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This study examined the physiological responses of seven volunteers exercising in the heat while wearing three different toxicological protective systems. The Toxicological Agent Protective (TAP) suit has been available for use for more than 30 years while the other two protective systems are developmental efforts. The Self-Contained Toxicological Environmental Protection Outfit (STEPO) includes either a backpack-rebreather (with CO_2 scrubber) and ice-cooling vest (STEPO-R), or a tether system which supplies breathing/cooling air inside the suit (STEPO-T). After the volunteers were heat acclimated, the three toxicological protection systems were evaluated utilizing a counter-balanced experimental design initially in a hot (38°C, 30% rh), and then in a cool (18°C, 30% rh) environment while subjects walked at

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19. Abstract (Cont'd)

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PHYSIOLOGICAL EVALUATION OF MEN WEARING THREE DIFFERENT TOXICOLOGICAL PROTECTIVE SYSTEMS

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This study examined the physiological responses of seven volunteers exercising in the heat while wearing three different toxicological protective systems. The Toxicological Agent Protective (TAP) suit has been available for use for more than 30 years while the other two protective systems are developmental efforts. The Self-Contained Toxicological Environmental Protection Outfit (STEPO) includes either a backpack-rebreather (with CO_2 scrubber) and ice-cooling vest (STEPO-R), or a tether system which supplies breathing/cooling air inside the suit (STEPO-T). After the volunteers were heat acclimated, the three toxicological protection systems were evaluated utilizing a counter-balanced experimental design initially in a hot (38°C, 30% rh), and then in a cool (18°C, 30% rh) environment while subjects walked at 1.12 m/s, 0% grade for an attempted two hours. In the hot environment, the STEPO-T system allowed a longer exercise time (65.0 ±5.3 min) compared to the TAP (51.3 ±2.2 min) or STEPO-R (54.5 ±3.2 min) systems. Evaporative sweating rate was significantly greater for the STEPO-T (523.0 ±58.6 $g/m^2/h$) compared to either the STEPO-R (210.2 ±45.2 $g/m^2/h$) or TAP (78.8 ±18.5 $g/m^2/h$) systems, while the change in rectal temperature was less for the STEPO-T compared to the other systems. There was no statistical advantage of any one system in terms of exercise time in the cool environment. While evaporated sweating rate was greater for the STEPO-T (230.7 ±18.9 $g/m^2/h$) in the cool environment compared to both STEPO-R (161.1 ±52.7 $g/m^2/h$) and TAP (29.4 ±3.2 $g/m^2/h$), rectal temperatures were not significantly different between systems. While the STEPO-T system appeared to be somewhat advantageous in the hot environment, neither STEPO system enhanced performance in the cool environment. Two subjects wearing the STEPO-T and STEPO-R systems suffered back spasms severe enough to necessitate their withdrawal from testing. Human factors design limitations were identified which detracted from the overall performance of these STEPO systems. Development efforts to improve the STEPO system designs continue, and physiological evaluation of new developmental models is underway.

INTRODUCTION

For personnel working with highly toxic substances, protective clothing is essential. The Toxicological Agent Protective (TAP) suit has been employed to protect individuals from toxic agents for over 30 years. For respiratory protection, the TAP suit employs a chemical protective mask/hood assembly for filtering ambient air. In accordance with the Occupational Safety and Health Administration's revised safety standards for allowable exposure to toxic agents, The Surgeon General of the Army and the Army Materiel Command safety community have identified the need for an improved protective suit. An interim Self-Contained Toxicological Protective Outfit (STEPO) has been developed by the U.S. Army Natick Research, Development and Engineering Center. To facilitate design improvements, our Institute has evaluated the STEPO systems for physiological strain they may impose on human volunteers.

