Research Article

The Effects of Metabolic Work Rate and Ambient Environment on Physiological Tolerance Times While Wearing Explosive and Chemical Personal Protective Equipment

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This study evaluated the physiological tolerance times when wearing explosive and chemical (>35 kg) personal protective equipment (PPE) in simulated environmental extremes across a range of differing work intensities. Twelve healthy males undertook nine trials which involved walking on a treadmill at 2.5, 4, and 5.5 km⋅h⁻¹ in the following environmental conditions, 21, 30, and 37 °C wet bulb globe temperature (WBGT). Participants exercised for 60 min or until volitional fatigue, core temperature reached 39 °C, or heart rate exceeded 90% of maximum. Tolerance time, core temperature, skin temperature, mean body temperature, heart rate, and body mass loss were measured. Exercise time was reduced in the higher WBGT environments (WBGT37 < WBGT30 < WBGT21; P < 0.05) and work intensities (5.5 < 4 < 2.5 km⋅h⁻¹; P < 0.001). The majority of trials (85/108; 78.7%) were terminated due to participant’s heart rate exceeding 90% of their maximum. A total of eight trials (7.4%) lasted the full duration. Only nine (8.3%) trials were terminated due to volitional fatigue and six (5.6%) due to core temperatures in excess of 39 °C. These results demonstrate that physiological tolerance times are influenced by the external environment and workload and that cardiovascular strain is the limiting factor to work tolerance when wearing this heavy multilayered PPE.

1. Introduction

Personal protective equipment (PPE) is required in sporting and occupational settings to protect the wearer from a range of hazards [1]. Unfortunately, PPE may increase the rate of metabolic heat production at rest and during exercise. Concomitant elevations in thermoregulatory and cardiovascular strain during exercise in high ambient temperatures and humidity can lead to progressive increases in body heat content and if left unchecked this may lead to heat related illnesses [2]. In humans, the primary source of heat dissipation during exercise is through increased skin blood flow and sweating [2–4]. Wearing PPE may impede evaporative heat loss through sweating and a condition of uncompensable heat stress may occur [5, 6]. Consequently, information regarding work tolerance and rest cycles is of paramount importance for the health of the wearer in an occupational setting.

Several studies have examined the physiological strain encountered by fire fighters [7], police officers [8, 9], security guards [10, 11], pilots [12], and military personnel [13, 14] where PPE is a necessity. The major focus of this research has been the development of safe occupational guidelines for participants wearing PPE in the workplace. This is of particular importance as symptoms of heat illness ranging from headache to loss of consciousness and even death have previously been reported in emergency first responders and military personnel [15–17]. However, there has been comparatively little research done to represent the physiological strain experienced by explosive ordinance disposal (EOD) technicians.

We have previously examined the physiological effects of wearing EOD PPE in the field [17, 18] and in a controlled laboratory [19] setting. However, in theatre EOD technicians regularly have to don chemical PPE in addition to the EOD
ensemble when the severity or type of threat is unknown. Typically clothing which confers protection from chemical threats is fully encapsulating and impermeable in nature and requires the use of a respirator or self-contained breathing apparatus [1, 5, 6, 20]. In preparation for such operational scenarios, these technicians regularly train and operate while wearing these ensembles in extreme environments. It is well established that, in isolation, multiple layers of protective clothing, load-carryage, and the use of a respirator have a negative effect on ventilatory function, thermoregulation, and exercise tolerance during prolonged submaximal exercise [1, 13, 21]. Multiple clothing layers and load-carryage increase the energy cost of physical activity, apart from the added weight of the clothing per se [22]. Each layer of protective clothing also traps air between the skin and/or other clothing layers, and a microenvironment which serves as an insulator is created [23, 24]. Moreover, chemical protective garments typically have a high water vapour resistance and this further reduces the ability of the wearer to evaporate sweat [1, 25]. Respirators are also known to impair exercise capacity [21] by placing extra stress on the cardiorespiratory system during exercise. Ultimately, these components combine to increase an individual's metabolic rate and reduce their ability to dissipate heat during exercise, and a condition of uncompensable heat stress is created. Taken together, these findings suggest that the addition of chemical PPE to an EOD ensemble may impair thermotolerance and increase the risk of heat related illness.

