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Physiologic Strain during Treadmill Electrocardiography in the Medical Evaluation of Candidates for Hazardous Materials Duty, with and without Added Heat Stress

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Abstract

Purpose: To compare the Physiologic Strain Index (PSI) induced by maximal treadmill exercise with and without added heat stress as part of medical evaluation for hazardous materials (hazmat) work requiring protective ensembles which block evaporative and convective heat transfer. Also, to extend comparison of PSI versus published values from hazmat simulations.

Methods: Candidates for hazmat duty (N=203) underwent maximal, symptom-limited Bruce protocol treadmill electrocardiography (standard Bruce test wearing gym clothes, SBT) during which changes in tympanic temperature (TT) and heart rate (HR) enabled calculation of PSI. A subgroup of candidates (N=39) later performed a second Bruce test, wearing novel, inexpensive apparel chosen to impede dissipation of metabolic heat (Hot Bruce test, HBT). Thermal discomfort was gauged using the Young index (4, neutral; 8, maximal discomfort).

Results: SBT duration was 12.2 ± 2.6 SD minutes and the rise in TT and PSI averaged 0.5 ± 0.4°C and 5.9 ± 1.1, respectively. The rate of rise of TT was 0.038°C per min. of treadmill exertion. In the subgroup of 39 candidates, HBT duration was 13.7 ± 3.3 min. (p>0.05). TT rose more after HBT than SBT: 1.3 ± 0.7°C vs. 0.5 ± 0.4°C (p<0.001). The rate of rise of TT during HBT was 0.10°C per min. and was associated with greater physiological strain (PSI=7.4 vs. 6.2, p<0.001). The Young index was 6.2 ± 0.8 for SBT vs. 7.3 ± 0.6 (p<0.001) for HBT. Maximal heart rate was 181 bpm during both SBT and HBT.

Conclusions:

1. The rate of rise of TT–0.038°C per min. of SBT treadmill exertion -- is similar to that of two smaller studies, but less than the only other published report.

2. PSI during HBT exceeded that from SBT and was similar to PSI observed during hazmat simulations, suggesting that HBT, which also induced heavy sweating and thermal discomfort, may be more appropriate than SBT in the medical evaluation of hazmat candidates.

Keywords: Physiological Strain Index; Treadmill exercise; Bruce protocol; Hazmat; Heat stress

Abbreviations

BEI: Borg Exertion Index; CI: Chronotropic Index; DTS: Duke Treadmill Score; Hazmat: Hazardous Materials; HBT: Hot Bruce Test; HR: Heart Rate; HRR: Heart Rate Recovery, Post-Exercise; ITT: Ingested Thermistor Temperature; METS: Metabolic Equivalents; MIN: Minute; PSI: Physiologic Strain Index; SBT: Standard Bruce Test; SCBA: Self-Contained Breathing Apparatus; SLT: Sublingual Temperature; TT: Tympanic Temperature; YTDI: Young Thermal Discomfort Index

Introduction

Heat stress and heavy exertion may contribute to the morbidity and mortality associated with fire-fighting [1-3]. These stresses may affect other workers who have potential contact with hazardous materials (hazmat).Whilst potentially exposed to chemical, biological and/or ionizing radiation sources, they may need to don impermeable protective suits. These suits block evaporative and convective heat loss by which metabolic thermal energy is normally dissipated. Impeding these modes of heat transfer can result in marked thermal stress, often magnified by high ambient temperatures [4-8]. In addition to wearing these 20-kg. protective ensembles whose internal temperature is often 10-15°C above ambient levels, hazmat responders may also experience heavy exertion such as when extracting persons overcome by toxic agents. In-suit temperatures may be further increased by fire or explosive incidents perpetrated by terrorist agents. Advisory groups have therefore recommended that stress testing be included in the medical evaluation of hazmat workers [9]; American Academy of Family Physicians 1994; US Preventive Services Task Force 1996). Moreover, federal guidelines in the US direct physicians to consider it. The Bruce protocol is a well-validated instrument and a likely choice for this application. However preliminary observations have shown

