

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
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1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE 2008	3. REPORT TYPE AND DATES COVERED Journal Article - Eur J Appl Physiol	
4. TITLE AND SUBTITLE Impact of a protective vest and spacer garment on exercise-heat strain			5. FUNDING NUMBERS	
6. AUTHOR(S) S.N. Cheuvront, D.A. Goodman, R.W. Kenefick, S.J. Montain, M.N. Sawka				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Thermal and Mountain Medicine Division U.S. Army Research Institute of Environmental Medicine Natick, MA 01760-5007			8. PERFORMING ORGANIZATION REPORT NUMBER M07-17	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Same as #7 above			10. SPONSORING / MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) Protective vests worn by global security personnel, and weighted vests worn by athletes, may increase physiological strain due to added load, increased clothing insulation and vapor resistance. The impact of protective vest clothing properties on physiological strain, and the potential of a spacer garment to reduce physiological strain, was examined. Thirteen men performed 3 trials of intermittent treadmill walking over 4h in a hot, dry environment (35° C, 30% rh). Volunteers wore the U.S. Army battledress uniform (trial B), B + protective vest (trial P), and B + P + spacer garment (trial S). Biophysical clothing properties were determined and found similar to many law enforcement, industry, and sports ensembles. Physiological measurements included core (T _c), mean skin (T _{sk}) and chest (T _{chest}) temperatures, heart rate (HR), and sweating rate (SR). The independent impact of clothing was determined by equating metabolic rate in all trials. In trial P, HR was + 7 b/min higher after 1h of exercise and + 19 b/min by the fourth hour compared to B (P< 0.05). T _c (+ 0.30° C), T _{sk} (+ 1.0° C) and Physiological Strain Index were all higher in P than B (P< 0.05). S did not abate these effects except to reduce T _{sk} (P > S) via a lower T _{chest} (-0.40° C) (P< 0.05). SR was higher (P< 0.05) in P and S versus B, but the magnitude of differences was small. A protective vest increases physiological strain independent of added load, while a spacer garment does not alter this outcome.				
14. SUBJECT TERMS Body armor, Spacer vest, Passive cooling, Heat stress			15. NUMBER OF PAGES 7	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT Unclassified	

Impact of a protective vest and spacer garment on exercise-heat strain

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Accepted: 19 November 2007 / Published online: 4 December 2007
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Abstract Protective vests worn by global security personnel, and weighted vests worn by athletes, may increase physiological strain due to added load, increased clothing insulation and vapor resistance. The impact of protective vest clothing properties on physiological strain, and the potential of a spacer garment to reduce physiological strain, was examined. Eleven men performed 3 trials of intermittent treadmill walking over 4 h in a hot, dry environment (35°C, 30% rh). Volunteers wore the US Army battledress uniform (trial B), B + protective vest (trial P), and B + P + spacer garment (trial S). Biophysical clothing properties were determined and found similar to many law enforcement, industry, and sports ensembles. Physiological measurements included core (T_c), mean skin (T_{sk}) and chest (T_{chest}) temperatures, heart rate (HR), and sweating rate (SR). The independent impact of clothing was determined by equating metabolic rate in all trials. In trial P, HR was +7 b/min higher after 1 h of exercise and +19 b/min by the fourth hour compared to B ($P < 0.05$). T_c (+0.30°C), T_{sk} (+1.0°C) and Physiological Strain Index were all higher in P than B ($P < 0.05$). S did not abate these effects except to reduce T_{sk} ($P > S$) via a lower T_{chest} (−0.40°C) ($P < 0.05$). SR was higher ($P < 0.05$) in P and S versus B, but the magnitude of differences was small. A protective vest

increases physiological strain independent of added load, while a spacer garment does not alter this outcome.

