecting elements of the sensor in the SCBA mask face piece.

piece/forehead interface. This distance also prevents larger wearers from exceeding the 1.9 cm limit when the inter-sensor rubber is stretched. The final separation of the two sensor components was found to provide a continuous signal as judged by both plethysmographic waveform and failure of the oximeter's processor to detect any time points with signal dropout for all wearers under both resting and active conditions.

To confirm that the post-manufacturing modification of the face pieces did not compromise their integrity as life safety devices, they were returned to Interspiro, Inc for testing (Figure 3). All masks exceeded NIOSH specifications for seal properties and ventilatory performance (Figure 4). Volunteer subjects also evaluated the modified masks for comfort; they were worn for up to an hour without difficulty. This is in contradistinction to previous prototypes in which the sensors protruded from the surface of the mask, causing localized pressure and discomfort to the forehead within a few minutes.

The initial prototype generation of the oximetry system utilizes an OEM pulse oximeter board from BCI, Inc. This board has three primary operating protocols that are determined through jumper settings. Each of the different protocols provides a variety of options and advantages. For the operation of this prototype, a protocol that communicates through an RS-232, 3 wire, 19200 baud, even parity, 1 stop bit, 8 data bits interface was selected. The SCBA masks are fitted with 9-pin sub-miniature D connector that can connect directly to oximeter processors from BCI, Nonin and Nellcor. Because most manufacturers use a "lookup table" to translate the IR to red signal ratio into oxygen saturation (SpO_2) levels, it is important to note that the accuracy of the calculated SpO_2 value must be re-calibrated when using sensors and processors from different manufactures.

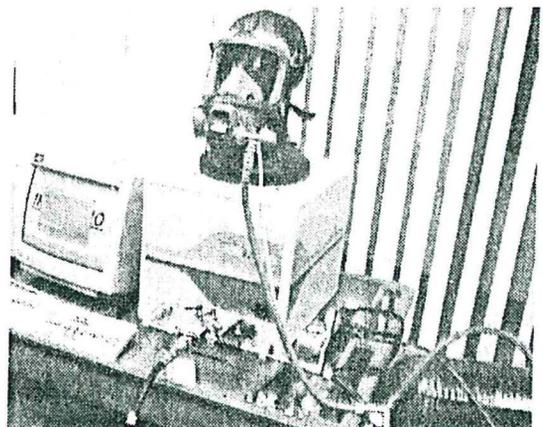


Figure 3. Modified SCBA mask on Posi-Chek[®] test apparatus, testing ability to maintain positive pressure, vacuum, and performance under high and low minute ventilation workloads.

A serial cable was tethered between the oximetry processor board and a laptop computer for the present studies. The laptop computer operates in a "terminal" mode capturing a byte data stream from the oximeter processor. Using the BCI OEM board's protocol 2, the board generates 5 bytes at a rate of 120 Hz. Contained within the data packet are signal strength, the subject's heart rate (HR), the calculated SpO_2 , the

significant difference in performance vs. separation distance once the sensors were within 1.9 cm, center to center. Starting at 4 cm, decreasing the distance between the detector and the emitters increased the reflectance measured. The signal strength did not seem to affect the "reported" results. This is likely because the signal measured is a ratio of the red signal to the IR signal, which increases proportionally as the emitter and detector get closer. A final center-to-center separation of 1.27 cm was selected to provide adequate pliable material between the elements to maintain uniform tension on the rubber strip containing the sensors and integrity of the seal at the face