The STEPO is designed to be used in two configurations, one with a backpack rebreather-respirator and cooling vest (STEPO-R), and one tethered to a clean air supply for breathing and cooling (STEPO-T). The TAP suit contains no tether, rebreather, or microclimate-cooling option. All three systems are totally encapsulating and made mostly of impermeable butyl rubber-coated nylon. Since these systems limit the normal physiological mechanisms of heat dissipation, particularly evaporative sweating, one would expect the physiological strain from the heat to be exacerbated when combined with exercise. The thermal responses associated with wearing protective clothing, with and without microclimate cooling have been documented, and microclimate cooling has been shown to be effective in reducing heat strain during exercise in hot environments (Shapiro et al., 1982; Pandolf et al., 1987).

The present study assessed the physiological responses (rectal temperature, mean skin temperature, heart rate and sweating rate) and endurance time of heat-acclimated soldiers during exercise in temperate and hot environments. Volunteer soldiers were evaluated while they wore the TAP suit, the STEPO-R, and the STEPO-T systems in each environment. The results of this study have been reported in part by Pandolf et al. (1989).

METHODS

Seven soldiers, medically cleared and with no known history of heat injury or chronic respiratory illness, volunteered to participate in this study. After being informed of the purpose, testing procedures, known health risks, and their right to discontinue participation at any time without penalty, the soldiers signed a statement of informed consent, indicating their understanding and desire to serve as volunteers in this study. The physical characteristics of the subjects (mean±SD) were: age, 21 ±6 yr; height, 177 ±7 cm; weight, 72 ±11 kg; body fat, 16 ±3%; and maximal aerobic power, 57 ±7 ml O_2/kg/min (~4L O_2/min).

<u>Experimental design</u>

Maximal aerobic power ($\dot{V}o_2max$) was determined for each subject using a continuous treadmill exercise protocol (Sawka et al., 1984). The subjects spent ~10 hours during a 5-day training period becoming familiar with wearing the protective outfits and walking on the treadmill in them.

Following familiarization, subjects participated in an exercise/heat-acclimation program for eight days. Acclimation consisted of daily treadmill exercise [1.56 m/s, 4% grade] in a hot environment [42°C (108°F), 30% rh, 0.89 m/s wind speed] for 120 min. This exercise represented ~36% $\dot{V}o_2max$ for these subjects. During acclimation, subjects wore shorts, T-shirts, socks and athletic shoes. Of the total seven heat-acclimated subjects, five completed both the heat- and the cool-stress tests. The sixth test subject completed only the heat-stress tests, while the seventh completed only the cool-stress tests.

After the acclimation period, the three protective systems (TAP weighing ~8 kg, STEPO-R ~30 kg, and STEPO-T ~20 kg), each worn over a layer of light cotton clothing, were evaluated on six different days, first for three days in the heat [38°C (100°F), 30% rh, 0.89 m/s wind speed], and then three days in the cool environmental condition [18°C (65°F), 30% rh, 0.89 m/s wind speed]. Within each of the two environments, the three protective ensembles were evaluated in a counterbalanced order, while the subjects attempted to walk on the treadmill (1.12 m/s, 0% grade) for two hours.

<u>Experimental procedures</u>

During acclimation and each exercise-heat/cool stress test (EXT), the electrocardiogram was telemetered to a cardiotachometer unit, displayed continuously on an oscilloscope, and heart rate (HR) was recorded every 10 min. Rectal temperature (T_{re}) was measured from a flexible thermistor inserted ~10 cm beyond the anal sphincter, and skin temperature was measured via a three point (forearm, chest, calf) thermocouple skin harness with mean weighted skin temperature ($\bar{T}_{sk}$) calculated according to Burton (1935). The T_{re} and $\bar{T}_{sk}$ were continuously monitored and recorded every min. Total body sweat loss was determined from nude body weight changes pre- to post-exercise, and corrected for water ingestion and urine output. Unevaporated sweat in clothing was calculated to determine evaporative sweating rate.

During acclimation, subjects were allowed to drink water <u>ad libitum</u> but were encouraged to drink enough to maintain hydration. During the EXT, prior to encapsulation in the protective systems, subjects drank 500 ml of water, after which time they refrained from drinking until each test was completed. Metabolic rates were determined during the familiarization sessions only (when the mask/hood assembly was not in use), via open circuit spirometry. Periodically during the EXT, subjects were asked to rate their perception of effort based on the Borg Scale (Borg, 1970), and their thermal sensation based on a scale modified (Young et al., 1987) from Gagge et al. (1967).