that the degree of heat stress induced by the Bruce protocol is quite modest [10]). In addition, we attended three hazmat responders who developed heat illness during hazmat exercises, despite having undergone an uneventful SBT several months earlier. Moreover, as described by Busko et al. (2005), SBT performance was not predictive of successful "rescue" of a manikin. A subsequent study found that a 45-minute treadmill walk could induce a degree of heat stress similar to that of hazmat exercises, but such duration would limit its use when large numbers of candidates need to be medically evaluated for such duty [11]. We therefore extended these observations to evaluate a novel test protocol, a "Hot Bruce test," which might induce greater physiological strain than the standard Bruce test and be more suitable for medical screening of hazmat candidates.

Methods

Subjects

Over three-quarters of the 203 study subjects (Table 1) were current or potential hazmat responders, the former referred by their employers for medical evaluation (or re-evaluation) for such duty. Other subjects included medical staff who had volunteered to participate in homeland defense activities in the banking community of Charlotte, North Carolina, U.S.A.

Exclusion criteria

Persons with the following conditions were not enrolled:

- Persons with known cardiovascular disease or prior abnormal SBT.
- Inflammatory bowel disease (Crohn's disease or ulcerative colitis).
- History of obstructing peptic ulcer disease.
- Previous abdominal radiation or surgery other than uncomplicated appendectomy or inguinal hernia repair.
- Potentially obstructive bowel disorders including Barrett's esophagus, achalasia, esophageal stricture or diverticula, progressive systemic sclerosis (scleroderma), or diverticulitis.
- Inability to swallow the ingestible thermistor pill (see Methods).
- Diabetic gastroparesis or other motility disorder.
- Demyelinating disease such as multiple sclerosis.
- Hemoglobinopathy.
- Body Mass Index over 35.

Temporary Deferral Criteria: Potential participants who described the following symptoms, or displayed conditions as follows, were deferred until recovered:

- Acute febrile illness.
- Pregnancy.
- Use of the following within 24 hours: beta-blocker, clonidine,. hydralazine, anticholinergic, antihistamine or antipyretic (aspirin, acetaminophen/Tylenol, or nonsteroidal anti-inflammatory medication such as Aleve, Mortin, etc).
- Symptoms suggestive of cardiac ischemia, pending evaluation to exclude such condition.
- Significant musculoskeletal symptoms (e.g., acute back, neck, shoulder or other strain).
- Blood donation within two weeks.
- Any intoxication.

