Effect of Air-Filled Vest on Exercise-Heat Strain When Wearing Ballistic Protection

J. D. Adams, Brendon P. McDermott*, Christian B. Ridings, Lacey L. Mainer, Matthew S. Ganio and Stavros A. Kavouras

Human Performance Laboratory, Department of Health, Human Performance, and Recreation, University of Arkansas, HPER 321, 155 Stadium Drive, Fayetteville, AR 72701, USA

*Author to whom correspondence should be addressed. Tel: +1-479-575-6762; fax: +1-479-575-2853; e-mail: brendonm@uark.edu

Submitted 14 March 2014; revised 22 April 2014; revised version accepted 23 May 2014.

ABSTRACT

Objectives: The purpose was to determine if an air-filled vest worn under ballistic protection reduces physiological strain during exercise in the heat either while wearing a tactical military (TM) protective vest or a law enforcement (LE) concealable vest.

Methods: Sixteen men (24.5 ± 3.9 years; 179.5 ± 5.6 cm; 84.6 ± 12.3 kg) performed either two or four trials of treadmill walking (1.34 m s⁻¹; 2% grade) over 120 min in a hot, dry environment (37°C, 30% relative humidity, wind speed 3.5 m s⁻¹). Participants completed trials wearing a TM or LE, with either the air-filled vest (TM; LE) or no vest (TM; LE) in random order. During trials, participants wore Army Combat Uniform pants. Physiological variables measured every 5 min included gastrointestinal temperature (TGI), mean skin temperature (Tsk), and heart rate (HR). Sweat rate (SR) was calculated based on fluid intake and body mass measures.

Results: In the tactical trial (TM versus TM), no differences in final TGI (38.2 ± 0.4 versus 38.3 ± 0.4°C), Tsk (35.0 ± 0.9 versus 35.0 ± 1.0°C), HR (142 ± 19 versus 143 ± 23 bpm) existed (P > 0.05). In the LE trials (LE versus LE), no differences in final TGI (38.0 ± 0.4 versus 38.1 ± 0.3°C), Tsk (35.3 ± 1.1 versus 35.6 ± 0.9°C), HR (132 ± 20 versus 135 ± 20 bpm) existed (P > 0.05). Despite slightly higher SR, there was no statistical difference in TM (1.15 ± 1.13 versus 1.54 ± 0.46 l h⁻¹; P = 0.10) or in LE (1.39 ± 0.52 versus 1.37 ± 0.18 l h⁻¹; P = 0.35) during trials.

Conclusion: When participants exercised with a TM or LE while wearing the air-filled vest, there were no thermoregulatory and physiological differences compared to control trials. In our testing conditions, the air-filled device had little effect on physiological responses during prolonged mild exercise in the heat.

KEYWORDS: law enforcement; military; thermoregulation

INTRODUCTION

Ballistic vests provide upper body protection for a variety of personnel such as soldiers, customs patrol, security forces, and journalists reporting from war zones (Lehmacher et al., 2007; Ricciardi et al., 2008). This body armor consists of outer vests, front and rear ballistic plates, and various attachments for protection of the neck, groin, and upper arms and can add in excess of 9.9 kg, in some cases (Endrusick et al., 2006). This material typically covers roughly 30% of the body surface area (BSA), mostly the torso, with synthetic, impermeable materials. Law enforcement (LE)...
officials use similar protective equipment although, in most cases, this is lighter and slightly more permeable (Richmond et al., 2013).

Similarly, weighted vests of comparable mass and surface area are used by athletes for training or by older adults for therapeutic exercise (Greendale et al., 2000; Puthoff et al., 2006). While the effects of wearing a weighted and protective vest regarding metabolic rates have been well described, less attention has been given to the physical properties of protective vests to restrict airflow, increase heat storage, and increase physiological strain [e.g. increased core temperature, heart rate (HR), and sweating] in response to heat stress (Gonzalez and Sawka, 1988; Larsen et al., 2014).