Keywords Body armor · Spacer vest · Passive cooling · Heat stress

Introduction

Protective vests provide upper body ballistics defense for soldiers, journalists reporting from war zones, global security personnel, customs patrol, police, and private security forces (Ricciardi et al. 2007; National Institute of Justice 2001; Lehmacher et al. 2007). Likewise, weighted vests of similar mass and surface area (but not ballistic protection) are also used by athletes for training (Rusko and Bosco 1987; Puthoff et al. 2006) or by older adults for therapeutic exercise (Greendale et al. 2000). While the metabolic costs of weighted (Rusko and Bosco 1987; Puthoff et al. 2006) and protective vests (Ricciardi et al. 2007) are well described, less attention has been given to the biophysical potential (Gonzalez 1988) of protective vest properties to restrict air flow, impede body heat loss, and increase physiological strain (e.g., increased core temperature, heart rate, sweating) in response to heat stress.

Protective vests may increase physiological strain due to added carriage load and more importantly increased insulation (clo) and vapor resistance (i_m/clo) (Gonzalez 1988). The lightest of protective vests (Type I), when worn in temperate conditions, may impose minimal physiological strain on the wearer (Lehmacher et al. 2007). Several evaluations of heavier protective vest systems (Type IV) show that they can add substantial physiological strain during work in hot environments (Cadarette et al. 2001; Cadarette et al. 2005; Yarger et al. 1969), but in none of

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these assessments has there been control for load carriage. The currently fielded Interceptor Body Armor (IBA) system used by the US military represents a design advance in Type IV protective vest systems. Although it is both lighter and stronger than older styles of military body armor, model predictions from manikin testing indicate that in hot environments it will still increase physiological strain independent of load (Endrusick et al. 2006).

Numerous cooling technologies have been developed to reduce physiological strain when wearing a variety of protective clothing and equipment ensembles. Although loose weave undershirts may provide a modest improvement in airflow and sweat evaporation when worn beneath some protective vests (National Institute of Justice 2001), “spacer garments” represent a design advance over loose weave shirts for they resist compression and distance a protective or weighted vest from the clothing surface itself, thus increasing ventilation and the evaporative cooling potential of the torso. The “stand-off” distance created between protective vest and torso produces a continuous air channel that reduces clo and increases i_m/clo (Endrusick et al. 2006; Havenith 1999). This spacer garment approach is considered “passive” as no forced ventilation or conditioning (air cooling/dehumidification) is used due to increased weight, noise, and cost. Thermal manikin and modeling analyses at 1 m/s airflow indicate that passive spacer garment technologies may substantially reduce physiological strain when worn in warm-hot environments (Endrusick et al. 2006).

At present, there are no experimental human test data to confirm or refute biophysical analyses and mathematical model predictions of added physiological strain from a Type IV protective vest or reduced physiological strain from a spacer garment. Because this step is essential for clothing and development (Levine et al. 1998), the purposes of this study were to (1) examine the effects of a IBA (Type IV protective vest) on physiological strain during exercise-heat stress; and (2) determine to what extent a spacer garment can reduce physiological strain. Metabolic rate was held constant in order to ascertain the impact of vest clothing properties on heat strain independent of load. Our hypothesis was that the protective vest would increase physiological strain for which the spacer garment would provide little reduction.

Methods

Subjects

Eleven healthy male volunteers participated in this study. Descriptive characteristics (mean $\pm$ SD) for this group were age 24 ± 4 years, height 172 ± 5 cm, mass

75.4 ± 8.0 kg, and body surface area (BSA) (DuBois and DuBois 1916) 1.88 ± 0.12 m². All volunteers were provided informational briefings and gave voluntary and informed written consent to participate. The appropriate Institutional Review Boards approved this study. Investigators adhered to policies for protection of human subjects as prescribed in Army Regulation 70-25 and United States Army Medical Research and Materiel Command Regulation 70-25 and the research was conducted in adherence with the provisions of 45 Code of Federal Regulations Part 46.

