Eur J Appl Physiol (1995) 70: 322–328 © Springer-Verlag 1995

ORIGINAL ARTICLE

B.L. Bennett · R.D. Hagan · K.A. Huey · C. Minson
D. Cain

Comparison of two cool vests on heat-strain reduction while wearing a firefighting ensemble

Accepted: 5 August 1994

Abstract This study evaluated the effectiveness of a six-pack versus a four-pack cool vest in reducing heat strain in men dressed in firefighting ensemble, while resting and exercising in a warm/humid environment [34.4°C (day bulb), 28.9°C (wet bulb)]. Male volunteers ($n = 12$) were monitored for rectal temperature (T_{re}), mean skin temperature (T_{sk}), heart rate, and energy expenditure during three test trials: control (no cool vest), four-pack vest, and six-pack vest. The cool vests were worn under the firefighting ensemble and over Navy dungarees. The protocol consisted of two cycles of 30 min seated rest and 30 min walking on a motorized treadmill ($1.12\ m \cdot s^{-1}$, 0% grade). Tolerance time for the control trial (93 min) was significantly less than both vest trials (120 min). Throughout heat exposure, energy expenditure varied during rest and exercise, but no differences existed among all trials ($P > 0.05$). During the first 60 min of heat exposure, physiological responses were similar for the four-pack and six-pack vests. However, during the second 60 min of heat exposure the six-pack vest had a greater impact on reducing heat strain than the four-pack vest. Peak T_{re} and T_{sk} at the end of heat exposure for 6-pack vest [mean (SD) 38.0(0.3)°C and 36.8(0.7)°C] were significantly lower compared to four-pack [38.6(0.4)°C and 38.1(0.5)°C] and controls [38.9(0.5)°C and 38.4(0.5)°C]. Our findings suggest that the six-pack vest is more effective than the four-pack vest at reducing heat strain and improves performance of personnel wearing a firefighting ensemble.

Key words Heat strain · Cool vests · Body temperatures · Heart rate

B. L. Bennett (✉) [1]
Naval Health Research Center, P.O. Box 85122, San Diego, CA 92186-5122, USA

R.D. Hagan · K.A. Huey
GEO-CENTERS, Inc., Fort Washington, M 20744, USA

C. Minson · D. Cain
San Diego State University Foundation, San Diego, CA 92182, USA

Present address:
[1] Department of Military and Emergency Medicine, Uniformed Services University of the Health Sciences, 4301 Jones Bridge Road, Bethesda, MD 20814-4799, USA

Introduction

Understanding the impact of heat strain on the performance of naval personnel has important applications to shipboard fire-suppression activities. Firefighting is associated with heat strain (HS) as demonstrated by large increases in skin (T_{sk}) and core temperatures and near maximal heart rates (f_c Duncan et al. 1979; Romet and Frim 1987; Bennett et al. 1992). These responses can be attributed to body heat production caused by wearing up to 20 kg of personnel protection equipment, the physical effort associated with carrying equipment, and the heat gain due to exposure to high ambient temperatures and humidity.

Evidence supports the benefits of the use of microclimate cooling systems to reduce HS (Speckman et al. 1988). The benefits of microclimate cooling are documented in Air Force ground crews (Terrian and Nunneley 1983), helicopter crews (Banta and Braun 1992), shipboard personnel working in high-heat areas (Janik et al. 1987), and armored vehicle crew and soldiers wearing chemical protection overgarments in the heat (Speckman et al. 1988; Muza et al. 1988). However, microclimate cooling systems using air- or water-cooled undergarments may not be practical for shipboard firefighters. Pimental et al. (1991) reported that a six-pack cool vest employing frozen gel blocks worn under the firefighting protective ensemble reduced HS during rest and exercise. However, the size of the six-pack size about the constraints of the single-piece firefighting ensemble make it necessary to determine if a smaller and lighter four-pack cool vest can provide cooling comparable to the six-pack vest. Therefore, the purpose of this study was to compare differences in the HS reduction of a six-pack and four-pack cool vests with a no-vest condition (control) in naval firefighters performing rest and exercise cycles in a warm/humid environment.

Methods

The protocol and procedures for this study were reviewed and approved by our center's committee for the protection of Human subjects.

