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13. ABSTRACT *(Maximum 200 words)*
This study determined whether a torso-vest forced ambient air body ventilation system (BVS) reduced physiological strain during exercise-heat stress. Seven heat-acclimated volunteers attempted nine, 2-h treadmill walks at 200 W m(-2) in three environments, -40 degrees C, 20% rh (HD), 35 degrees C, 75% rh (HW), and 30 degrees C, 50% rh, (WW) wearing the Army Combat Uniform, interceptor body armor (IBA) and Kevlar helmet. Three trials in each environment were BVS turned on (BVS(On)), BVS turned off (BVS(Off)), and no BVS (IBA). In HD, BVS(On) significantly lowered core temperature (T (re)), heart rate (HR), mean skin temperature (T (sk)), mean torso skin temperature (T (torso)), thermal sensation (TS), heat storage (S), and physiological strain index (PSI), versus BVS(Off) and IBA (P < 0.05). For HW (n = 6), analyses were possible only through 60 min. Exercise tolerance time (min) during HW was significantly longer for BVS(On) (116 + /- 10 min) versus BVS(Off) (95 + /- 22 min) and IBA (96 + /- 18 min) (P < 0.05). During HW, BVS(On) lowered HR at 60 min versus IBA, T (sk) from 30 to 60 min versus BVS(Off) and IBA, and PSI from 45 to 60 min versus BVS(Off) and at 60 min versus IBA (P < 0.05). BVS(On) changes in T (re) and HR were lower in HD and HW. During WW, BVS(On) significantly lowered HR, T (sk), and T (torso) versus BVS(Off) and IBA (P < 0.05) during late exercise. Sweating rates were significantly lower for BVS(On) versus BVS(Off) and IBA in both HD and WW (P < 0.05), but not HW. These results indicate that BVS(On) reduces physiological strain in all three environments by a similar amount; however, in hot-dry conditions the BVS(Off) increases physiological strain.

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ORIGINAL ARTICLE

Efficacy of body ventilation system for reducing strain in warm and hot climates

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Abstract This study determined whether a torso-vest forced ambient air body ventilation system (BVS) reduced physiological strain during exercise-heat stress. Seven heat-acclimated volunteers attempted nine, 2-h treadmill walks at 200 W m^{-2} in three environments, –40°C, 20% rh (HD), 35°C, 75% rh (HW), and 30°C, 50% rh, (WW) wearing the Army Combat Uniform, interceptor body armor (IBA) and Kevlar helmet. Three trials in each environment were BVS turned on (BVS_{On}), BVS turned off (BVS_{Off}), and no BVS (IBA). In HD, BVS_{On} significantly lowered core temperature (T_{re}), heart rate (HR), mean skin temperature (T_{sk}), mean torso skin temperature (T_{torso}), thermal sensation (TS), heat storage (S), and physiological strain index (PSI), versus BVS_{Off} and IBA ($P < 0.05$). For HW ($n = 6$), analyses were possible only through 60 min. Exercise tolerance time (min) during HW was significantly longer for BVS_{On} (116 ± 10 min) versus BVS_{Off} (95 ± 22 min) and IBA (96 ± 18 min) ($P < 0.05$). During HW, BVS_{On} lowered HR at 60 min versus IBA, T_{sk} from 30 to 60 min versus BVS_{Off} and IBA, and PSI from 45 to 60 min versus BVS_{Off} and at 60 min versus IBA ($P < 0.05$). BVS_{On} changes in T_{re} and HR were lower in HD and HW. During WW, BVS_{On} significantly lowered HR, T_{sk}, and T_{torso} versus BVS_{Off} and IBA ($P < 0.05$) during late exercise. Sweating rates were significantly lower for BVS_{On} versus BVS_{Off} and IBA in both HD and WW ($P < 0.05$), but not HW. These results indicate that BVS_{On} reduces physiological strain in all three environments by a similar amount; however, in hot-dry conditions the BVS_{Off} increases physiological strain.

Keywords Ambient air ventilation · Convection · Evaporation

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Introduction

Many occupations, for example law enforcement, industrial hygiene, military, customs patrol, and security require the use of protective heavy clothing/equipment particularly protective body armor vests used for ballistics protection. Data from military subjects suggest that protective body armor vests worn in hot climates add a significant amount of physiological strain (Cadarette et al. 2001, 2005; Cheuvront et al. 2008; Yarger et al. 1969). The insulation (clo) and vapor resistance (i_m/clo), characteristics of protective body armor vests increase physiological strain equivalent to an increase in wet bulb, globe temperature (WBGT) index of ∼2.8°C (Cadarette et al. 2005). In combination with increased physical activity, the net heat gain resulting from the wear of protective body armor vests during work in hot climates degrades physical performance capabilities and increases the risk of serious heat illness (Cadarette et al. 2001; US Army 2003).