Experimental design

Initial observations involved a standard Bruce protocol test (SBT) included as part of the medical evaluation of the potential hazmat responders, to which were added the measurement of body temperature and of thermal and exertional discomfort. Subjects were given a description of the baseline SBT, with which many were familiar, as well as the methods and purposes of assessing body temperature and thermal discomfort. A subset of 39 of these men and women were later recruited for a second Bruce test, termed a "Hot Bruce Test" (HBT) during which they were to wear thermally-restrictive clothing intended to add heat stress. Risks and benefits of the HBT were explained, including a stipend of 100 US dollars for each exercise session. The SBT was described as "a second treadmill test while dressed in a cotton flannel sweat suit, a plastic 'Sauna Suit' and a diver's wet suit hood intended to cause heat stress, like you would have while wearing Level A protective gear." (All were familiar with the need to wear such totally-encapsulating Level A apparel (Figure 1), during hazmat training and actual responses.) The experimental protocol and consent document were approved by the Institutional Review Board of Carolinas HealthCare System, and procedures were performed in accordance with the Declaration of Helsinki.
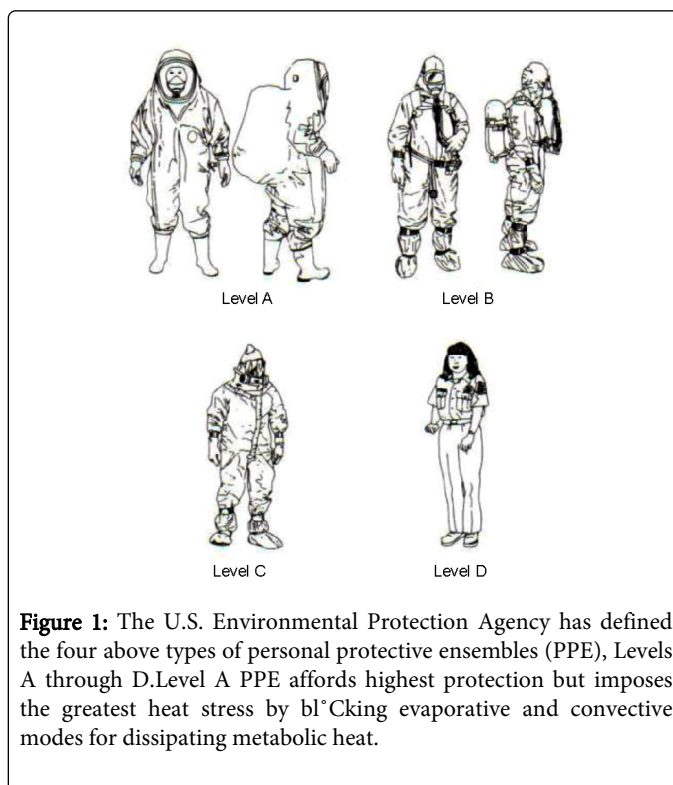

Figure 1: The U.S. Environmental Protection Agency has defined the four above types of personal protective ensembles (PPE), Levels A through D.Level A PPE affords highest protection but imposes the greatest heat stress by bl˚Cking evaporative and convective modes for dissipating metabolic heat.

Experimental protocols

Baseline Testing: After undergoing a medical and Occupational history and physical examination, each subject underwent a maximal, symptom-limited SBT on a motorized treadmill (Q4500 Stress Test Monitor, Quinton Instruments, Bothell WA) according to recommended practices as previously described. [12-16]. All testing was done in mid-day with the subject wearing underwear, gym shorts and tee shirt, athletic socks and running shoes. All 39 HBT subjects later underwent a second maximal Bruce test during which they donned the above clothing, over which they wore the following: (1) A

cotton flannel sweatshirt and sweatpants, (Jerzees, Russell Corp., Box 190, St. George, Ontario N0E 1N0) and (2) an impervious vinyl top and trousers (Model 7628 Solar Conditioning Suit, 2XS, Wal-Mart Co., Bentonville AR). (3) a diver's wet suit hood of 3-mm thick nylon, spandex and neoprene (O'Neill MX0042, 14350 Myford Rd., Irvine CA 92606).

In both the baseline SBT and the later "Hot Bruce Test (HBT)" -- in which added thermal stress was imposed -- exercise testing proceeded until the subject wished to stop, unless any of the following ˚Ccurred sooner: blood pressure over 250/115 or systolic pressure less than 100, chest or jaw pain, ischemic ST-segment depression of >2mm, or complex dysrhythmias including three or more premature ventricular beats (PVBs) in succession, >10 PVBs per minute, >5 multifocalPVBs per minute, or a fall in exercise heart rate below 100/min. Body temperature over 103 ˚F (39.3˚C) or development of significant Q-waves (>0.04 sec) or new ST-segment elevation >2 mm were also criteria to curtail testing, though not encountered. All tests were done by a licensed physician and nurse, both experienced in such testing. A 12-lead electrocardiogram was continuously monitored and blood pressure periodically measured with a blood pressure cuff was placed over vinyl suit on the right biceps. Sublingual (SLT) was measured by an oral thermistor probe (WelchAllyn SureTemp Model 678, Welch Allyn, San Diego CA 92121), being included in order to document its unreliability as an index of central body temperature, lest it be used by clinic personnel in exercise testing of hazmat candidates. Tympanic temperature (TT) was estimated with the use of a thermistor bolometer (Omron Model MC-505, Omron Health Care, Inc., Vernon Hills IL 60061). TT was estimated by making three measurements in each ear, and recording the highest of the six values. Each subject was asked periodically to describe her/his thermal and exertion sensations, according to the Young scale (4=neutral, 8=maximal heat stress [8] and Borg scale (0=no exertion, 20=maximum tolerable exertion [17]. The reason for termination was also recorded (e.g., breathlessness, leg discomfort). On completion of the recovery period, during which the participant sat at rest, final readings were taken and he/she was given a preliminary account of their results, plus answers to any questions.