Subjects

Twelve men served as subjects. All were experienced in the use of firefighting protection equipment. Their physical characteristics were [mean (SD)] 25.3(3.5) years, 175(8) cm, 74(14) kg, 1.88(0.2) m^2, and 17.7(4.5)% body fat. Nine of the 12 worked from 1 to 5 h a day in a hot environment, 5 days per week.

Medical screening

Each man gave informed consent before participation. All underwent medical screening that included a medical history questionnaire, body composition assessment, and resting electrocardiogram (ECG). Body surface area was calculated according to the height and weight regression equation of DuBois (Carpenter 1964). A U.S. Navy regression equation was used to calculate percentage body fat pram height and circumference measures of the neck an abdominal region (Hodgdon and Beckett 1984).

Two ECG electrodes were placed on the upper chest near the shoulders, two on the waist toward the sides of the body, and six on the chest around the lower border of the left chest. Resting ECGs and blood pressures (P_a) were taken in supine, seated, and standing postures. All the men completed an incremental treadmill exercise test to voluntary exhaustion. The maximum heart rate (f_c) reached during the test was measured.

Experimental procedures

The previous night and on the morning of the heat-exposure test, subjects were instructed to drink 1 l of a non-caffeine beverage, to ensure normal body hydration. Urine was collected prior to testing for measurement of specific gravity to assess body fluid level.

The heat exposure protocol consisted of two cycles of 30 min seated rest, and 30 min walking on a motorized treadmill at 1.12 $m \cdot ^{-1}$ and 0% grade. The ambient environment during heat exposure was [mean (SD)] 34.4(0.5)°C (dry bulb), 28.9(0.4)°C, (wet bulb).

All men participated in three different tests with: (1) no vest (control), (2) a four-pack cool vest, and (3) a six-pack cool vest, administered in random order. The vests were worn under the firefighting ensemble. During each test, subjects wore a T-shirt, long-sleeved cotton shirt, jeans (Navy dungarees), socks, and boondocker boots as basic undergargments. In the cool-vest trials, the vest was worn over this clothing ensemble and under the protective overgarment. The cool vests (Steele, Kingston, Wash.) contained either four (425 g each) or six (765 g each) frozen gel thermostrips, which were kept frozen at −28°C until use. The six-pack vest had three frozen gel strips placed horizontally across the front of the vest in separate pockets, and three corresponding strips across the back. The four-pack had two strips placed vertically on the front, and two strips placed horizontally on the back. Each pocket of the two vests was externally insulated with Thinsulate. During each test, the subjects wore the standard Navy-issue damage control gear: flash hood, helmet, gloves, single-piece Nomex firefighting ensemble, and oxygen breathing apparatus.

Before each exposure, the men inserted a thermistor to a depth of 200 mm in the rectum. Skin thermistors were placed over the right upper arm, upper right chest, mid-lateral thigh, and mid-lateral calf. Three ECG electrodes were placed on the chest to monitor f_c. T_{re}, weighted mean T_{sk}, and f_c were recorded at 1-min intervals by a portable data logger (Squirrel; Science/Electronics, Miamisburg, Ohio) worn outside the ensemble. f_c was also recorded by a ECG telemeter (Heartwatch; Polar, Stamford, Conn). Pre-test and post-test nude body mass, and fluid intake and output were recorded.

Oxygen uptake and carbon dioxide production were measured once during each rest and exercise period at minutes 15, 45, 75, and 105, and used to calculate energy expenditure. The helmet and oxygen breathing apparatus were removed and the subject's expired air was collected for 2 min in a meteorological balloon in series with a mouthpiece and two-way valve. Expired oxygen and carbon dioxide concentrations were measured by gas analyzers (Med-Graphics Metabolic System), and gas volume was determined in a 120-1 Tissot Spirometer. During the rest and exercise periods, subjects were allowed to drink as much water (21°C) as desired.

Any one of the following criteria were used for removal of the subject from heat exposure; T_{re} of 39.5°C; systolic P_a of 29.3 kPa or diastolic P_a of 16 kPa; f_c of 85% of predicted maximum or greater for 20 min; absence of sweating or presence of chills, nausea, weakness, or dizziness; or subject wanting to give up.