Preliminary procedures

Before experimental testing subjects were heat acclimated to reduce variability in physiological responses and exercise-heat tolerance (Sawka et al. 1996). This was achieved using 5–10 days of treadmill walking at 1.56 m/s, 4% grade for up to 100 min at 49°C, 20%rh (Lind and Bass 1963). Nude body mass was measured each morning to ensure proper hydration and establish a representative baseline body mass for later use (Cheuvront et al. 2004). Following exercise, subjects were rehydrated within 1% of initial body weight before leaving the laboratory. All experimental testing was begun within 48 h of completing heat acclimation.

Design

Three experimental trials were performed in a hot, dry environment (35°C, 30%rh, 1 m/s wind speed), separated each by 48–72 h. This environment was selected to maximize potential improvements in evaporative cooling while minimizing volunteer attrition due to heat rash or exhaustion ($E_{req} < E_{max}$) (Pandolf and Goldman 1978) and is representative of a warm summer day within most of the United States. The US Army Battledress Uniform (BDU) is the standard uniform worn by army personnel and has similar clo and i_m/clo values to security personnel and industrial work wear (National Institute of Justice 2001; Bernard 1999). The BDU was worn in all 3 trials, either alone (trial B), combined with an IBA Type IV protective vest (trial P), or combined with protective vest and spacer garment (trial S). Although IBA was chosen for study based on our volunteer population and its use on the modern battlefield, it is very similar to protective vests worn by global security personnel (National Institute of Justice 2001) and is very alike in weight and surface area to weighted vests worn by athletes and others (Rusko and Bosco 1987). The combinations of clothing worn also have similar clo and i_m/clo properties to numerous industrial protective clothing ensembles (Bernard 1999) and American football uniforms (McCullough and Kenney 2003).

Four hours of intermittent treadmill walking was performed (50 min walking bouts separated by 10 min rest intervals). This duration of exercise was selected principally because modeling data suggested physiological strain differences between trials P and S that increased progressively with time beyond 2.5 h (Endrusick et al. 2006). In trial B, walking speed was 1.56 m/s with a grade of 3%. In trials P and S, the grade was reduced to 2% to compensate for the added weight of IBA, which allowed examination of the clothing property contributions to physiological strain independent of added load carriage. Trial order was balanced using a Latin Square arrangement. All experimental testing was conducted at the same time of day to control for circadian fluctuations in body temperature.

Clothing

All biophysical clothing measurements were made on a sweating thermal manikin for each clothing configuration tested (B, P, S). In trial B, the BDU was worn with field cap, sleeves down, and athletic shoes, rather than field boots, to reduce blister formation (B: clo = 1.12, i_{m}/clo = 0.44 at wind speed 1 m/s). In trial P, subjects also wore IBA to include front and rear ballistic protective inserts (throat and groin protection excluded). The outer vest is made of a fine Kevlar weave and the protective plates of boron carbide ceramic with spectra shield backing. The total weight of the vest as used was 7.5 kg and it covered ~25% of the total BSA (P: clo = 1.35, i_{m}/clo = 0.27 at wind speed 1 m/s). In trial S, subjects additionally wore a 1 cm thick vest of proprietary knit fabric in between the IBA and BDU (S: clo = 1.28, i_{m}/clo = 0.32 at wind speed 1 m/s). The weight of the spacer garment was nominal (0.2 kg). Although the spacer garment is designed as a “one size fits all” vest, in this study they were cut in accordance with manufacturer recommendations to fit each individual subject.

Procedures

At the start and conclusion of each trial, nude body mass was measured on an electronic precision balance scale (Toledo 1D1, Worthington, OH; accuracy ± 20 g). To minimize differences in hydration state between trials, a standard 250 mL water bolus was given approximately 1 h before starting exercise. Body mass measures that fluctuated by less than 1% of the 5–10-day mean were considered normal (Cheuvront et al. 2004) and a similar hydration state from trial to trial was assumed. Additional fluid was given on the morning of a test only if body mass

deviated downward by more than 1% of the 10-day mean (Cheuvront et al. 2004).