Personal cooling systems can mitigate the increased physiological strain from protective clothing in hot climates (Chen et al. 1997; Muza et al. 1988; Pandolf et al. 1995). However, the bulk weight, and requirement of an external power source (tethered system) to operate the personal cooling systems restrict user mobility making them impractical and unusable for real world applications. A recent study evaluated a lightweight spacer vest garment, worn beneath body armor that requires no power source, but found that it did not mitigate physiological strain during exercise-heat stress (Cheuvront et al. 2008). However, it was suggested that using a similar spacer-vest technology with forced-air ventilation might improve the evaporative cooling potential of the torso and mitigate physiological strain during exercise-heat stress.

Recently, a portable, lightweight, forced-air ventilation system (body ventilation system; BVS) was designed to be worn under body armor. The BVS consists of a spacer vest liner with an impermeable outer layer and ambient air blower. The BVS blower circulates ambient air around the torso through the spacer vest liner, which should enhance the evaporative cooling and possibly reduce the physiological strain during exercise-heat stress. In comparison to previous ambient air-cooling systems (Chen et al. 1997; Muza et al. 1988), the BVS is up to 41% lighter (2.3 kg) and consumes 67% less energy (battery life = 7–8 h continuous operation) at similar airflow rates. Therefore, the BVS could be a cost-effective cooling solution for workers in hot climates who are required to use protective body armor vests. It was the intent of this study to determine if the BVS, worn under a protective body armor vest, mitigates physiological strain during exercise-heat stress in warm and hot environments. Metabolic rate was held constant to determine the impact of the BVS on physiological strain independent of load. Our primary hypothesis was that the BVS would increase evaporative cooling and reduce physiological strain during exercise-heat stress in multiple environments. Secondly, because it is ambient air versus cooled air distributed around the torso, we hypothesized that the reduction in strain would be directly related to the biophysics of heat transfer in the different environmental conditions.

Methods

Subjects

Seven healthy volunteers (six male and one female) with mean ± SD age 19.6 ± 2.0 years, height 174 ± 4 cm, mass 73.1 ± 8.5 kg, and percent body fat 17.6 ± 4.9% participated in this study after being medically cleared as healthy with no underlying problems. Before testing began, all volunteers were fully briefed both orally and in writing on the purpose and risks of the study and gave their free and informed, voluntary written consent to participate in the research. Investigators adhered to US Army Regulation 70-25 and US Army Medical Research and Material Command Regulation 70-25 on the Use of Volunteers in Research, and the research was conducted with the provisions of 32 CFR, Part 219.

Experimental procedures

Heat acclimation

Prior to testing, the volunteers completed a 12-day, exercise-heat acclimation program to reduce physiological variability in response to heat stress and to reduce the risk of exhaustion from heat strain during the experimental trials. During each heat acclimation day, volunteers walked wearing shorts, t-shirt, and athletic shoes on a motor-driven treadmill (1.56 m s^{-1}, 4% grade) in a hot, dry environment (45°C T_{db}, 16.9 T_{dp}, 20% relative humidity, wind speed 1.1 m s^{-1}) until reaching the earliest of three criteria: (1) 100 continuous minutes of exercise, (2) core temperature of 39.5°C, or (3) voluntary cessation. Core temperature (T_{re}) and heart rate (HR) were monitored continuously and recorded every 5 min. Rating of perceived exertion (RPE) (Borg 1970), thermal sensation (TS) (Gagge et al. 1967), and thermal comfort (TC) (Berglund 1998) were recorded at 15 min intervals. Each morning volunteers were provided with ad libitum fluids and a light meal, approximately 2 h before testing. An additional 250 ml of water was given 1 h before testing to standardize hydration state. Volunteers were rehydrated after exercise to within 1% of their initial weight before being released.

Clothing and cooling system

Uniform configuration was the same for all trials, the Army Combat Uniform (ACU) with sleeves down, Kevlar helmet, athletic shoes, and the interceptor body armor (IBA) vest with small arms protective inserts. The total weight of the IBA is ~8 kg and covers ~22% of body surface area.

Experimental design

The test environments for the study were: (1) 40°C dry bulb (T_{db}), 12.4°C dew point (T_{dp}), 20% rh (27.6°C WBGT) (HD); (2) 35°C T_{db}, 29.9°C T_{dp}, 75% rh (32.2°C WBGT) (HW); and (3) 30°C T_{db}, 18.3°C T_{dp}, 50% rh (24.5°C WBGT) (WW) each with a 1.1 m s^{-1} wind speed. The configurations for the tests were designated as BVS worn but turned on (BVS_{On}), the BVS worn and turned off (BVS_{Off}), and no BVS worn (IBA). During each trial, volunteers walked on a treadmill (1.34 m s^{-1}, 0% grade to elicit a metabolic rate of ~200 W m^{-2}) for 2 h on nine separate occasions. Testing was terminated when the first of three criteria were met: (1) 120 continuous minutes of exercise, (2) core temperature of 39.5°C, or (3) voluntary cessation. Trial order was randomized within a preselected set of all possible orders. Testing was separated by 48–72 h.