T_{sk} was calculated as the weighted average of four T_{sk} measurements (Ramanathlan 1964). Mean body temperature (T_b) was calculated according to a weighting equation (Stolwijk and Hardy 1966) using T_{re} and T_{sk}. Change in body heat content was calculated using T_b and the specific heat constant of 3.48 $KJ \cdot °C^{-1}$. HS ($KJ \cdot Kg^{-1}$) equaled the difference in heat content between pre-resting heat exposure and peak values.

The average total body sweat loss was calculated as the difference between pre-test and post-test body mass with the post-test weight corrected for fluid input and urine output. Fluid balance ($l \cdot h^{-1}$) was calculated as the sum of fluid intake, urine output, and sweat loss.

Statistical analysis

All dependent variables were statistically analyzed by a repeated measures analysis of variance with two factors, time and condition. Evaluation of significant differences between means was achieved using 95% confidence intervals. Complete data were analyzed through the second rest period. Repeated measured analysis of variance was also done through the second exercise period; however, only six control group subjects were included in the analysis due to reduced tolerance time. Significance is reported at $P < 0.05$.

Results

Heat exposure time

The heat exposure time for the control group was significantly less than both vest conditions. The mean (SD) heat exposure time was 92.8(19.9) min in the control condition. Six men completed between 68 and

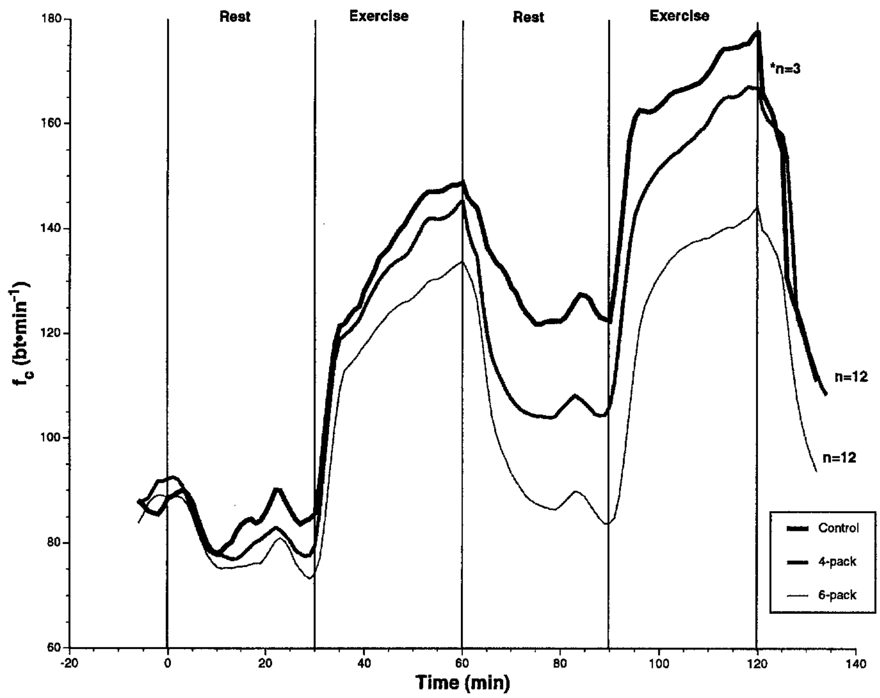


Fig. 1 Average heart rates during rest and exercise in a fireighting ensemble at 95°F and 65% relative humidity. Only 3 of the 12 control subjects completed the 2-h protocol

84 min, three between 99 and 101 min, and three 120 min. Termination occurred as a result of physical symptoms of fatigue and feeling "hot." All the men, wearing either the four-pack or six-pack vests completed the 120 min of heat exposure.

Energy expenditure and heart rates

Energy expenditure averaged 107(16) W during the 30-min rest periods and 422(8) W during the 30-min exercise periods. There were no differences ($P > 0.05$) in energy expenditure in the three conditions either at rest or during exercise.