Heart rate (HR) (Polar a3, Polar Electro, Inc, Woodbury, NY) and core (intestinal) body temperature (T_c) (JonahTM core body temperature capsule, Mini Mitter Company, Inc, Bend, OR) were measured continuously and recorded at 10 min intervals. These two measures were weighted to evaluate the combined cardiovascular and thermal load calculated from the Physiological Strain Index (PSI) (Moran et al. 1998):

$$\text{PSI} = [5(T_c - T_{c0}) / (39.5 - T_{c0})] + [5(\text{HR} - \text{HR}_0) / (180 - \text{HR}_0)] \quad (1)$$

where T_c and HR are measurements made simultaneously at the end of hours 1, 2, 3 and 4; T_{c0} and HR_0 are values measured at the start of the experiment during rest. Skin temperature was measured from thermocouples located at four sites (forearm, chest, thigh and calf). Mean skin temperature (T_{sk}) was calculated using the equation (Ramanathan 1964):

$$T_{sk} = 0.3(T_{\text{chest}} + T_{\text{forearm}}) + 0.2(T_{\text{thigh}} + T_{\text{calf}}) \quad (2)$$

Heat storage (S) was calculated by thermometry according to the equation (Gagge and Gonzalez 1996):

$$S = (0.97 \times \text{body mass/BSA}) \times (\Delta T_b / \Delta t) \quad (3)$$

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 (Esk) 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):

$$T_b = xT_c + (1 - x)T_{sk} \quad (4)$$

where x is the appropriate weighting coefficient (0.90) for hot environments (Gagge and Gonzalez 1996).

Metabolic rate was measured from a 90-s sample of expired air collected approximately 30 min into each 50 min exercise work bout using indirect calorimetry via Douglas Bags, dry gas meter, and metabolic cart (TrueMax, ParvoMedics, Sandy, Utah). Exercise heat production (M) was calculated as (Gagge and Gonzalez 1996):

$$M = (0.23[R] + 0.77) \times 5.873 \times \text{VO}_2 \times (60/\text{BSA}) \quad (5)$$

where R is the respiratory quotient and VO_2 is in L/min. Heat production at rest was estimated as approximately one metabolic equivalent. The actual amount of metabolic energy converted to heat was calculated from the time weighted average of exercise and rest. All temperatures were measured in °C and heat balance data calculated in W/m² units.

Water from pre-measured bottles was available to drink *ad libitum* during all trials and a snack (~200 kcal sports bar) was provided during the second 10 min rest break. The precise weight of all water, food, and urine was measured on an electronic scale (Ohaus E1M210, Switzerland; accuracy ± 1 g). Actual sweat losses were determined by calculating water balance using a modified Peters–Passmore equation (8):

$$\begin{aligned} \text{sweat loss (kg)} = & \Delta \text{body mass} + (\text{solids in} - \text{solids out}) \\ & + (\text{fluids in} - \text{fluids out}) \\ & - (\text{Gases in} - \text{Gases out}) \end{aligned} \quad (6)$$

where Δ body mass is the difference in nude body mass pre-to-post exercise, fluids and solids in = water and food, fluids out = urine and respiratory water losses (Mitchell et al. 1972), solids out = fecal mass (none), and gases represent CO_2 – O_2 exchange (Mitchell et al. 1972; Consolazio et al. 1963). The sum of the entire equation represents actual sweat losses (kg). Sweat volume and mass were considered equivalent (i.e., 1 mL = 1 g) and were expressed as a rate (volume per unit time, L/h). The level of dehydration at the end of each trial, expressed as a percentage, was calculated as:

$$\begin{aligned} \% \text{ dehydration} = & (\Delta \text{body mass/pre-exercise body mass}) \\ & \times 100 \end{aligned} \quad (7)$$

where Δ body mass was also corrected for respiratory water losses and gas exchange (Mitchell et al. 1972; Consolazio et al. 1963).