Exercise is known to increase heat production, which is then either released during skeletal muscle contraction to perform mechanical work or released into the tissue as heat. Dissipation of this body heat is mediated by the evaporation of sweat from the surface of the skin and the non-evaporative transfer of heat from the body to the surrounding environment via convective, conductive, and radiative mechanisms (Gonzalez and Sawka, 1988). The most efficient cooling mechanism for humans in dry climates is evaporation, providing up to 90% heat dissipation. Clothing and ballistic vests can exacerbate physiological strain by impeding evaporative heat loss and increasing metabolic heat production as a result of increased load carriage (Endrusick et al., 2006; Cheuvront et al., 2008; Hadid et al., 2008).

Several techniques have been developed regarding cooling and efficiency of vest design to abate physiological strain when wearing protective clothing. Undergarments with various openings and loose weave undershirts provide a modest improvement in airflow and sweat evaporation when worn beneath some protective vests (Endrusick et al., 2006; Cheuvront et al., 2008). Garments that provide space and allow airflow between the skin and ballistic vest represent a design advance over other techniques as they can increase evaporative cooling within the BSA typically hampered by protective vests. This technique is regarded as ‘passive’ as there is no forced ventilation or air cooling (Hadid et al., 2008).

Previous thermal manikin and modeling analyses at 1.00 m s⁻¹ airflow indicate that passive spacer garment technologies may substantially reduce physiological strain when worn in warm-hot environments (Endrusick et al., 2006). However, Cheuvront et al. (2008) confirmed that a spacer garment did not prevent these effects in human participants under exercise-heat stress conditions compared to control subjects wearing only a protective vest.

The purpose of this study was to examine thermoregulatory responses when wearing a novel perforated air-filled vest (CTAV; CORTAC; Hendersonville, TN, USA) under either a military or LE protective vest during exercise in a hot, dry environment [37°C, 30% relative humidity (rh)]. Our hypothesis was that wearing the air-filled vest with either military or LE protective vest would provide no reduction in physiological strain measures.

METHODS

Subjects

Sixteen healthy male volunteers participated in this study. Descriptive characteristics (mean ± SD) for this group were age: 24.5 ± 3.9 years, body mass: 84.9 ± 12.3 kg, percent body fat: 24.1 ± 10.5%, and BSA (Du Bois and Du Bois, 1916): 2.04 ± 0.14 m². All volunteers were provided informational briefings and gave voluntary and informed written consent to participate. This study was approved by the University of Arkansas Institutional Review Board and the study was conducted in the late spring and early summer months.

Familiarization visit

At least 72 h prior to the first experimental trial, subjects completed a familiarization visit where body mass (Health O Meter Professional®, 349 KLX), height, and body composition were measured using Dual-energy X-ray absorptiometry (General Electric®, Lunar Prodigy Promo). During this visit, subjects completed a brief walking test (15 min, 1.34 m s⁻¹, 2% grade) and were further instructed on the procedures during the experimental trial. Participants were also sized for US Army Combat Uniform (ACU) pants and their appropriate ballistic vest via the manufacturer’s instructions (Survival Armor, Fort Myers, FL, USA). Official military-grade ACUs are made of 50% nylon and 50% cotton.

Ten hours before arrival, subjects were given an ingestible thermistor to measure gastrointestinal temperature ($T_{GI}$, HQ Inc., Palmetto, FL, USA) and subjects refrained from the consumption of alcohol,
caffeine, and over-the-counter medication for the 24h prior to testing. Participants also refrained from the ingestion of food other than water for 2 h prior to experimental trials.