There was a significant effect of time and condition on f_c. The cyclical f_c response paralleled energy expenditure over the rest and exercise cycles (Fig. 1). There was no significant difference in f_c between the three conditions during the first rest/exercise cycle. However, during the second rest period f_c was different ($P < 0.05$) between conditions. At min 90, the mean (SD) f_c was 129(12), 103(15), and 84(8) beats·min^{-1} for control, four-pack vest, and six-pack vest conditions, respectively. At the end of the second exercise period (Table 1), f_c was lower ($P < 0.05$) for six-pack vest compared to four-pack vest and control.

Body temperatures and HS

There was increase in T_{re} (Fig. 2), T_{sk} (Fig. 3), and T_b (Fig. 4) through heat exposure which differed significantly among the three conditions. Peak T_{re}, T_{sk}, and T_b values recorded at the end of heat exposure are shown in Table 1. At the end of the first exercise period, control had a higher ($P < 0.05$) T_{re} than six-pack vest. After the second rest period, T_{re} was significantly different between control, four-pack, and six-pack conditions, respectively, with the six-pack and four-pack conditions showing progressively lower values. These trend differences ($P < 0.05$) between vest conditions continued through the final exercise period.

T_{sk} rose progressively during the first rest period for the control and four-pack conditions. At the end of the first exercise period, T_{sk} was different ($P < 0.05$) between all conditions, the highest temperature belonging to the control condition, followed by the four pack and then the six-pack vest conditions. This trend in differences ($P < 0.05$) continued throughout the second rest/exercise cycle.

Convergence of T_{re} and T_{sk} occurred in 7 of the 12 subjects during the control condition, and in 2 of 12 subjects during the four-pack vest condition. During the six-pack vest condition, no subjects experienced convergence of T_{re} and T_{sk}.

Table 1 Mean (SD) peak rectal temperature (T_{re}), weighted mean skin temperature (T_{sk}), mean body temperature (T_b), and heart rate (f_c) responses during heat exposure

	Peak T_{re} (°C)	Peak T_{sk} (°C)	Peak T_b (°C)	Peak f_c (beats·min^{-1})
Control (no vest)	38.9(0.5)*	38.4(0.5)*	38.7(0.5)*	176(15)*
Four-pack vest	38.6(0.4)*	38.1(0.5)*	38.4(0.4)*	169(16)*
Six-pack vest	38.0(0.3)	36.8(0.7)	37.7(0.3)	148(15)

*Significantly higher than six-pack ($P < 0.05$)

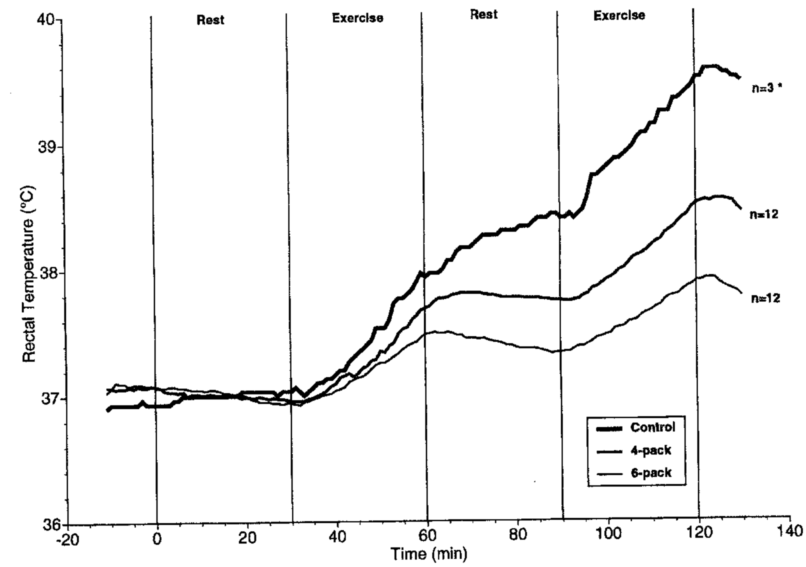


Fig. 2 Average rectal temperatures during rest and exercise in a firefighting ensemble at 95°F and 65% relative humidity. Only relative humidity 3 of the 12 control subjects completed the 2-h protocol