Thus, the purpose of the present investigation was to examine the physiological tolerance times while wearing chemical and explosive protective clothing concurrently across a range metabolic work rates and ambient environments. Establishing this information has implications for determining safe tolerance times for EOD technicians when required to wear this PPE in various environments.

2. Methods

2.1. Participants. Twelve healthy, recreationally active males [(mean ± SD): age = 24.1 ± 3 years, height = 1.79 ± 0.06 m, body mass = 76.4 ± 8.4 kg, body surface area 2.0 ± 0.1 m², sum of eight skinfolds 79.1 ± 31.6 mm, maximal oxygen uptake (VO₂ max) 56 ± 5 mL·kg⁻¹·min⁻¹, heart rate max 195 ± 9 beats·min⁻¹] volunteered to participate in the study. The study was approved by the university human research ethics committee and all participants completed an informed consent form and medical history questionnaire. To eliminate the confounding influences of gender on physiological responses to heat stress, only nonacclimatised, nonsmoking males, free from any known cardiovascular, metabolic, and respiratory diseases, were considered. Participants were asked to refrain from vigorous exercise and avoid the consumption of caffeine and alcohol during the 24 hours preceding the laboratory visits.

Participants attended the laboratory on four separate occasions, at the same time of day, separated by a minimum of 7 days. In the initial visit height and nude body mass were recorded and body surface area was subsequently calculated [26]. Skinfold thickness measures were obtained, using Harpenden (John Bull, West Sussex RH15 9LB, UK) callipers, at eight sites (biceps, triceps, subscapular, iliac crest, supraspinale, abdominal, front thigh, and medial calf). VO₂ max was determined by indirect calorimetry during a progressive incremental running protocol on a motorised treadmill [27]. Participants were also provided with the opportunity to familiarise to the PPE ensemble by walking around the laboratory and on the treadmill at the speeds to be utilised for the trials.

2.2. Experimental Protocol. In the three remaining laboratory visits participants wore a fully encapsulating NFPA 1994 Class 3 chemical/biological protective garment, including outer gloves and booties (Extended Response Suit, Lion Apparel, Regency Park 5942, South Australia, Australia; 1.35 kg), and a respirator (Promask with a pro2000 PF10 filter; Scott Safety, Lancashire, England; 0.7 kg). The garment was made from trilaminate, a three-layer chemical/biological protective fabric, consisting of a selectively permeable barrier film laminated between outer and inner textiles. A Med-Eng EOD9 suit (Allen Vanguard, Ogdensburg, New York, USA) consisting of a jacket, trousers, groin protection, and a helmet (33.4 kg) was donned over the chemical PPE and respirator. The combined weight of the ensemble was 35.45 kg. Participants' base layer consisted of a t-shirt, shorts, socks, and underwear [28]. Athletic shoes with a soft rubber sole were also worn during testing [28]. During the trials the participants walked on a treadmill, while wearing the PPE, in an environmental chamber (4 × 3 × 2.5 m; length, width, height, resp.). A wet bulb globe temperature (WBGT) of 21, 30, or 37°C was obtained by the following ambient temperatures and relative humidities: 24°C, 50%; 32°C, 60%; and 48°C, 20%; respectively. A simulated wind speed equivalent to ~4.5 km·h⁻¹ and a radiant heat load (two radiant heaters positioned ~1.3 m from the participant) were incorporated throughout the testing. These environmental conditions were also monitored independently (Quest Temp, Airmet, Australia). During each of these laboratory visits the participant completed three treadmill-walking trials of 2.5, 4, and 5.5 km·h⁻¹ with a 1% gradient. This equated to an external work rate [29] of ~135, 207, and 307 W·m⁻² for a 76 kg individual with a body surface area of 2.0 m². The order of the testing, for both the work rate and the environment, was randomised using a random number generator in a controlled crossover design.