During the acclimation sessions and each EXT, testing was terminated if: (1) T_{re} rose at a rate exceeding 0.6°C in five min; (2) T_{re} reached 39.5°C; (3) HR exceeded 180 b/min for five consecutive min; or, (4) if an individual felt faint, sick or was otherwise unable to continue. Testing was also discontinued for any subject wearing a protective system when there was a failure in the rebreather-respirator, the cooling vest or the tethered-air system.

Statistical treatment

These data were analyzed using a repeated measures analysis of variance, followed by Tukey's post hoc test. Statistical significance was accepted at the $P<0.05$ level.

RESULTS

FIGURE 1 ABOUT HERE

While treadmill speed and grade were the same for all EXT, because of differing ensemble weights, the exercise intensity was ~26% of $\dot{V}o_2$max during the TAP tests, ~34% of $\dot{V}o_2$max during the STEPO-R tests, and ~30% of $\dot{V}o_2$max during the STEPO-T tests, as measured during the familiarization sessions. Figure 1 presents the exercise times (mean±SE) during the EXT for each suit. While exercising in the cool environment, there were no statistically significant differences ($P=0.08$) in exercise time among the three ensembles (TAP, 120.0±0; STEPO-R, 83.0 ±11.9; STEPO-T, 94.5 ±12.9 min). However, during the TAP suit test, all subjects completed the two hour walk, while only two subjects completed the two hours in the STEPO-R and three subjects did in the STEPO-T systems. When the three ensembles were tested in the heat, use of the STEPO-T system resulted in a significantly extended exercise time (65.0 ±5.3 min) compared to either TAP (51.3 ±2.2 min) or STEPO-R (54.5 ±3.2 min). The briefest exercise time for an individual was 44 min during the TAP suit test, while the longest time achieved in the heat was 84 min during the STEPO-T test.

Figure 2 illustrates the final T_{re}, final $\bar{T}_{sk}$, and final HR of the EXT for the three ensembles. These final values (mean ±SE) represent the point at which a test was terminated for each individual. Final T_{re} did not differ significantly among ensembles during either the cool or hot tests. However, when the change in rectal temperature (ΔT_{re}) from 0 to 50 min of the test was evaluated, there was less ($p<0.05$) of an increase in T_{re} (1.19 ±0.09°C) for soldiers in STEPO-T than during the TAP (1.84 ±0.11°C) or STEPO-R (1.63 ±0.11 °C) tests. The ΔT_{re} during the cool tests did not differ significantly among the three ensembles (TAP, 0.50 ±0.09; STEPO-R, 0.57 ±0.06; STEPO-T, 0.52 ±0.09°C). Figure 2 also illustrates that while final $\bar{T}_{sk}$ did not differ significantly among the three ensembles in the cool environment, during the hot tests it was greater ($p<0.05$) for the TAP suit compared to the STEPO-T system (TAP, 38.9 ±0.2; STEPO-R, 37.4 ±0.6; STEPO-T, 37.3 ±.3°C). Final HR in the cool tests was significantly higher for the STEPO-T system compared to the TAP suit, however final HR did not differ significantly among ensembles during the hot tests.