The BVS (Global Secure Safety Corp., Bear, DE) consists of the air distribution garment (ADG) and ventilation unit (VU). The VU contains the blower system and customized lithium ion battery pack and attaches to the IBA. Two particulate filters are provided with the system for operation in dusty environments. The ADG is a three-dimensional spacer liner worn between the ACU blouse and t-shirt, and is integrated with the VU. Flow rate is approximately 10 ft^3 min^{-1} (2.33 m s^{-1}). The weight of the BVS is ~2.3 kg.

Measurements

During the experimental trials, volunteers arrived to the laboratory at 0800 and consumed 250 ml of water. Nude body weights were recorded after self-placement of a flexible rectal thermistor (Yellow Springs Instruments, Yellow Springs, OH) inserted 10 cm beyond the anal sphincter for T_{re} measurements. After the initial body weight was recorded, fluid replacement was prohibited except during experimentation when water (300 ml) was provided every 30 min until test cessation. Skin thermocouples were placed on the left side of the body at five area-weighted sites (chest, back, forearm, thigh, and calf) to calculate mean skin temperature (T_{sk}). A heart rate monitor (Polar a_3, Polar Electro, Inc, Woodbury, NY) was secured around the chest and volunteers dressed in their respective uniform and equipment configuration. Fully dressed body weights were then recorded. T_{re} and T_{sk} were collected by the same data acquisition system and monitored at 1-min intervals. Heart rate was monitored continuously and recorded every 15 min throughout each trial along with RPE, TC and TS. Expired gases were collected in Douglas bags for 90 s approximately 30 min into testing for metabolic rate (M) determination using a dry gas meter and metabolic cart (TrueMax, ParvoMedics, Sandy, Utah). Dressed and nude body weights were again recorded at the conclusion of testing.

Calculations

Mean T_{sk} were calculated from five sites (forearm, chest, back, thigh and calf) using the equation: $0.15\ (T_{chest}) + 0.15\ (T_{back}) + 0.3\ (T_{forearm}) + 0.2\ (T_{thigh} + T_{calf})$ (modified from Ramanathan 1964). Mean skin torso temperatures (T_{torso}) were calculated as $0.5\ (T_{chest}) + 0.5\ (T_{back})$. Whole body sweating rate was determined from the change in nude body mass corrected for respiratory water loss (Gagge and Gonzalez 1996) and O_2–CO_2 exchange (Consolazio et al. 1963; Mitchell et al. 1972). The sum of the equation represents actual sweat losses (kg), which are then expressed as a rate (volume per unit time, L h^{-1}). Maximal evaporative capacity (E_{max}) dressed in military clothing and required evaporative capacity (E_{req}) were calculated for each environment (Gagge and Gonzalez 1996). The sweat trapped in clothing was calculated as the change in dressed weight subtracted from the whole-body sweat loss. The percentage of sweat evaporated was calculated as follows: 100 − [(sweat trapped in clothing/whole-body sweat loss) × 100]. Heat storage (S) was calculated by thermometry using the equation (Gagge and Gonzalez 1996): $S = (0.97 \times \text{body mass/BSA}) \times (\Delta T_b/\Delta t)$. Where body mass is in kg, ΔT_b is the change in mean body temperature (final − rest), and Δt is time in hours. This was done in favor of calorimetry due to potential differences among trials in sweat evaporation efficiency (E_{sk}) that could not be directly measured, given the study design. Any absolute error compared with calorimetry (Vallerand et al. 1992) was assumed equal among trials. T_b was calculated as (Gagge and Gonzalez 1996): $T_b = xT_c + (1 - x)T_{sk}$, where x is the appropriate weighting coefficient (0.90) for hot environments (Gagge and Gonzalez 1996). The physiologic strain index (PSI) was calculated at 15 min intervals (Moran et al. 1998). Because baseline heart rate values were collected while subjects were standing in the environmental chamber after 5 min, all PSI data were calculated by assuming a standard resting HR of 72 b min^{-1}, which should more accurately reflect increased strain from rest.

Statistical analyses

One-way (trial) and two-way (time × trial) analyses of variance for repeated measures were performed. For sphericity violations, F values were corrected using the Geisser-Greenhouse procedure. A significant F-test was further analyzed with Student-Newman–Keuls post hoc test to detect differences among means. Sample size estimates were made *a priori* using $\alpha = 0.05$ and $\beta = 0.20$ values and assuming a standard deviation of 0.3°C for T_{re} (Cadarette et al. 2001). Power analysis revealed that five subjects were sufficient to detect a 1.25-fold (0.375°C) difference for T_{re} between trials. All data are presented as mean ± SD.