**Design**

Participants completed two trials in a tactical military (TM) plate carrier vest ($n = 12$) and/or two trials in a LE concealable vest ($n = 12$) in a hot, dry environment (37°C, 30% rh, wind speed 3.5 m s$^{-1}$) separated by 6 days. This environment was selected to maximize potential improvements in evaporative cooling while minimizing volunteer attrition due to heat exhaustion (Pandolf and Goldman, 1978). The subject was fitted with ACU pants and given a shirt (Starter® Dri-Star Wicking Tee, 100% polyester) to wear underneath the protective vest. This was provided to participants to provide comfort and standardization for trials without altering physiological parameters. The ACU pants and spandex shirt were worn in all trials along with a TM vest (Covert Overt, Survival Armor) with front and rear protective plates or an LE vest (Paragon6, NIJ-STD-0101.06, Survival Armor) with either the air-filled garment (TM; LE) or no spacer garment control (TM; LE).

One hundred and twenty minutes of exercise were performed during each trial. This was in context with recommendations for heat tolerance testing for return to duty for athletes and service members. In each trial, walking speed was 1.34 m s$^{-1}$ with a grade of 2%. Trials were randomized and testing was conducted at the same time of day for each participant to control for circadian fluctuations in body temperature.

**Procedures**

At the start and conclusion of each trial, nude body mass was measured on an electronic scale. Prior to each trial, euhydration was verified via urine specific gravity ≤1.020 by a refractometer (Sper Scientific®, 300005; Scottsdale, AZ, USA) from a voided urine sample.

HR (Polar a3, Polar Electro, Inc., Woodbury, NY, USA) and gastrointestinal temperature ($T_GI$) were measured throughout the trial at 5-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):

$$PSI = \left[ \frac{5(T_{GI} - T_{GI,0})}{39.5 - T_{GI,0}} \right] + \left[ \frac{5(HR - HR,0)}{180 - HR,0} \right]$$

Skin temperature was measured from thermocouples (Omega Engineering, Stamford, CT, USA) located at four sites (forearm, chest, thigh, and calf). Mean skin temperature ($T_{sk}$) was calculated using the equation (Ramanathan, 1964):

$$T_{sk} = 0.3(T_{Chest} + T_{Forearm}) + 0.2(T_{Thigh} + T_{Calf})$$

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

$$S = \left( \frac{0.97 \cdot \text{body mass}}{\text{BSA}} \right) \left( \frac{\Delta T_{b}}{\Delta t} \right)$$

where body mass is in kg, $\Delta T_{b}$ is the change in mean body temperature (final – pre exercise), and $\Delta t$ is time in hours. BSA was calculated from the measurements of weight and height according to Du Bois and Du Bois (1916).

$T_{b}$ was calculated as (Gagge and Gonzalez, 1996):

$$T_{b} = xT_{GI} + (1-x)T_{sk}$$

where $x$ is the appropriate weighting coefficient (0.90) for hot environments. All temperatures were measured in °C and heat balance data were quantified using W m$^{-2}$ units. To localize the effect of the spacer garment on torso skin temperature, subscapular temperature was also recorded.

Since dehydration independently alters core temperature responses during exercise (Montain and Coyle, 1992), dehydration was prevented during exercise by having subjects ingest equal boluses of body temperature water (3 ml kg$^{-1}$ body mass each at ~37°C) just before and at 15-min intervals until the completion of exercise. Whole body sweat rate (SR), corrected for fluid ingestion (Gagge et al., 1967), was calculated using pre- and postexercise nude body mass. Thermal sensation was recorded every 10 min, which included 17 categories of thermal comfort, ranging from 0.0 (‘unbearably cold’) to 8.0 (‘unbearably hot’), in increments of 0.5 U (Young et al., 1987).
Statistical analyses
Statistical analysis was performed using SPSS v.20 for Windows (IBM SPSS Software, Armonk, NY, USA). Data are reported as mean ± SD. An alpha level of 0.05 was used for all significance tests. A two-way (group versus time) repeated measures of analysis of variance were used to test the significance of mean differences. Differences between the vests and controls were examined by comparing the two experimental trials separately. Post hoc pairwise *t*-tests and Bonferroni alpha corrections were used when appropriate. Effect sizes (Rice and Harris, 2005) were calculated for each variable. Weighted-mean estimate of the effect sizes was calculated to account for sample size differences. Cohen’s classification of effect size magnitude was used, whereby *d* < 0.19 = negligible effect; *d* = 0.20–0.49 = small effect; *d* = 0.50–0.79 = moderate effect and *d* > 0.8 = large effect (Rice and Harris, 2005).