Statistical analyses

Of principal interest in this study was the impact that an IBA protective vest and spacer garment had on physiological strain during exercise-heat stress. Statistical comparisons among trials were made using a one-way (trial) or two-way (trial $\times$ time) analysis of variance for repeated measures. Where the assumption of sphericity was violated, F values were adjusted using Greenhouse-Geisser or Huynh-Feldt values as appropriate. Tukey's HSD procedure was used to identify differences among means following significant main or interaction effects. Sample size estimates were made for comparing group differences in core body temperature using conventional $\alpha = 0.05$ and $\beta = 0.20$ values. Between 6 and 9 subjects was determined as a sufficient sample size to detect a meaningful difference in core temperature among trials, defined herein as an effect size >1.0 with an anticipated measurement

variability of $\sim 0.20^\circ\text{C}$ (Consolazio et al. 1963). Graphical data are presented with unidirectional error bars for presentation clarity. All data are reported as means $\pm$ SD.

Results

Classical heat acclimation responses (Lind and Bass 1963; Sawka et al. 1996) were observed in all volunteers prior to experimental testing (Table 1). These included a lower final HR and T_{c} despite substantially longer walk times in the heat. SR also increased 17% ($P = 0.06$). All 11 volunteers took part in the 3 trials as designed. Equipment malfunction precluded a complete repeated measures analysis of core temperature $\times$ time data, and therefore also PSI $\times$ time calculations and T_{c} change comparisons, each of which represent $n = 9$. All other data represent $n = 11$.

Hydration and Metabolic Rate. Ad libitum fluid intakes resulted in marginal fluid deficits among all trials (% dehydration = 0.6 (B); 0.8 (P); and 1.0% (S); $P > 0.05$). There were no differences in metabolic rate among trials (B: 279 ± 20 ; P: 281 ± 19 ; S: 282 ± 21 W/m²; $P > 0.05$). Thus, volunteers were adequately matched among trials for hydration status and energy expenditure.

Body Temperature and Cardiovascular Responses. Figure 1 provides the T_{c} , HR, and PSI for the three experimental trials. T_{c} was similar among all three trials until after 2 h of exercise when P and S rose 0.25 – 0.31°C higher ($P < 0.05$) than B (Fig. 1a). The changes in T_{c} from rest to exercise cessation were not different between P ($1.34 \pm 0.28^\circ\text{C}$) and S ($1.32 \pm 0.42^\circ\text{C}$), but both were larger than B ($1.03 \pm 0.26^\circ\text{C}$) ($P < 0.05$). Similarly, body heat storage was higher in P (13 ± 3 W/m²) and S (13 ± 5 W/m²) trials compared with B (10 ± 3 W/m²) ($P < 0.05$). HR was higher in P and S trials than B throughout the duration of exercise (Fig. 1b). The differences ranged from seven beats per min after the first hour to 19 beats per min at the conclusion of the fourth hour of

Table 1 Physiological adaptations to heat acclimation

Measure	Day 1	Final day ^a
Heart rate (b/min)	178 ± 15	$167 \pm 13^*$
Core temperature ($^\circ\text{C}$)	39.43 ± 0.16	$39.24 \pm 0.22^*$
Sweat rate (L/h)	1.27 ± 0.24	1.49 ± 0.39
Walk time to exhaustion (min) ^b	68.4 ± 11	$92.0 \pm 12^*$

^a Day 5 ($n = 4$), day 10 ($n = 7$)

^b Exhaustion defined as inability to continue, request to stop, or pulled for reaching critical core temperature safety limit (39.5°C) before completing the 100 min walk

* Significantly different from day 1 ($P < 0.05$)