Results

40°C, 20% rh environment (HD)

Mean metabolic rates ranged from 209 to 216 W m^{-2} and did not differ among trials ($P > 0.05$). Figure 1 illustrates the BVS_{On} impact on T_{re} and HR. From 60 to 120 min, BVS_{On} resulted in a significantly ($P < 0.05$) lower T_{re} when compared to BVS_{Off} and from 90 to120 min for BVS_{On} versus IBA. HR was significantly ($P < 0.05$) lower throughout most of the exercise for BVS_{On} when compared with BVS_{Off} (Fig. 1). The change in T_{re} during BVS_{On} and IBA was significantly lower ($P < 0.05$) versus BVS_{Off}, while the change in HR during BVS_{On} was significantly lower ($P < 0.05$) compared with BVS_{Off} (Table 1). Main effects

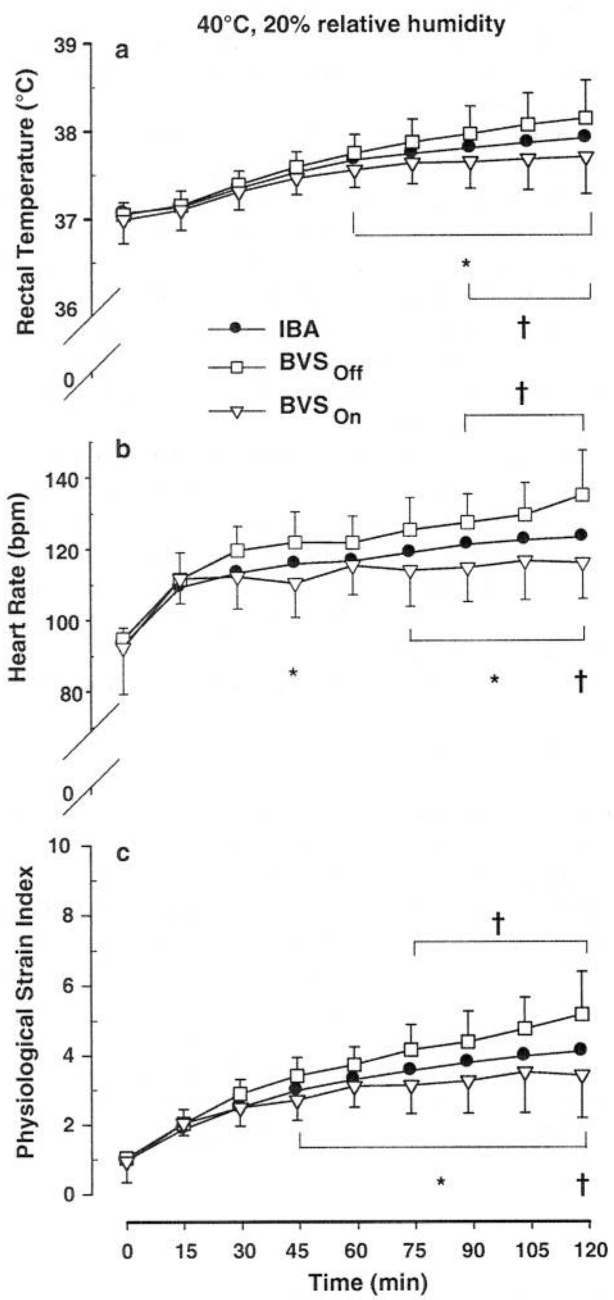

Fig. 1 Rectal temperature (**a**), heart rate (**b**), and PSI (**c**) during 2 h of continuous exercise in a 40°C, 20% relative humidity (27.6°C WBGT) environment. *Different from BVS_{Off} ($P < 0.05$); †different from IBA ($P < 0.05$)

for T_{sk} and T_{torso} were significantly lower ($P < 0.05$) for BVS_{On} relative to BVS_{Off} and IBA (Table 1). BVS_{On} induced a lower PSI throughout much of exercise as compared with BVS_{Off} and IBA, while BVS_{Off} showed a higher PSI during much of the second half of exercise when compared with IBA ($P < 0.05$) (Fig. 1). Final *S* values were lower during BVS_{On} compared to BVS_{Off} and IBA, and IBA versus BVS_{Off} ($P < 0.05$) (Table 1). TS values were significantly lower throughout most of exercise during BVS_{On} versus other trials ($P < 0.05$). However, BVS_{On} had a minimal impact on TC and no differences for RPE with respect to BVS_{Off} and IBA. The mean sweating rate was significantly lower during BVS_{On} relative to BVS_{Off} and IBA ($P < 0.05$) (Table 1). The sweat trapped in clothing and equipment was significantly lower for BVS_{On} compared to BVS_{Off} and IBA ($P < 0.05$) (Table 1).