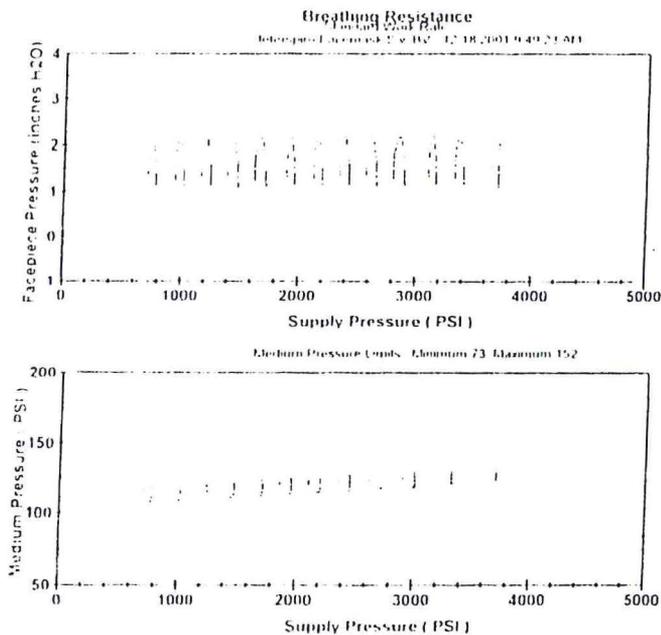


Figure 4. Ventilatory performance of modified Interspiro SCBA mask demonstrated by pressure tracings on Posi-Check apparatus. All masks exceeded NIOSH specifications for facepiece and medium pressure under both standard and maximal respiratory rates.

that the evaluation of that status would still occur largely on the processor board, using operator specific calibration data.

4. EXPERIMENTAL MODEL

4.1 Environmental Chamber

The sensor system is tested using fire fighters as test subjects performing simulated fire ground tasks under the controlled conditions of an environmental chamber. The chamber is one of several located in the John B. Pierce Laboratories at Yale University, and provides roughly 1,680 ft³ of uniform, precisely controlled temperature and humidity conditions for conducting thermal stress experiments. Apparatus and equipment required to complete the simulations are arranged within the chamber to facilitate sequential completion of the tasks. Two investigators, one monitoring data acquisition and one leading the fire fighter through the protocol while observing for hazards or signs of clinical decompensation, are present inside the chamber throughout each experiment.

To establish individual baselines for each subject under conditions where normal evaporative cooling is possible, the protocol is initially performed with the participant wearing gym shorts, T-shirt, and SCBA, and the chamber temperature set at 65° F. An identical trial in full PPE and with the chamber maintained at 104° F is also performed by each fire fighter to assure technical feasibility and reliability of the equipment under these conditions. Chamber humidity is maintained at 45% with both temperatures. Blood pressures and body weights are obtained at the beginning and end of each chamber experiment to crudely estimate hydration status. Total air depletion from the SCBA cylinders is also recorded.

The temperature of the heated chamber is significantly lower than that encountered during structural fire fighting. It was selected to give a large margin of safety to the human subjects participating in the studies, precluding any danger of burns, which are regularly suffered in the line of duty despite the protective ensemble worn by fire fighters. For purposes of this study, an ambient temperature of 104° F is adequate to

value of a plethysmographic wave, several bits of operating status and bits used to confirm the current averaging rates and scaling status as well as a data packet validity checksum. There is also a single bit used to indicate when the processor has calculated that a heart beat has occurred. These data are currently kept in byte form while being generated and used as a source file for analysis after a test protocol is completed.

A second generation of the system performs a direct calculation of the plethysmographic data through a custom processor board. The vast majority of the data are stored on a memory card attached to the processor system, while a small sub-set of the data is telemetered to a portable PC through the use of a simple wireless serial connection. This connection is not used to transmit the entire data acquisition, rather just enough data so that personnel monitoring data trials can confirm the quality of the acquired data. Once the unit transitions from a research tool to a field-able sensor, personnel status can also be telemetered; however it is anticipated

ensure that subjects, especially while wearing full PPE, will not be cooled by passive release of metabolic heat through the skin into the environment.

4.2 Human Subjects

The Yale University School of Medicine's Human Investigation Committee approved these studies. The investigators obtain informed consent from each subject prior to participation in the study. All participants are Class A (interior structural) fire fighters and members of the Branford Fire Department, Branford, CT. All were medically cleared for full fire fighting duty by the Yale Occupational and Environmental Medical Program clinic using NFPA 1582, Standard on Medical Requirements for Fire Fighters, 1997 edition, within one year of participation in the study. A total of 10 currently active fire fighters between the ages of 20 and 50 years comprise the study group.