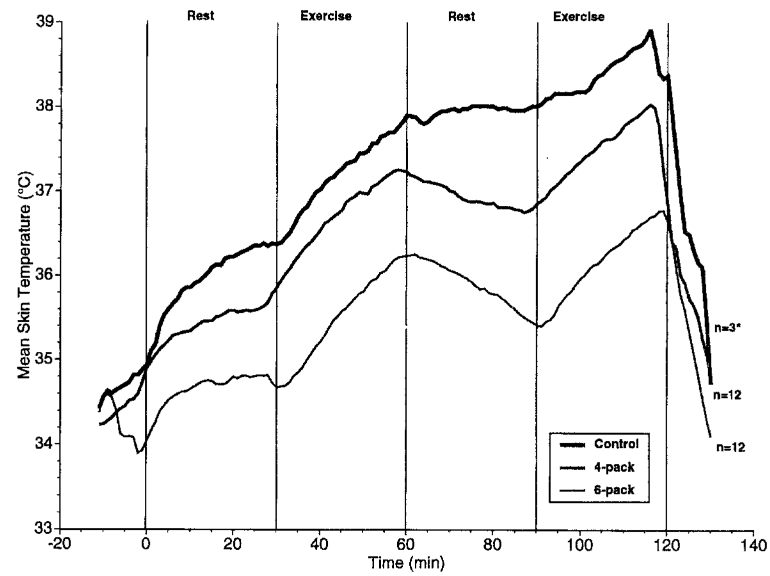


Fig. 3 Mean skin temperatures during rest, and exercise in a firefighting ensemble at 95°F and 65% relative humidity. Only 3 of the 12 control subjects completed the 2-h protocol

T_b was significantly different among the conditions during the first exercise and second rest/exercise cycle the highest temperature belonging to the control condition followed by the four-pack and six-pack vest conditions. Heat exposure for 120 min produced average heat storage values of 6.2(1.2) and 3.9(0.9) $kJ \cdot kg^{-1}$ for the four-pack and six-pack vest conditions, respectively (Fig. 5). For the control condition, the average HS was 5.3(1.2), 7.9(1.1), and 9.4(0.7) $kJ \cdot kg^{-1}$ for tolerance times of 68–84 min, 99–101 min, and 120 min, respectively.

Fluid exchange

Total body sweat loss [755(421) g], water intake [876(381) ml], urine output [121(199) ml] and fluid balance [− 0.84(0.69) ml] were similar in the three conditions.

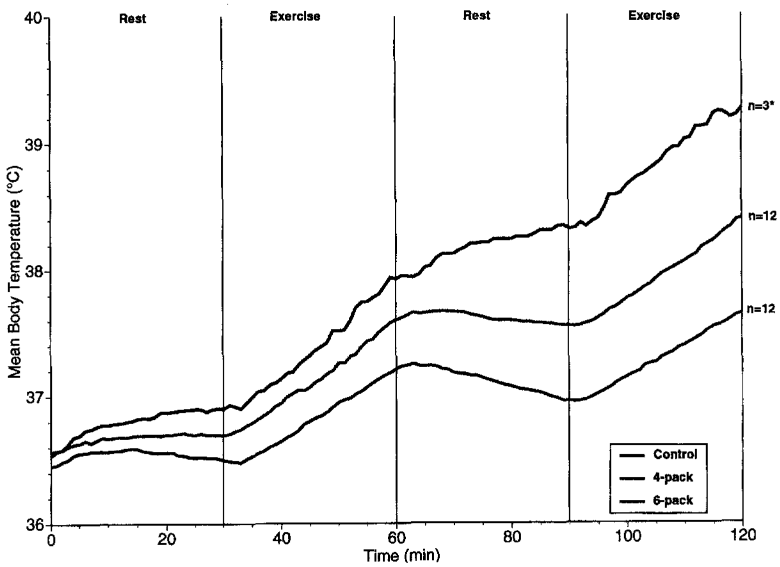
Discussion

This study demonstrates the effect of cool torso vests on HS in naval personnel during rest and exercise cycles in a warm/humid environment. The cool vests resulted in lower HS, and completion of the 2-h test protocol.