35°C, 75% rh environment (HW)

This environment was tested with $N = 6$. Mean metabolic rates ranged from 204 to 208 W m^{-2} and did not differ ($P > 0.05$) among trials. Because of subject attrition at various time points during each trial, statistical analyses was only possible through 60 min of exercise. T_{re} was not significantly different among trials during the first 60 min of exercise (Fig. 2); however, the change in T_{re} from 0 to 60 min was significantly lower ($P < 0.05$) for BVS_{On} versus BVS_{Off} and IBA (Table 1). BVS_{On} induced a significantly ($P < 0.05$) lower HR at 60 min compared with IBA (Fig. 2) and the change in HR from 0 to 60 min was lower ($P < 0.05$) for BVS_{On} relative to BVS_{Off} and IBA (Table 1). Main effects for T_{sk} and T_{torso} were significantly ($P < 0.05$) lower during BVS_{On} as compared with BVS_{Off} and IBA (Table 1). Mean PSI values were lower ($P < 0.05$) for BVS_{On} from 45 to 60 min of exercise relative to BVS_{Off} and at 60 min relative to IBA (Fig. 2). Exercise tolerance time in this environment was significantly ($P < 0.05$) higher during BVS_{On} (116 ± 10 min) versus BVS_{Off} (95 ± 22 min) and IBA (96 ± 18 min). Final *S* values were lower during BVS_{On} versus BVS_{Off} and IBA ($P < 0.05$) (Table 1). No significant ($P > 0.05$) differences were observed between trials for sweating rate, sweat trapped in clothing, RPE, TC, and TS in this environment.

30°C, 50% rh environment (WW)

Mean metabolic rates ranged from 200 to 205 W m^{-2} and did not differ among trials ($P > 0.05$). No significant ($P > 0.05$) difference was observed among trials for T_{re} or the change in T_{re} (Table 1; Fig. 3). BVS_{On} did produce significantly ($P < 0.05$) lower HR at some time points when compared with BVS_{Off} and IBA (Fig. 3), but the change in HR was not significantly ($P > 0.05$) different between the trials (Table 1). During BVS_{On}, T_{sk} and T_{torso} main effects were significantly lower ($P < 0.05$) versus BVS_{Off} and IBA (Table 1). The sweat trapped in clothing and equipment was significantly ($P < 0.05$) lower for BVS_{On} compared to BVS_{Off} and IBA (Table 1). No significant differences were observed for PSI, S, RPE, TC, TS, and sweating rate in this environment ($P > 0.05$) (Table 2).

Table 1 Indexes of cardiovascular and thermoregulatory strain during 2 h (1 h for 35°C, 75% rh) of continuous exercise heat-stress

Environment	Trial	ΔHR b $\min^{-1}$	ΔT_{re}, °C	T_{sk},°C	T_{torso}, °C	S, W m^{-2}	Sweating rate, g $\min^{-1}$	Sweat in clothing, kg	Evaporation, %
40°C, 20%rh (27.6°C WBGT)	IBA	30 ± 8	0.85 ± 0.29*	35.7 ± 0.4	36.7 ± 0.2	21.9 ± 7.9*	13.4 ± 2.6	0.52 ± 0.22	71
	BVS_{Off}	40 ± 11	1.09 ± 0.34	36.0 ± 0.5	37.1 ± 0.8	27.1 ± 9.9	14.5 ± 3.6	0.64 ± 0.31	68
	BVS_{On}	24 ± 17*	0.70 ± 0.44*	35.3 ± 0.2*	35.1 ± 0.1†	17.3 ± 11.6†	11.8 ± 1.9*	0.26 ± 0.13*	84
35°C, 75%rh (32.2°C WBGT)	IBA	49 ± 13[a]	1.35 ± 0.21[a]	36.2 ± 0.8	36.8 ± 0.2	50.2 ± 7.5[a]	17.6 ± 7.1	1.13 ± 0.54	35
	BVS_{Off}	54 ± 14[a]	1.42 ± 0.22[a]	36.3 ± 0.8	37.0 ± 0.1	50.8 ± 11.5[a]	18.7 ± 8.3	1.20 ± 0.54	33
	BVS_{On}	40 ± 9[a]†	1.17 ± 0.18[a,]†	36.0 ± 0.6†	36.4 ± 0.1†	40.2 ± 6.4[a]†	17.1 ± 7.1	1.14 ± 0.65	46
30°C, 50%rh (24.5°C WBGT)	IBA	11 ± 12	0.55 ± 0.21	34.3 ± 0.1	36.3 ± 0.7	12.9 ± 5.4	9.2 ± 1.9	0.43 ± 0.20	63
	BVS_{Off}	16 ± 11	0.56 ± 0.25	34.2 ± 0.2	36.5 ± 0.6	13.6 ± 5.3	9.7 ± 2.4	0.48 ± 0.21	60
	BVS_{On}	5 ± 11	0.50 ± 0.17	33.7 ± 0.2†	34.1 ± 0.4†	9.6 ± 4.5	7.7 ± 1.1*	0.22 ± 0.06*	76

Values are mean ± SD. ΔHR; change in HR, ΔT_{re}; change in rectal temperature, T_{sk}; mean skin temperature (main effect), T_{torso}; mean torso temperature (main effect), S; heat storage

*Different from BVS_{Off} ($P < 0.05$); †different from IBA and BVS_{Off} ($P < 0.05$)

[a] 0–60 min of exercise

Results summary

PSI provides a composite index of physiological strain. Figure 4 presents final PSI difference values among configurations for the three environments. BVS_{On} reduced PSI by a similar magnitude in each environment, however, BVS_{Off} increased PSI in the hot-dry environment when biophysics of heat exchange would maximize dry heat gain.