On study days, each off duty fire fighter scheduled to participate in that day's protocols is queried by the principal investigator regarding present health status prior to ingestion of the CorTemp[®] capsule. Any fire fighter who reports any symptoms that might be referable to undiagnosed cardiac ischemia is disqualified from study participation and referred for immediate cardiac evaluation before returning to duty as a fire fighter. Any fire fighter who feels fatigued or unwell, who has soreness or discomfort in joint(s) or muscle(s), who has taken any antihistamine in the previous 24 hours, or who has experienced a fever, nausea, diarrhea, vomiting, or respiratory symptoms in the previous 24 hours are excluded from that day's work in the environmental chamber. Oral temperatures and saliva alcohol analysis are also performed at that time. An oral temperature greater than or equal to 99.5 °F or a non-zero alcohol reading disqualifies the individual from participation in that day's study. Fire fighters taking beta-blockers or digoxin are ineligible to participate as their physiologic responses to exercise and/or stress may be markedly blunted by these medications.

4.3 Simulations

Each fire fighter goes through the protocol twice, as described above. The 2 trials are performed on different days. The series of simulated fire ground tasks is designed to be roughly equivalent to the work that would be performed while consuming two cylinders of air during the initial attack on a structure fire. The protocol is also designed to reproduce some of the emotional stimulation associated with working on the fire ground.

The protocol consists 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 enters the chamber, picks up a harnessed ~50 lb high rise hose pack, and walks at 4 mph on a treadmill at 2% grade for two minutes
4. The subject dismounts the treadmill, drops the hose pack, and proceeds to the stair climbing apparatus for an additional two minutes
5. The subject then proceeds to a pre-determined corner of the chamber, at which time the lights in the chamber are turned off. The subject performs a right hand search around the periphery of the darkened chamber while pulling a nozzle attached to 1 3/4" hose line, bundled and tied for safety.
6. After the nozzle has been pulled back to the starting corner, and with the chamber still dark, the subject drags or carries a 120 lb rescue dummy from the same corner around the periphery of the chamber, keeping contact with the wall, until the door is reached.
7. The subject pulls the dummy out of the chamber, drops it, and is assisted with changing the SCBA air cylinder. During this cylinder change, the subject can drink water *ad libitum*.
8. The subject then re-enters the chamber, repeats the stair climb in # 4 above
9. The subject spends ten minutes (or to volitional fatigue) on a weighted breach and pull simulation using a pike pole that it is worked from mid-chest level to just over the top of the head.
10. The individual exits the chamber, removes all PPE, rehydrates *ad lib*, and continues to have all clinical parameters monitored.

The total protocol and the individual tasks were defined by their relevance to actual fire fighting tasks. For example, the high rise hose pack used in task 3 comprises 3 connected 50 foot lengths of 1 1/2" canvas jacketed hoseline harnessed for carrying over the shoulder with webbed strapping. This represents the standard configuration for hose carried by fire fighters to obtain water from standpipes in multi-storied buildings. The combination of walking and climbing for approximately 4 minutes is based on estimates of time taken to get from fire apparatus or nearby hydrants to the interior fire floor of commercial, multiple storied structures. The search pattern described in task 5 is that used to locate victims in degraded visibility due to smoke and/or darkness, and the environmental chamber is approximately the size of a room inside a typical residential occupancy. The rescue dummy may be light compared with most U.S. adults. The apparent weight of the loosely packed sand dummy normally used by fire personnel in training evolutions is greater because of its unwieldy limbs and the requirement that it be dragged rather than carried over the chamber floor. Fire fighting activities, after initial knockdown of the free burning phase and search of the occupancy for victims, focus on activities collectively known as overhaul. On the fire ground, these activities expose building compartments where unapparent fire may still be smoldering. The breach and pull apparatus used to simulate this phase of fire fighting is a smaller version of the Molitor Machine[®] developed for use in the Candidate Physical Agility Test (CPAT, Ref). The CPAT and each of its tasks were validated as essential job tasks for interior structural fire fighters. Further, the counter-weights used in the breach-and-pull apparatus were validated with strain gauge analysis of the force required to penetrate and dislodge standard gypsum board walls and ceilings with a pike pole. The modification of the apparatus developed for the present studies is shorter, due to height constraints of the environmental chamber. It requires the subjects