RESULTS
In the tactical vest trial (TM a versus TM c), no differences in T GI (38.2 ± 0.4 versus 38.3 ± 0.2°C; *P* = 0.726; effect size = 0.24; Fig. 1), T sk (35.0 ± 0.9 versus 35.0 ± 0.7°C; *P* = 0.901; effect size = 0.00; Fig. 2), or HR (142 ± 19 versus 143 ± 23 bpm; *P* = 0.772; effect size = 0.05; Fig. 3) existed. Heat storage was also similar between the two trials (15.7 ± 9.6 versus 18.6 ± 10.9 W m⁻²; *P* = 0.25; effect size = 0.27, respectively). Similarly, PSI (Fig. 4) was not different (*P* = 0.755; effect size = 0.00) between TM a versus TM c (5 ± 1 versus 5 ± 2, respectively). After 2 h of walking, the PSI for both groups (TM a versus TM c) was ‘low to moderate’ (Moran et al., 1998). Rate of rise in GI temperature revealed no differences between TM a versus TM c (0.0063 ± 0.0031 versus 0.0076 ± 0.0044°C min⁻¹; *P* = 0.128; effect size = 0.00; Fig. 5). Thermal sensation showed no differences between groups (TM a versus TM c) at the end of the exercise bout (5 ± 1 versus 5 ± 1; *P* = 0.37; effect size = 0.00). SR was similar in the TM a versus TM c trials (1.28 ± 0.21 versus 1.42 ± 0.27 l h⁻¹; *P* = 0.10; effect size = 0.17), respectively. Average fluid intake every 15 min for the TMs versus TM c trials was 250.4 ± 29.1 ml, which resulted in a total intake of 2003.3 ± 232.6 ml.

In the LE vest trial (LE a versus LE c), no differences in T GI (38.0 ± 0.4 versus 38.1 ± 0.3°C; *P* = 0.538; effect size = 0.28; Fig. 1), T sk (35.3 ± 1.1 versus 35.6 ± 0.9°C; *P* = 0.240; effect size = 0.29; Fig. 2), or HR (132 ± 20 versus 135 ± 20 bpm; *P* = 0.538; effect size = 0.14; Fig. 3) existed. Similarly, there were no differences in heat storage between LE a and LE c (12.9 ± 10.7 versus 17.6 ± 9.1 W m⁻²; *P* = 0.13; effect size = 0.47, respectively). PSI (Fig. 4) was not different (*P* = 0.086; effect size = 0.00) between LE a versus LE c (4 ± 1 versus 4 ± 2, respectively). After 2 h of walking, the PSI for both groups (LE a versus LE c) was ‘low’ (Moran et al., 1998). Rate of rise in GI temperature (°C min⁻¹) revealed no differences between LE a versus LE c (0.0047 ± 0.0034

1 Mean ± SD gastrointestinal temperature during 120 min of exercise for LE and tactical vest trials. There were no significant differences between control and air-filled vest trials in either tactical (*P* = 0.726) or LE (*P* = 0.538) vests.
versus $0.0065 \pm 0.0037$; $P = 0.121$; effect size = 0.51; Fig. 5). Thermal sensation showed no differences for both groups (LE versus LE$_c$) when asked in the final segment of exercise ($6 \pm 1$ versus $6 \pm 1$; $P = 0.19$). SR was similar in the LE versus LE$_c$ trials ($1.32 \pm 0.38$ versus $1.37 \pm 0.18$ l h$^{-1}$; $P = 0.35$; effect size = 0.58), respectively. Average fluid intake every 15 min for the LE$_a$ and LE$_c$ trials was 251.7 ± 40.7 ml, which resulted in a total intake of 2013.3 ± 325.5 ml.