Discussion

This study demonstrated that the BVS effectively reduced physiological strain while wearing body armor during exercise-heat stress. In contrast to our hypothesis, the reduction in strain was similar in all three environments (Fig. 4), despite the varying level of heat stress and humidity imposed in each condition, To ensure that variability for markers of strain were minimized, volunteers were heat acclimated, fluid intakes were standardized, body weights were regularly monitored, and exercise metabolic rates were held constant during testing. The findings herein while wearing body armor expand upon previous observations on the benefit of portable, ambient forced ventilation while enclosed in protective clothing (Chen et al. 1997; Muza et al. 1988).

Because of the high air temperature and low humidity, the HD environment would allow for a high degree of evaporative cooling during exercise-heat stress in individuals unencumbered by protective equipment such as body armor and helmets. The calculated E_{max} while dressed in military clothing in this environment is approximately 460 W compared to the calculated E_{req} of approximately 420 W (Gagge and Gonzalez 1996). The higher T_{sk} and T_{torso} (Table 1) in the IBA and BVS_{Off} trials suggest that the addition of protective equipment reduced the evaporative potential of the torso, which ultimately increased physiological strain relative to BVS_{On}. Despite the relatively small surface area of the torso (~25% BSA), BVS_{On} appeared to improve the evaporative efficiency sufficiently to lower T_{re}, HR, T_{sk}, T_{torso}, and PSI. The substantially lower T_{torso} likely reduced torso skin blood flow to a degree that may have increased central blood volume and lowered HR as seen in Fig. 1. The lowered HR during late BVS_{On} exercise resulted in a lower PSI compared to BVS_{Off} and IBA, where both T_{re} and HR increased incrementally over time.

While the BVS_{On} configuration in HD reduced physiological strain relative to both BVS_{Off} and IBA, the BVS_{Off} condition resulted in greater final S and strain compared to IBA from 75 min to the end of testing. This could be the result of the elastic cummerbund style waist and impermeable outer layer of the air distribution garment. While this design serves to maximize airflow over a greater torso surface area during BVS_{On}, its drawback is that no airflow during BVS_{Off} would nullify convective and evaporative cooling and would likely insulate body heat resulting in the greater S and PSI penalty compared to IBA (Fig. 5). Therefore, in occupations where long-term use is required, it would be especially important to maintain a sufficient supply of batteries to run the BVS blower to avoid the added S and PSI penalty so that it does not become a liability.

The BVS_{On} condition also proved to be beneficial in the HW environment, which had a calculated E_{max} of approximately 235 W compared to a calculated E_{req} of approximately 365 W (Gagge and Gonzalez 1996). The low E_{max} and high WBGT made HW the most thermally stressful environment. By 60 min of exercise, the T_{torso} in the IBA and BVS_{Off} conditions were approaching 38°C. These torso temperatures were the highest T_{sk}'s observed among the three tested environments, which greatly narrowed $T_{re} - T_{sk}$ gradient and limited core-to-skin heat transfer.