During each trial, standard termination criteria were applied in accordance with the American Society for Testing and Materials guidelines [28]: (1) core body temperature reaching 39.0°C; (2) 60 minutes of exercise; (3) heart rate > 90% of maximum; or (4) fatigue or nausea. Following the attainment of one of the termination criteria, the participant exited the environmental chamber and donned the EOD protective clothing. Participants were then instructed to rest in an air-conditioned room. In the following recovery period participants were provided with food and fluid to a volume equivalent to 125% of the body mass loss in the preceding trial. This was undertaken to ensure recovery of body mass
and hydration status prior to commencement of subsequent trials. Core temperature and heart rate were monitored and following their return to baseline levels the participant provided a blood sample, had their nude body mass assessed, and commenced donning the EOD protective clothing for the subsequent trial. Three trials were conducted in this manner per testing session.

2.3. Outcome Measures. The primary outcome measure of the current study was physiological tolerance times measured to the nearest 0.5 min. Core temperature was recorded using an ingestible sensor (CorTemp, HQ Inc., Palmetto, FL, USA) swallowed ~6 hours before each trial. This was to allow sufficient time for the sensor to pass from the stomach to the intestines, where the reading of core body temperature is optimal [30]. Weighted mean skin temperature (Tsk) was calculated using four thermochrons (iButton, Maxim Integrated, CA, USA) attached to the back of neck, inferior border of right scapula, dorsal right hand, and proximal third of the right tibia [31]. Mean body temperature was calculated using the equation proposed by Stolwijk and Hardy [32]. Participants also wore a heart rate monitor (Polar Team2, Kempele, Finland) that was attached before entering the environmental chamber. Physiological strain index (PSI) using simultaneous measurements of core temperature and heart rate was calculated using Morán’s [33] equation. PSI was rated on a scale of 1–10, with five indicating moderate, seven high, and nine very high physiological strain [33].

To determine if baseline physiological and hydration indices were similar, pretrial heart rate, mean body temperature, serum osmolality, and body mass were also analysed in a similar manner. The effect of environment, work intensity, and their interaction were tested. Paired t-tests, using a Bonferroni correction, were conducted where significant differences were observed. All data was analysed using SPSS (SPSS version 21.0, SPSS Inc., Chicago, USA). Significance was set a priori at the $P < 0.05$ level.

3. Results

3.1. Baseline Data. Participants commenced all nine trials from a resting physiological baseline (Table 1), with no significant differences between trials in heart rate ($P = 0.213$), mean body temperature ($P = 0.176$), serum osmolality ($P = 0.407$), or body mass ($P = 0.894$). The mean ± SD (range) duration of rest was $91 ± 18$ min ($58–155$) when multiple trials were performed on the same day.

3.2. Tolerance Times and Termination Criteria. All twelve participants completed all nine trials (total trials: 108) with no serious adverse events recorded. The majority of trials (85/108; 78.7%) were terminated due to participants’ heart rate exceeding 90% of their maximum (Table 2). A total of eight trials (7.4%) lasted the full duration of 60 min. Finally, nine (8.3%) trials were terminated due to volitional fatigue and six (5.6%) due to core temperatures in excess of 39°C.

A significant main effect in tolerance time (Figure 1, Table 2) was observed for environment ($WBGT_{37} < WBGT_{30} < WBGT_{21}; P < 0.001; 1 – \beta = 1.0$), work intensity ($5.5 < 4 < 2.5 \text{ km·h}^{-1}; P < 0.001; 1 – \beta = 1.0$), and their interaction ($P < 0.001; 1 – \beta = 0.999$).