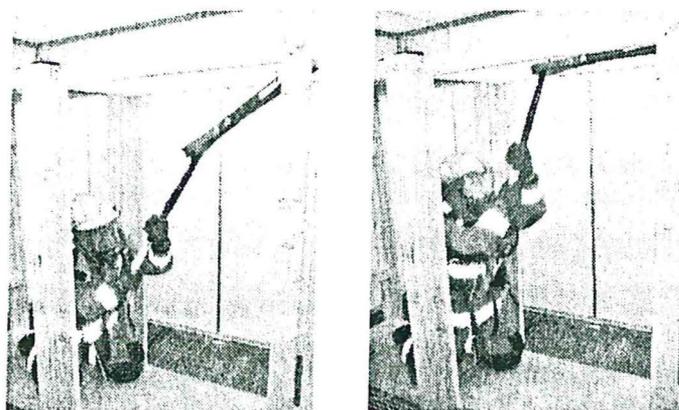
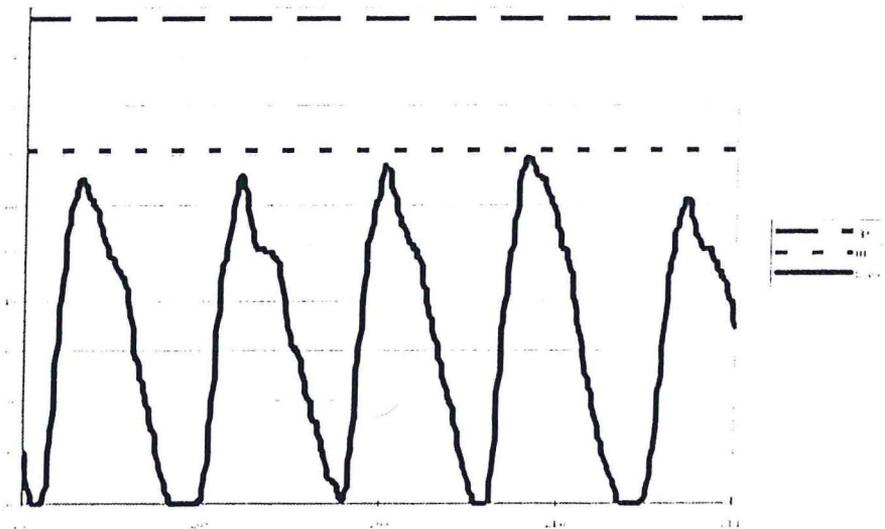


Figure 5. Breach and pull apparatus, using a pike pole to pull down against 80 lb counter-weight. To breach, the pike pole is used to push up a 60 lb trap door at the same height as the frame shown.

perform the pike pole work on their knees (Figure 5), as if they were working in crawl spaces, which is not a rare occurrence in fire suppression. Elapsed time to complete the study protocol approximates the CPAT, as well.

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Figure 6. Oxygen saturation, heart rate and plethysmographic waveform recording from reflectance mode oximetry during protocol.



In addition to the above considerations, the test protocol is subjectively validated for workload intensity and specific task demands by the experienced fire fighters participating as study subjects. The reliability of the sensorized SCBA mask under simulated fire ground conditions is confirmed through documentation of valid signal acquisition time (Figure 6) reported as a percentage of total protocol time. Finally, the measured and derived parameters of DC oximetry and IIRV are assessed for their ability to distinguish the difference in physiologic stress between protocol replications by individuals under conditions of normal cooling and uncompensable heat stress.

5. SUMMARY

A SCBA-based oximetry system for physiological monitoring of fire fighters has been described. It is used in a model system of simulated fire ground tasks for experimental purposes, and is designed for field deployment. Applications of this system extend beyond fire fighters. When commercially available, this technology will have broad applications to a variety of workers who wear respiratory protection in potentially hazardous environments. The system is suitable for confined space operations where personnel cannot be visibly monitored, such as fuel tank maintenance, shipyards, mining, and utility services. The current U.S. military emphasis on preparation for operations in urban settings mirrors the requirements of the civilian fire service for protective equipment and medical support logistics. The increasing risk of future conflicts involving chemical and/or biological weapons means that our forces will require personal protective equipment. Furthermore, heat stress has consistently been a significant problem with deployed military forces.

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