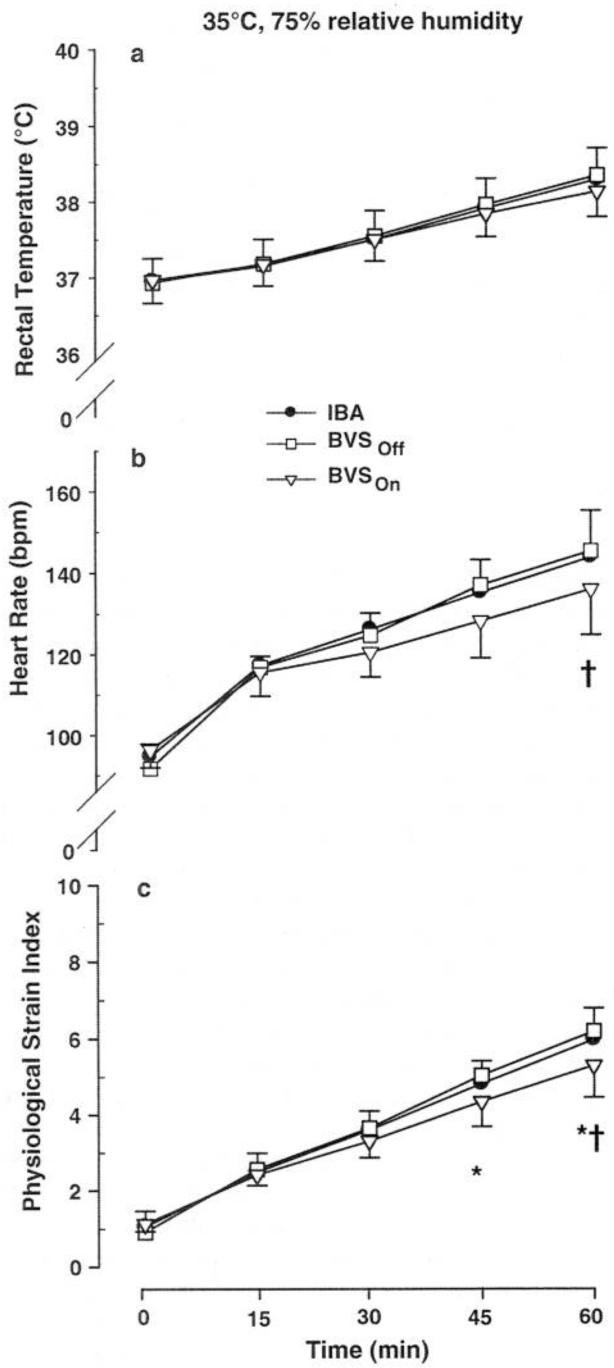

Fig. 2 Rectal temperature (**a**), heart rate (**b**), and PSI (**c**) during 1 h of continuous exercise in a 35°C, 75% relative humidity (32.2°C WBGT) environment. *Different from BVS_{Off} ($P < 0.05$); †different from IBA ($P < 0.05$)

Since this environment compromised evaporative cooling, BVS_{On} must have provided some convective removal of heat from the skin surface. By 60 min, during BVS_{On}, T_{torso} was ~1.1°C less than the T_{re} in this environment, which resulted in the widest $T_{re} - T_{sk}$ gradient versus the other two configurations. As a result, the lower T_{torso} and conse-

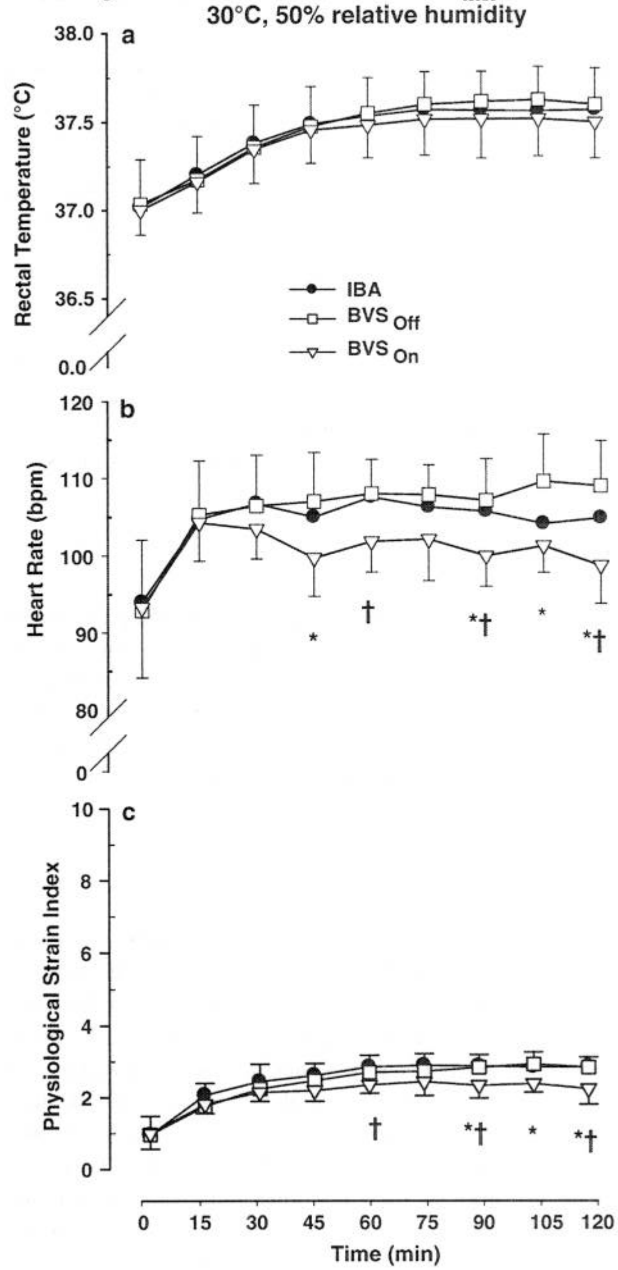

Fig. 3 Rectal temperature (**a**), heart rate (**b**), and PSI (**c**) during 2 h of continuous exercise in a 30°C, 50% relative humidity (24.5°C WBGT) environment. *Different from BVS_{Off} ($P < 0.05$); †different from IBA ($P < 0.05$)

quent T_{sk} observed during BVS_{On} appeared to positively impact HR and PSI (Fig. 2) possibly because of reduced distribution of blood to periphery (Rowell et al. 1966) and therefore greater effective central blood volume relative to the other trials. The lower skin temperatures and increased central blood would have indeed produced the lowest subject attrition and improved tolerance time as seen during