The risk of cardiac disease for each participant was estimated from horizontal or down-sloping depression of the electrocardiographic ST-segment as an indicator of myocardial ischemia (Froelicher [16]. To improve prognostic value of the test we also assessed heart rate recovery at one minute after exercise (HRR), the chronotropic index (CI), and the Duke Treadmill Score (DTS), these parameters being better predictors of mortality [18-20].

For both the SBT and the HBT, the Physiological Strain Index (PSI) was derived from changes in heart rate and body temperature in the manner described by Moran et al. (1998) and validated using the data whose subjects had worn military protective clothing. PSI values of 5-6 indicate moderate strain, 7-8 high strain, and >8 very high strains, calculated as follows:

$$PSI=5 (HR_p-HR_i)/(180-HR_i)+5(T_p-T_i)/(39.5-T_i)$$

Where, HR_i and HR_p are the initial resting heart rate and peak heart rate, and T_i and T_p are the initial central body temperature and peak central body temperature (degrees Centigrade) measured with either the tympanic bolometer or the ingested thermistor. Values of PSI from earlier investigations were calculated in the same manner, except for those in which pre-procedure, resting heart rates were not available; in such instances, a value of 72 beats per minute was assumed, on the basis of those reports in which such resting heart rates were provided.

Ingestible thermistor for HBT subjects: In the 39 subjects undergoing the HBT, an ingestible, disposable thermistor (CorTemp HT150002 Core Body Temperature Sensor, HQ Inc., Palmetto FL 34221) was swallowed by each participant, no less than three nor more than 14 hours prior to coming to the clinic. This ingested thermistor (ITT) provided an additional measure of central body temperature during the HBT, in addition to the SLT, TT, and subjective thermal discomfort.

Statistical procedures

All statistical analyses were done with commercially available software (Excel. Microsoft Corp., Redmond WA 98052). Descriptive statistics, including means and standard deviations, and counts and percentages, are reported. The primary analysis compares the mean change in body temperature (TT and ITT) from pre- to post-exercise, using the paired t-test of Student. A priori, the success of the HBT to be gauged by a rise in central body temperature of >1.0˚C [4,5,7] and the development of increased thermal discomfort with profuse sweating, uncommon in SBT.

Sample size of the HBT was based on the use of pre- and post-exercise temperatures. However, the standard deviations for the difference in temperatures were not known, so effect sizes were used in determining the sample size. Thirty-two subjects were needed to detect an effect size of 0.5 with an alpha = 0.5 and a power of 80%. An effect size of 0.5 is when the clinically important difference is one-half of a standard deviation. In addition, PSI results from the present study were compared with those published by others.

Results

The demographics of the 203 participants are shown in Table 1. Most were hazmat responders or health care workers. Only 11 percent were smokers. SBT performance (12.2 ± 2.6SD minutes, equivalent to 15 METS) was limited by dyspnea, leg fatigue or a burning sensation in the thigh and/or calf muscles, but without chest pain, cardiac dysrhythmia or evidence of cardiac ischemia. Hence it was not necessary for any of the experimental procedures to be terminated by the monitoring physician. No adverse effects occurred in any subject. Mean values of maximum heart rate, HRR, CI and DTS were 181 ± 12, 36 ± 12, 0.98 ± 0.1, and 10.9 ± 4.7, respectively. DTS was in the low-risk range in all except two subjects whose scores were 1.6 and -2, the latter also having n abnormal CI of 0.68. SBT duration was negatively correlated with Body Mass Index (r=-0.522, p<0.001) but not with age (r=-0.159, p>0.05).