FIGURF 2 ABOUT HERE

Figure 3 displays the total body sweating rate (M_{sw}), the evaporative sweating rate (E_{sw}) and the ratio of evaporative to total sweating rate (E_{sw}/M_{sw}) comparing the three ensembles during the EXT. During testing in the cool environment, M_{sw} was significantly greater for subjects using the STEPO-R system compared to the TAP suit. The M_{sw} was similar ($P>0.05$) among the three ensembles in the hot environment. In contrast to M_{sw}, the E_{sw} during the cool tests was significantly greater in the STEPO-T system compared to the TAP suit (TAP, 29.4 ±3.2; STEPO-R, 161.1 ±52.7; STEPO-T, 230.7 ±18.9 g/m²/h). During the hot tests, the E_{sw} was significantly greater for the STEPO-T system compared to either the STEPO-R or TAP ensembles (TAP, 78.8 ±18.5; STEPO-R, 210.2 ±5.2; STEPO-T, 523.0 ±58.6 g/m²/h). In the cool environment, the evaporative sweating rate represented 11.8%, 43.5% and 68.3% of the total sweat loss for TAP, STEPO-R and STEPO-T, respectively. The difference between the TAP suit and STEPO-T system was significant ($p<0.05$). During the hot tests, the evaporative sweating rate represented 9.2%, 27.8% and 64.4% of the total sweating rate for TAP, STEPO-R and STEPO-T respectively, with all three values being significantly different.

FIGURE 3 ABOUT HERE

During the cool tests, the final rated perceived exertion (RPE) was significantly higher for the STEPO-R system (perceived as somewhat hard) compared to either the TAP suit or STEPO-T system (perceived as fairly light). However, during the hot tests there were no significant differences in final RPE among these ensembles (all perceived as somewhat hard). During the cool tests, thermal sensation (TS) was significantly greater for the STEPO-R (perceived as warm) compared to the STEPO-T system (perceived as comfortable). However, during the hot tests, TS did not differ significantly among these three ensembles (all perceived as between warm and hot). More detailed RPE and TS data are reported by Pandolf et al. (1989).

DISCUSSION

Clothing which affords protection for individuals working in toxic environments is of importance to civil defense, emergency service, industrial and military groups. However, these protective clothing ensembles are primarily constructed of impermeable butyl rubber-coated nylon which results in limited evaporative cooling. Thus, these toxicological protective garments restrict the body's normal heat dissipating mechanisms, namely the evaporation of sweat, and generally result in diminished exercise-heat tolerance (Pandolf and Goldman, 1978). In addition, improvements over the filter/mask system of the current TAP suit have led to the development of these prototype systems.

In the cool environment, there were no statistically significant differences in exercise time among the three systems; however, only during the TAP tests did all six subjects complete the two-hour walk. While the evaporative sweating rate was greater for the STEPO-T system in the cool environment, the rectal temperature and change in rectal temperature were not different between the three systems. Thus, in the cool environment, the limited evaporative sweating rate in the TAP suit was adequate for dissipating body heat and avoiding significant heat storage given these specific metabolic demands and environmental conditions. The heart rate response during the STEPO-T cool tests was higher than for the other two systems, and even though this was not the heaviest ensemble, metabolic rates for this system were somewhat elevated. From an exercise duration and physiological standpoint, none of these three systems offered a distinct advantage during the cool tests. However, from a perceptual standpoint, both rated perceived exertion and thermal sensation were higher during the STEPO-R cool tests. The total ensemble weight for the STEPO-R greatly exceeded the other two systems and heavy external loads are known to elevate rated perceived exertion (Pimental and Pandolf, 1979; Robertson et al., 1982). However, thermal sensation is generally thought to be influenced by skin temperature (Young et al., 1987) which did not differ between systems during these cool tests.

In the hot environment, the STEPO-T system seemed advantageous since longer exercise times were achieved; however, final rectal temperature and heart rate did not differ between the three systems. The longer exercise time for the STEPO-T system during the hot tests was probably associated with the greater evaporative sweating rate over time for this system. The rate of rise in rectal temperature, which is related to the rate of body heat storage, has been suggested to be a good indicator of exercise-heat tolerance (Pandolf and Goldman, 1978; Pandolf et al., 1987). The perceptual responses of rated perceived exertion and thermal sensation during the hot tests did not differ between systems. It is interesting to note that the higher mean skin temperature observed for the TAP suit during the hot tests did not influence the thermal sensation.

Two subjects suffered back spasms severe enough to require their removal from the specific test day (and in one case further testing) while wearing the STEPO-T and STEPO-R. These injuries were probably related to the weight of the prototypes and/or the altered walking posture or gait that may have resulted from wearing these systems.