3.3. Physiological Data. Work intensity (Table 3) had a significant effect on core temperature ($P < 0.001; 1 – \beta = 0.992$), skin temperature ($P = 0.002; 1 – \beta = 0.936$), mean body temperature ($P < 0.001; 1 – \beta = 0.997$), heart rate ($P = 0.022; 1 – \beta = 0.682$), and body mass loss ($P < 0.001; 1 – \beta = 1.0$). Core temperature ($P < 0.01$), skin temperature ($P < 0.05$), and mean body temperature ($P < 0.01$) were lower at the end of the $5.5 \text{ km·h}^{-1}$ trials compared to the $2.5$ and $4 \text{ km·h}^{-1}$ trials. Body mass loss was also greater in the lower work intensities ($5.5 < 4 < 2.5 \text{ km·h}^{-1}; P < 0.01$). Conversely, despite a trend for an increase in heart rate at the $2.5 \text{ km·h}^{-1}$ trials compared to the $4 (P = 0.055)$ and $5.5 (P = 0.077)$ km·h$^{-1}$ trials, no post hoc differences were observed.

| Table 1: Baseline physiological and hydration indices ($n = 12$). |
|-------------------|-------------------|-------------------|-------------------|
| Speed (km·h$^{-1}$) | HR (bpm) | $T_{mb}$ (°C) | Serum osmolality (mOsmol·kg$^{-1}$) | Body mass (kg) |
| 2.5 | 102 ± 4.7 | 36.5 ± 0.08 | 291 ± 1 | 76.7 ± 2.26 |
| 4 | 103 ± 4.1 | 36.5 ± 0.06 | 292 ± 1 | 76.7 ± 2.29 |
| 5.5 | 99 ± 3.9 | 36.4 ± 0.08 | 292 ± 1 | 76.7 ± 2.26 |

Values are means ± SEM. HR, heart rate; bpm, beats per minute; $T_{mb}$, mean body temperature.
(3) cardiovascular, rather than thermoregulatory, strain is the limiting factor to work tolerance when wearing this ensemble.

As anticipated, tolerance time was reduced in the higher ambient environment and work intensities (Table 2; Figure 1) when wearing the EOD and chemical PPE. However, the ambient temperature and vapor pressure had far less impact on physiological tolerance time as the metabolic rate increased. When the metabolic rate exceeds 250 W·m⁻² or 500 W, as evident in the 5.5 km·h⁻¹ trials, the role the environment plays in the rate of heat storage and work tolerance is limited [5]. These data complement the findings of Cheung and colleagues [5] and demonstrate minimal differences between the tolerance times in the highest work intensity (>300 W·m⁻²) across the three environments (20.4, 16.9, and 15.1 min in the WBGT21, 30 and -37 environments, resp.; Table 2). In contrast, significant differences were observed in the lower work intensities, especially in the 2.5 km·h⁻¹ trials, and tolerance times were greater in the cooler environments (53.1, 39.1, and 33.5 min; Table 2). The actual tolerance times in the WBGT21 environment, when walking at 2.5 km·h⁻¹,
are likely to be even greater compared to the other conditions as 8 of the 12 participants completed the maximum duration of 60 min (Table 2). These individuals were physically capable of exercising beyond the termination criteria of 60 min; however, work beyond this duration is unlikely when wearing this PPE in the field [17,18].

The current study is in agreement with previous research findings examining PPE of similar weight [1, 19] and further indicates that cardiovascular strain governs physiological tolerance times regardless of environment or work intensity. Over 78% of the trials in the current study were terminated based on heart rates in excess of 90% of maximum. These near maximal heart rates resulted in moderate to very high levels of physiological strain in almost all trials (Table 3), despite core temperature only reaching 39°C (P < 0.05); b significantly different to the same speed at WBGT 21°C (P < 0.05); c significantly different to 5.5 km·h⁻¹ at the same environmental condition (P < 0.05); d significantly different to 4 km·h⁻¹ at the same environmental condition (P < 0.05); e significantly different to the same speed at WBGT 30°C (P < 0.05).

Conclusions
In conclusion, this investigation has demonstrated that physiological tolerance times are significantly reduced in higher ambient environments and workloads when wearing explosive and chemical PPE. Secondly, despite the short durations of exercise, high to very high levels of physiological strain were experienced by all participants. Finally, cardiovascular strain is the limiting factor to work tolerance when wearing this heavy, multilayered, and encapsulating PPE.
Conflict of Interests
The authors declare that there is no conflict of interests regarding the publication of the paper.

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