Variable	
Age (years)	37 ± 10
Gender	
Male	183 (90)
Female	20 (10)
Body Mass Index (kg/m^2)	28.6 ± 4.9
˚Ccupation	
Hazmat responder	155 (76)

Health professional	39 (20)
Graduate student, other	9 (4)
Total	203 (100)
Subjects (N=39) who subsequently underwent Bruce testing with added heat stress.	
Age (years)	34 ± 9
Gender	
Male	29 (74)
Female	10 (26)
Body Mass Index (kg/m²)	28.6 ± 5.0
Values are expressed as means ± standard deviations or number (per cent)	

Table 1: Subjects (n=203) who underwent Bruce protocol treadmill testing and body temperature measurements without added heat stress.

Tympanic temperature in the 203 subjects rose by an average 0.5 ± 0.4°C during the SBT (Table 2) while the Young Index rose from 4 to 6.2 ± 0.8, accompanied by little sweating. There was no significant correlation between the temperature rise and the Young Index of thermal discomfort (r=0.25, p>0.05). The mean PSI of 6.0 ± 1.3 indicated a moderate degree of physiological strain. PSI was also not correlated with the Young Index (r=0.25, p>0.05). Sublingual temperature results (Table 2, SLT) demonstrated the unreliability of this metric in assessing thermal responses to exertion because of exercise hyperpnea.

The 39 subjects who underwent both SBT and HBT completed 13.7 ± 3.3 minutes of treadmill exercise during the HBT, a duration not significantly shorter than that of the subgroup's SBT (14.0 ± 3.4, p>0.05). Peak blood pressures were similar in SBT and HBT (systolic, 236 vs. 244 mm Hg; diastolic 55 and 59 mm Hg, respectively; p=0.22).

	Pre-exercise	End-exercise	6 minutes	10 minutes	Maximal	Rate of rise,
	_____	_____	post-exercise	post-exercise	increase, ˚C	˚C per minute
HBT						
ITT	37.1 ± 0.6	37.7 ± 0.6	37.9 ± 0.7	36.6 ± 0.6	0.8 ± 0.4	0.06 ± 0.03
TT	36.6 ± 0.6	37.8 ± 0.9	37.8 ± 0.8	37.6 ± 0.7	*1.3 ± 0.7	*0.10 ± 0.05
SLT	36.5 ± 0.3	36.3 ± 0.5	36.5 ± 0.4	36.8 ± 0.5	0.3 ± 0.4	0.02 ± 0.03
SBT						
TT	36.7 ± 0.6	37.2 ± 0.7	37.3 ± 0.7	37.1 ± 0.6	*0.5 ± 0.4	*0.04 ± 0.03
SLT	36.6 ± 0.3	36.4 ± 0.3	36.5 ± 0.3	36.6 ± 0.3	0.1 ± 0.4	0.01 ± 0.03
* Difference in TT between HBT and SBT, p=0.001						
Abbreviations: HBT: "Hot Bruce Test;" ITT: Ingested Thermistor Temperature; TT: Tympanic Temperature; SBT: Standard Bruce Test; SLT: Sublingual Temperature. NS: Non-Significant Difference						

Table 2: Body temperatures before and after maximal, symptom-limited treadmill exercise in 39 healthy men and women, with ("Hot Bruce Test, HBT) and without (standard Bruce protocol test, SBT) thermally-restrictive apparel. Duration of treadmill exercise, minutes: HBT, 13.7 ± 3.3SD; BPT, 14.0 ± 3.4, p=NS). The initial fall in SLT likely reflects exercise hyperpnea. Temperature values are in ˚C, mean ± standard deviation.