In conclusion, the STEPO-T system appeared to enhance performance in the hot environment, while neither STEPO system provided an advantage in the cool environment. However, the ensemble weight and human factors design were thought to limit the overall performance of the interim STEPO systems. Currently, improved STEPO ensembles are undergoing evaluation in our laboratory. Among the changes are modified weight distribution, enhanced visibility, a more supportive boot option, prolonged cooling time, and improved chemical protective fabrics, as well as a rebreather respirator that provides prolonged protected breathing.

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FIGURE LEGENDS

Figure 1. Exercise (exposure) times for the TAP suit, STEPO-R and STEPO-T systems during the hot (38°C, 30% rh) and cool (18°C, 30% rh) tests (mean±SE).

Figure 2. Final rectal temperature (FINAL T_{re}), final mean-weighted skin temperature (FINAL $\bar{T}_{sk}$) and final heart rate (FINAL HR) for the TAP suit, STEPO-R and STEPO-T systems for the hot and cool tests (mean±SE).

Figure 3. Total body sweating rate (M_{sw}), evaporative sweating rate (E_{sw}) and the ratio of the evaporative to total body sweating rate (E_{sw}/M_{sw}) for the TAP suit, STEPO-R and STEPO-T systems for the hot and cool tests (mean±SE).

Figure 1

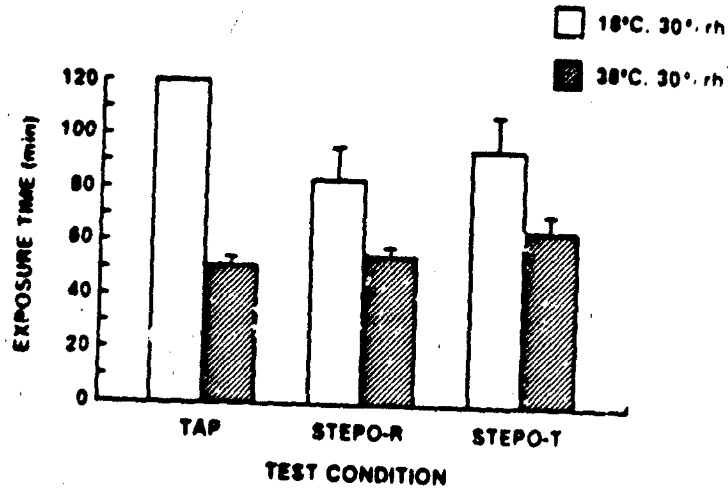

Figure 3

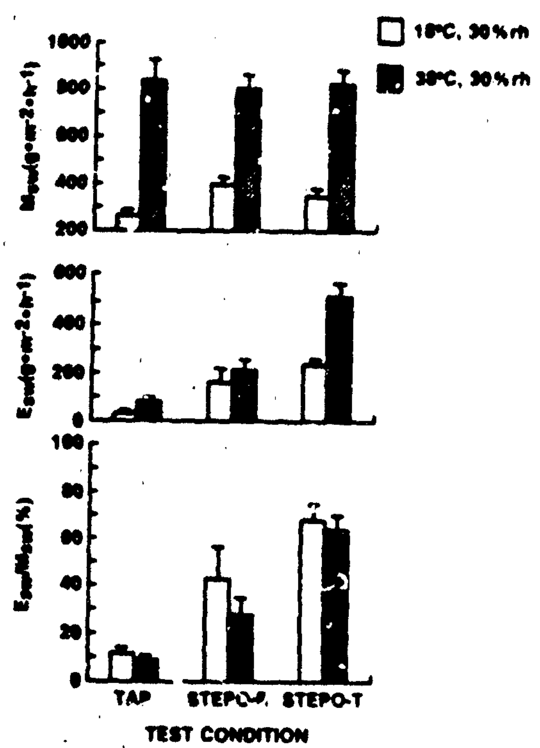

Figure 2