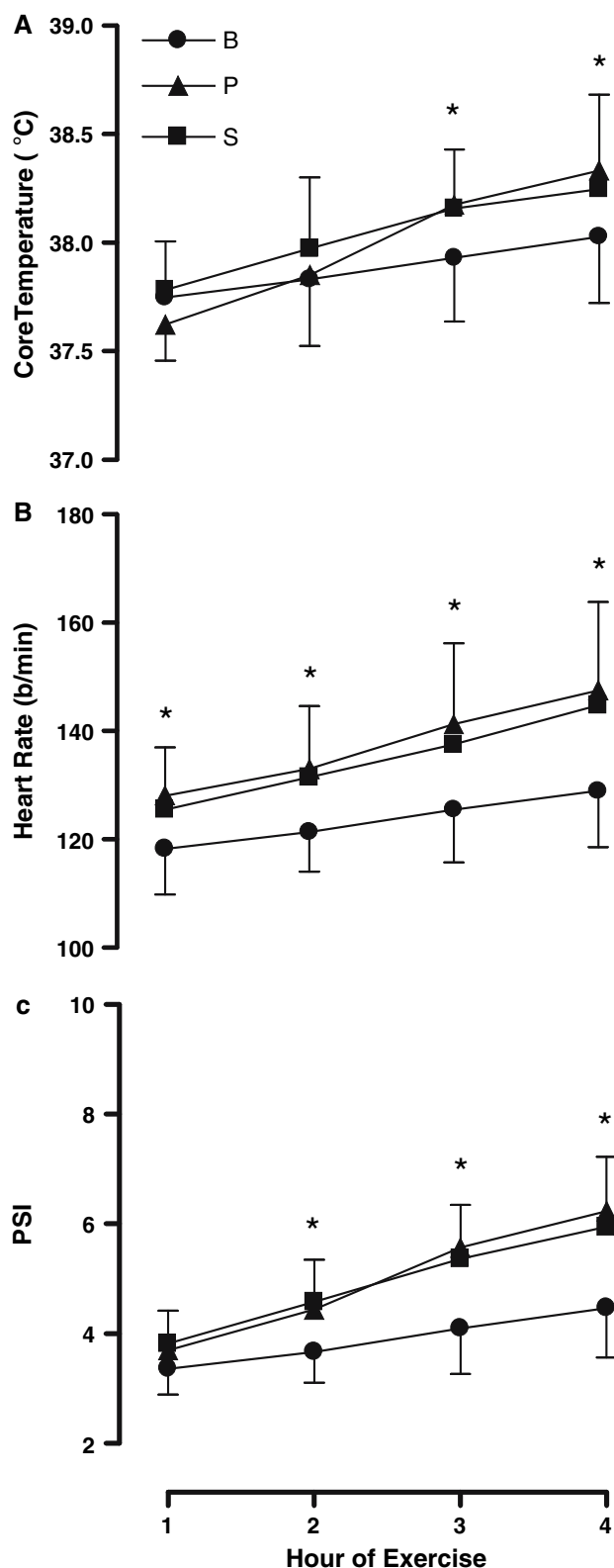


Fig. 1 Impact of clothing configuration (B, P, S) on core body temperature (a), heart rate (b) and the calculated physiological strain index (c) during 4 h of exercise-heat stress. * P and S > B (significant interaction, $P < 0.05$)

exercise. From 2 h of exercise onward, the calculated PSI was higher in P and S trials compared with B (Fig. 1c). The PSI at 4 h was “moderate to high” for P and S and “low to moderate” for B (Moran et al. 1998). Figure 2 provides T_{sk} and T_{chest} comparisons across trials. A main effect of trial was observed for T_{sk} and T_{chest} . Mean trial T_{sk} values were higher ($P < 0.05$) in P ($35.9 \pm 0.49^\circ\text{C}$) and S ($35.4 \pm 0.61^\circ\text{C}$) when compared with B ($34.9 \pm 0.44^\circ\text{C}$). These differences in T_{sk} were solely a function of differences in T_{chest} , where P and S were higher than B by 1.5°C , 1.1°C , respectively ($P < 0.05$).