Electrocardiographic results were also similar but HRR which was significantly slower under heat stress of the HBT (Table 3). Peak heart rate was 181 beats per minute under both SBT and HBT conditions. Thus, the higher PSI during Hot Bruce testing (7.4 ± 1.4 vs. 6.2 ± 1.0, p=0.001) reflected the greater rise in tympanic temperature (Table 2, 1.3 vs. 0.5°C, p=0.001). The rise in ITT (0.8 ± 0.4°C) was less than of TT. The Young Index of thermal discomfort (YTDI) was higher in the HBT (7.3 ± 0.6 vs. 6.2 ± 0.8, p=0.001). There was no significant correlation between the PSI and Young Index values, however (r=0.19, p>0.05). The Borg exertion index (BEI) was slightly higher for the HBT than the SBT (17.5 ± 2.6 vs. 16.9 ± 2.8) but the difference was not significant (p=0.28). Sweating was absent or minimal after the SBT. It was marked following the HBT but no direct measurements of sweat rate were made.

	PSI	YTDI	HRR	DTS	CI	BEI
SBT	16.9 ± 2.6	6.2 ± 0.8	30.5 ± 7.8	14.0 ± 3.4	0.98 ± 0.10	16.9 ± 2.6
HBT	7.4 ± 1.4	7.3 ± 0.6	27.6 ± 9.6	13.7 ± 3.3	0.98 ± 0.11	17.5 ± 2.6
p	0.001	0.001	0.01	> 0.05	> 0.05	>0.05

Table 3: Physiological Strain Index (PSI), Young thermal discomfort Index (YTDI), heart rate recovery at one minute post-exercise (HRR), Duke treadmill score (DTS), Chronotropic index (CI), and Borg exertion index (BEI) resulting from Bruce protocol treadmill exertion with ("Hot Bruce Test," HBT) and without (standard Bruce test, SBT) added heat stress in 39 healthy men and women. PSI, YTDI and HRR differed significantly between the two modes of testing.

Type of Testing

Discussion

There is little published information on the effect of Bruce protocol treadmill exercise testing upon body temperature. Thermal effects of such testing are usually not prominent, being overshadowed by dyspnea and leg discomfort which frequently limit the duration of the SBT, in the absence of angina or adverse electrocardiographic or hemodynamic changes. We could identify only three sets of body temperature changes related to SBT [21-23]. The report of Ferguson et al. [21] provided a comparison of rectal temperature changes during and after maximal treadmill exercise in groups of 20 marathoners, 20 joggers and 20 sedentary men in their fourth decades. The latter two groups are most comparable to firefighters and other hazmat personnel. They experienced increases in temperature of 0.5˚C which translated to 0.038 and 0.043˚C per minute of exertion, respectively, quite similar to the finding of 0.038˚C/min in our 203 subjects. Saito et al. [23] found increases in rectal temperature and TT in 20 healthy young men of and 0.77 ± 0.3˚C and 0.66 ± 0.4˚C, respectively, the latter translating to a rate of rise of 0.044˚C per minute of treadmill exertion, again similar to the present study. Northington et al. [22] however, found twice as high a rate of temperature rise (0.08 ± 0.5˚C/min.) based on an increase of 0.8˚C in ITT, in 8 men and 3 women whose SBT duration was only 10 minutes. The reason for this higher rate of increase in the latter group of subjects is unclear, but could have been due to differences in body mass index (BMI) which could also explain their short SBT duration. Although BMI values of the subjects of [22] were not included in their report, this metric has been ass˚Ciated with reduced treadmill endurance [10,24]) and can also alter heat dissipation. We believe that the results of the present study are more representative of hazmat candidates, since three quarters of our subjects were actual hazmat responders.

The maximum rise in ITT in the present study (0.8 vs. 1.3˚C) was less than that of TT, perhaps reflecting a slower thermal transient in perfusion of the abdominal organs surrounding the ingested thermistor, vis-à-vis the short (13.7 minute) duration of treadmill exertion.