**DISCUSSION**

The impact of the novel perforated air-filled vest on two different classes of protective vests had not been previously assessed. Hydration states and circadian patterns were controlled in this study to reduce potential physiological variability. The principal finding of this study was that an air-filled passive spacer garment did not decrease heat strain in either protective vest compared with controls. These results are
in agreement with previous research conducted with mesh clothing garments worn under body armor during exercise-heat stress (Cheuvront et al., 2008).

It has been confirmed that wearing protective gear increases physiological strain and metabolic cost during exercise and execution of tasks (Puthoff et al., 2006; Ricciardi et al., 2008). This increase in metabolic demand and physiological strain can increase fatigue (Pandolf and Goldman, 1978; González-Alonso et al., 1999; Dempsey et al., 2014) and risk for heat illness in various personnel such as soldiers, industrial workers, football players, or anyone else performing in the heat while wearing added load (Davis and Bishop, 2013).

Although contradicting previously reported results from manikin work and modeling (Endrusick et al., 2006), the garment tested in this study provided almost no measurable advantage in abating physiological strain under these exercise-heat stress conditions. The goal of the spacer garment and the study conditions was to induce a ‘chimney effect’ (Folk, 1974), by

4 Mean ± SD PSI during 120 min of exercise for LE and tactical trials. There were no significant differences between control and air-filled vest trials in either tactical ($P = 0.755$) or LE ($P = 0.086$) vests.

5 Mean ± SD rate of rise in gastrointestinal temperature during 120 min of exercise for LE and tactical trials. There were no significant differences between control and air-filled vest trials in either tactical ($P = 0.128$) or LE ($P = 0.121$) vests.
having a greater laminar airflow (>1.0 m s\(^{-1}\)). However, the study conditions of wind speed at 3.5 m s\(^{-1}\) did not increase evaporative cooling; thus, skin and GI temperatures were not mitigated. Future studies utilizing spacer garments should include more intense exercise or increased environmental strain to identify a potential benefit under more extreme conditions.

With the increasing weight of the respective armor, and with the increase in metabolic rate, air temperature, and humidity, the physiological strain on the individual will increase additionally. Testing the device in hotter conditions comparable to traditional heat tolerance testing (40°C, 40% rh) (Moran et al., 2004) might stress the individual to a greater degree, allowing for a possible enhancement of evaporative cooling with the spacer device. Despite anecdotal reports of subjective improved comfort while wearing the air-filled vest tested in this study, we saw no benefit on thermoregulation. Overall, the addition of other data suggesting ballistic benefit of the air-filled garment could be considered in determination of clinical application.

CONCLUSIONS

Although a weighted, protective vest increases carrying load and physiological strain, a perforated, passive air-filled vest did not reduce these effects. Under the conditions tested, there were no improvements in HR and GI temperature, thus not abating physiological strain. These data are important considerations when military forces, security, and police personnel wear similar protective equipment.

FUNDING

The Apax Group, Inc. d/b/a CORTAC.

DISCLAIMER

This experiment and its authors comply with the current laws of the United States of America in regards to performing research ethically.

ACKNOWLEDGMENTS

The authors would like to thank the participants for their work during this research project and the personnel of the Human Performance Laboratory for their dedication to this piece of science. J.D.A. participated in protocol planning, data collection, sample analysis, and data analysis and was the primary author of the manuscript. B.P.M. initiated the research question, participated in protocol planning, submission to review board, data collection, sample analysis, data analysis, and manuscript revision and approval. M.S.G., C.B.R., L.L.M., and S.A.K. participated in protocol planning, data collection, and manuscript revisions and approval. The authors declare that they have no competing interests.

REFERENCES