Sweating Rates. Sweating rates during P ($0.75 \pm 0.19 \text{ L/h}$) and S ($0.77 \pm 0.17 \text{ L/h}$) trials were higher than B ($0.66 \pm 0.13 \text{ L/h}$). Although the mean differences among trials were significant (B < P and S; $P < 0.05$), the magnitude of the differences was small and of questionable practical importance ($<0.125 \text{ L/h}$) (Cheuvront et al. 2007).

Discussion

The impact of an IBA protective vest and spacer garment technology during exercise-heat stress in humans had not been previously evaluated. Heat acclimation, hydration states and circadian pattern were controlled in this study to reduce physiological variability. Metabolic rate was held constant during testing in order to eliminate the influence of load carriage on heat strain. The principal findings of this study were that (1) the IBA protective vest significantly increased physiological strain independent of added weight, and (2) a passive spacer garment did not significantly abate heat strain.

The IBA protective vest and spacer garment increased heat storage, T_c , HR, and PSI (Fig. 1a–c) relative to the BDU trial. There was also a small but statistically significant increase in sweating rate compared to B. The design of this study supports that these effects are attributable to the biophysical clothing properties in trial P (higher clo, lower i_m/clo). These results indicate that the increased temperature offsets for WBGT when wearing body armor (Cadarette et al. 2005) or industrial protective clothing (Bernard 1999) are due in part to biophysical clothing properties as well as increased heat production associated with an added load. Indeed, the potential magnitude of physiological strain would be even greater during any task when superimposing the metabolic cost of the added mass of protective gear (Puthoff et al. 2006; Ricciardi et al. 2007; Rusko and Bosco 1987). This would have important implications for fatigue (e.g., Gonzalez-Alonso et al. 1999; Pandolf and Goldman 1978) and heat injury risk (Departments of the Army and Air Force 2003; Pandolf and

Goldman 1978) in soldiers, industrial workers, American football players, or anyone else working in the heat while wearing clothing that contributes similarly to heat load.

In contrast to the estimated reduction in physiological strain reported from manikin work and modeling for these environmental and wind conditions (Endrusick et al. 2006), the spacer garment provided almost no measurable advantage in abating physiological strain under the exercise-heat stress conditions tested. A 20% improvement in whole body evaporative efficiency in trial S (vs. P), estimated from manikin work (Endrusick et al. 2006), would have resulted in an additional 125 W of cooling (based on observed sweating rates in each trial). Similarly, at the same T_{c} , a lowering of whole body T_{sk} by 0.4°C could theoretically reduce whole body skin blood flow by >25% (Rowell 1986) and produce a reflex drop in heart rate due to a larger central blood volume. It is clear that the lower T_{sk} observed in S was localized to the relatively small body surface area of the torso (Fig. 2b). As a result, any improvement in evaporative efficiency was likely limited to the smaller surface area of the torso (~25% of BSA), which was inadequate to lower HR, T_{c} , or PSI (Fig. 1a–c). It remains possible that greater benefits of a spacer garment might be observed under conditions with greater laminar airflow (>1 m/s) or when performing movements and activities which create a greater “chimney effect” (Folk 1974). However, the external validity of our findings appears reasonable when considering that warm/hot ambient air forced across the torso must be substantial in flow (10–20 cfm) to reduce physiological strain demonstrably when protective clothing is worn (Muza et al. 1988). This equates to approximately a 2–4 m/s air channel directed precisely through a passive spacer vest (not simply higher ambient laminar air flow), which is unlikely in any circumstance except where forced air technology is used.