The mean PSI value of 6.0 ± 1.3 during SBT was linked to a rise in TT of 0.5˚C (ITT was not measured during SBT). This level of PSI, while consistent with a moderate degree of physiological strain was accompanied by little or no sweating. However, hydration was not controlled in our subjects and as [25] have stated, "sweat production by itself does not comprehensively represent heat strain." Sweating was not quantified either subjectively or by pre-and post-exercise body weight changes in our participants, thus weakening the value of this observation.

The SBT is a familiar, well-validated instrument for inducing maximal cardiovascular stress in a short time; hence it has been a likely choice for testing candidates for hazmat duty. It has some important disadvantages, however. First, it induces only a mild degree of thermal stress, partly because of its brevity. Secondly, SBT performance was not associated with ability to lift a manikin up a staircase or to complete a 45-minute treadmill walk in clothing--inexpensive "Sauna Suits" on top of gym clothes--chosen to partial simulate hazmat responses [11]. While this latter method induced body temperature increases similar to those found in hazmat drills, such a long duration of testing would be impractical when screening multiple candidates for hazmat duty in a clinical setting.

Because of the above considerations, a change in stress testing methodology seemed appropriate for the medical evaluation of candidates for hazmat duty, since heat stress was identified as the raison d'etre for stress testing of such workers Hazmat responses require the use of impermeable protective gear, thus making heat stress unavoidable for most of these responders. In addition to wearing 20-kg, protective ensembles whose internal temperature is often 10-15˚C above ambient levels, these workers often experience heavy exertion, such as in extracting persons overcome by toxic agents. In-suit temperatures may be further increased by fire or explosive incidents perpetrated by terrorist agents.

In the present study, a second layer of readily available clothing, i.e., a cotton "sweat suit" was added plus a neoprene diver's wetsuit balaclava hood. This combination, worn along with the Sauna Suit, enabled substantial heat stress to be accomplished in the same time as subjects were able to complete with the SBT. The PSI resulting from the HBT was indicative of a high level of strain, significantly greater than the moderate strain induced by the SBT, and more like PSI levels achieved by operational simulations of hazmat or firefighting responses [5-7,26-28]. There are a number of weaknesses in this study. HBT did not simulate hazmat responses, since completely encapsulating protective suits with self-contained breathing apparatus (SCBA) were not worn. The bulk and weight of such gear make it unsuitable for running on a treadmill, and its high cost makes it further impractical for application to stress testing in primary care, occupational medicine or cardiology clinics where medical evaluation of hazmat candidates may be done.

Although the difference in sweating between the HBT and SBT were pronounced in all 39 subjects, no attempt was made to quantitate this difference, such as measurement of pre- and post-exercise serum analytes, urine concentration or changes in body weight using a sensitive platform balance, for example. The present study thus did not include other serum markers of possible skeletal muscle overuse.

Kales et al. [2], Geibe et al. [29,30] have reported that pre-existing cardiovascular disease, current smoking and hypertension are strong predictors of adverse outcomes including death in firefighters and likely have similar impact on hazmat responders [31]. Adding the results of SBT alone has not been investigated as to the ability to provide additional predictive value for adverse cardiovascular outcomes of hazmat or firefighting duty [32], perhaps because indications of myocardial ischemia clearly require further investigation a priori, in order to qualify such a person [33] medically for this type of duty (NFPA 2007). Without further study [34], it would be premature to infer that the HBT is superior to the SBT in identifying hazmat candidates who require such investigation [35-38].

Conclusion

In summary, the limitation of the SBT in causing thermal stress was confirmed in a 203 examinees for hazmat duty, and a novel variation which might be termed a Hot Bruce Test (HBT) is described and shown to induce higher TT [39] and PSI values, both similar to those found in hazmat response simulations [40]. The HBT does not require more expensive equipment or longer testing time than the SBT, and may have added value in the medical evaluation of candidates for hazmat duty [41,42].

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