Table 2 Components of heat exchange within each environmental condition

Environment		E_{max}	E_{req}	P_a, kPa	P_{sk}, kPa	$P_{sk} - P_a$
40°C, 20%rh (27.6°C WBGT)	IBA	460	420	1.53	5.82 ± 0.12	4.29
	BVS_{Off}				5.93 ± 0.14	4.40
	BVS_{On}				5.71 ± 0.25*	4.18
35°C, 75%rh (32.2°C WBGT)	IBA	235	365	4.21	6.12 ± 0.09	1.91
	BVS_{Off}				6.09 ± 0.14	1.88
	BVS_{On}				6.04 ± 0.14	1.83
30°C, 50%rh (24.5°C WBGT)	IBA	355	330	2.07	5.42 ± 0.07	3.35
	BVS_{Off}				5.39 ± 0.19	3.32
	BVS_{On}				5.22 ± 0.14†	3.15

* Different from BVS_{Off} ($P < 0.05$); †different from IBA and BVS_{Off} ($P < 0.05$)

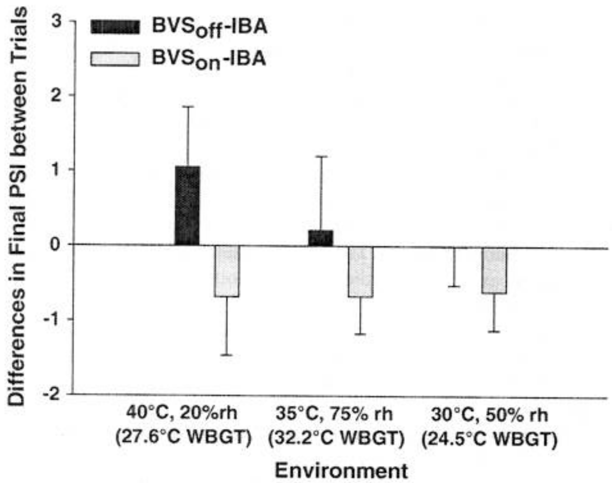

Fig. 4 Final PSI differences between BVS_{Off} versus IBA and between BVS_{On} versus IBA in each environment

BVS_{On} compared with the other trials in this environment (Sawka and Young 2006). Noteworthy is that the improved tolerance time during BVS_{On} (~20 min) would result in approximately 1.6 km (1 mile) greater distance covered at walking speed.

The exercise-heat stress in the WW environment created little heat strain in the volunteers. The calculated E_{max} for the environment was approximately 355 W with a calculated E_{req} of approximately 330 W (Gagge and Gonzalez 1996). During BVS_{Off}, where the greatest strain was expected, mean HR and T_{re} only increased 16 b min^{-1} and 0.6°C, respectively, over the 120 min testing period. While addition of BVS_{Off} possibly reduced both evaporative and convective capabilities relative to the IBA, the similar values of T_{re}, T_{sk}, and T_{torso} between the two configurations suggests that the extra layer of the air distribution system may not be a liability in this environment allowing greater dry heat exchange. Although the addition of BVS_{On} in the WW environment created a significant reduction in T_{torso}, HR and PSI, it had no impact on the change in T_{re} of the volunteers over the 2 h of exercise. This could be that the testing period for WW was too brief for the differences in T_{re} to be detected during BVS_{On}. The lower sweating rate (~16% lower vs. IBA) seen with BVS_{On} should contribute to reduced strain and fluid requirements during extended work periods in similar environments.

While numerous studies have evaluated different personal, portable cooling technologies in a variety of environments, relatively few have examined ambient air-cooling systems (Chen et al. 1997; McCullough et al. 2006; Muza et al. 1988). Chen et al. (1997) and Muza et al. (1988) reported that ambient air-cooling provided some benefit in subjects encapsulated in protective clothing. However, these studies examined ambient air-cooling in combination with conditioned air-cooling that employed work-rest cycles with ambient air cooling during work and conditioned air cooling provided at rest. McCullough et al. (2006) evaluated the cooling efficacy of an initial version of the BVS while subjects wore body armor during exercise-heat stress and only observed lower T_{sk} and T_{torso}. However, T_{re} was not lower which might likely reflect the air distribution system design (worn over both the t-shirt and Army Combat Uniform blouse) and the 40°C, 20% rh, with a 54.4°C mean radiant temperature employed, representing an extreme environmental desert condition (Cadarette et al. 2007).

In conclusion, BVS_{On} reduced strain in all the three environments tested; however, in contrast to our hypothesis, the reduction in strain was similar across all three environments (Fig. 4). However, the avenues of heat transfer from the body were different in each environment since the BVS is an ambient air blower system. Therefore, because the BVS resulted in similar reductions in physiologic strain in all environments compared to IBA, it appears to provide a low-cost and low-weight system to help sustain work and reduce physiological strain when wearing body armor.

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the Army position, or decision, unless so designated by other official documentation. Approved for public release, distribution unlimited.

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