This study and others (Cadarette et al. 2001; Yarger et al. 1969) support the general conclusion that protective vests worn in hot environments impose a substantial added heat load to the wearer. It is important, however, to consider these findings within context. The type of protective vest worn will make a difference. This choice must be determined by the expected threat level; light, flexible designs (Type I) for low velocity handguns and fully rigid protective vests (Type IV) for high velocity rifle and armor piercing rounds (National Institute of Justice 2001). The interaction with environment and metabolic rate is also critical (Montain et al. 1994). As metabolic rate, air temperature and humidity increase, the wear of a protective vest increases physiological strain (Yarger et al. 1969). Lighter protective vests (Type I), worn in temperate or cool environments (<30°C) when metabolic rate is low, should

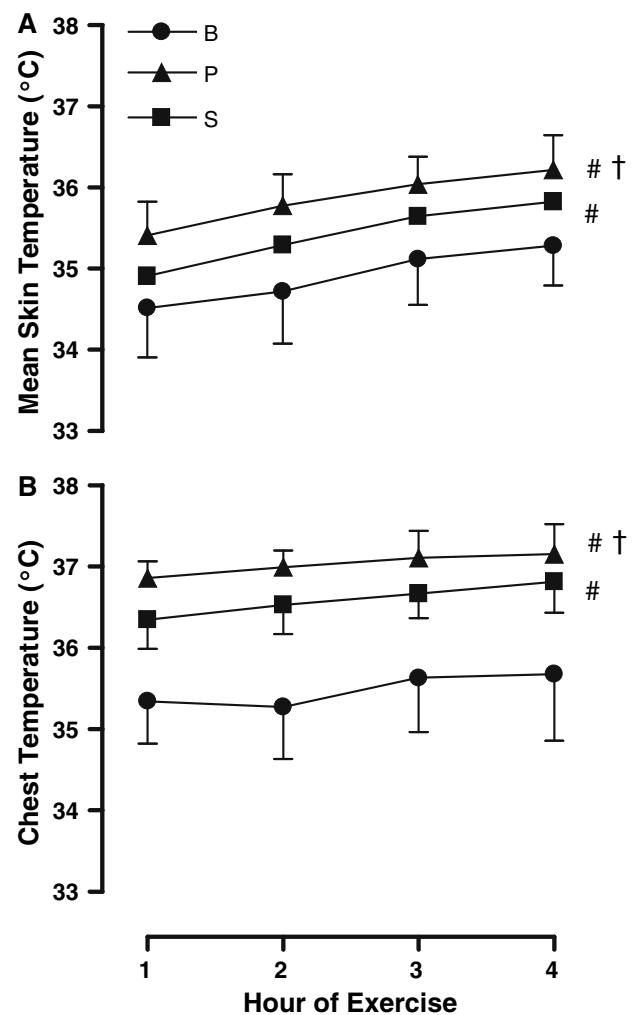


Fig. 2 Impact of clothing configuration (B, P, S) on mean skin (a) and chest temperatures (b). # P and S > B and † P > S (significant main effect of trial, $P < 0.05$)

have little impact on physiological strain (Lehmacher et al. 2007).

Conclusions

We conclude that the IBA protective vest increases physiological strain independent of added load. A passive spacer garment did not reduce these effects. Under the conditions tested, passive spacer garments appear to provide only a small local improvement in torso sweat evaporation, which is insufficient to alter measures of physiological strain such as T_{c} and heart rate. These results should be considered carefully when soldiers or global security personnel don similar protective vests or when athletes train using weighted vests in warm or hot environments.

Acknowledgments The authors wish to thank Rob Coleman and Rick Gallimore for providing the Interceptor Body Armor and spacer vests used in this study, respectively. We also thank the Biophysics and Modeling Division for manikin clothing data, Josh Bulotsky (Doriot Chamber facility), the entire Thermal and Mountain Medicine Division technical support staff, and most importantly the soldiers who volunteered their time to take part in this study. The view, opinions, and/or findings contained in this report are those of the authors and should not be construed as an official Department of the Army position, or decision, unless so designated by other official documentation. Approved for public release; distribution unlimited.

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