Effect of cool vests on body temperatures

During the first rest/exercise cycle, increases in core and peripheral body temperatures were similar

Fig. 4 Mean body temperatures during rest and exercise in a firefighting ensemble at 95°F and 65% relative humidity. Only 3 of the 12 control subjects completed the 2-h protocol



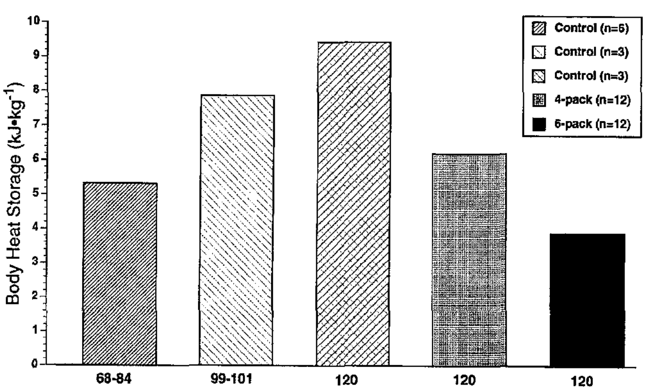


Fig. 5 Mean body heat storage at the termination of heat storage. □, Control ($n = 6$); □, control ($n = 3$); □, control ($n = 3$); □, four-pack ($n = 12$); ■, six-pack ($n = 12$)

between the four-pack and six-pack vest, but lower compared to controls. However, during the second rest/exercise cycle, body temperatures were lower for both vests compared to the control condition with the lowest temperatures belonging to the six-pack followed by the four-pack vest.

Use of the six-pack vest resulted in the smallest rise in both T_{re} and T_{sk} throughout the 120-min heat exposure period. T_{re} increased 0.8(0.28)°C which is comparable to the 0.9°C reported by Pimental et al. (1991) while wearing the six-pack cool vest. However, our T_{sk} peaks were greater than those reported by Pimental et al. for subjects wearing the six-pack vest [36.8(0.7) vs 33.2°C, respectively]. The difference in T_{sk} between these two studies may have resulted from two factors. First, there were slightly higher air temperature and humidity confronting our subjects. Second, the subjects in the study by Pimental et al. were heat acclimated prior to heat-exposure tests, which lowers the exercise T_{sk} response (Eichna et al. 1950). Thus, use of cool vests facilities heat loss during exercise in the heat. Cool vests in combination with heat acclimatization may have the potential to further minimize HS during exercise in warm environments.

Effect of cool vests on heat storage

The lower T_{re} and T_{sk} associated with the six-pack and four-pack vests were associated with lower levels of heat storage compared to controls. Heat storage averaged 6.2(1.2) and 3.9(0.9) $kJ \cdot kg^{-1}$ for the four-pack and six-pack vests, respectively. Thus, the cool vests greatly reduced HS. The lower HS for the vest conditions, with the larger vest providing a greater loss of heat compared to the four-pack vest, probably allowed these subjects to complete the 120-min test protocol.

It has been postulated that heat exposure tolerance is dependent upon thermal convergence (Pandolf and Goldman 1978). However, our findings provide evidence against the role of thermal convergence as a factor affecting heat exposure tolerance. In our study, thermal convergence occurred in six of our nine control subjects terminating heat exposure before 2 h. In the three control subjects finishing the 120-min protocol, only one showed brief periods of convergence. However, despite instances of thermal convergence, there were no signs of impending collapse or heat illness observed in any of the control subjects. This supports the findings of Nunneley et al. (1992) that thermal convergence is not a prelude to termination from heat exposure.

It has been postulated that heat exposure tolerance is related to the amount of heat stored (Craig et al. 1954; Kaufman 1963; Shvartz and Benor 1972; Henane et al. 1979). However, our findings provide evidence against the role of accumulated HS as a factor affecting heat exposure tolerance. In our study, heat storage for control subjects terminating heat exposure early ranged from 5.28 to 9.42(1.1) $kJ \cdot kg^{-1}$. These values are below the maximum theoretical value of 9.9 $kJ \cdot kg^{-1}$ reported by Kaufman (1963), and thus do not explain the reduced tolerance time for 9 of 12 control subjects terminating from heat exposure prior to 101 min of the test protocol. Thus, our findings suggest that accumulated heat storage is not related to heat tolerance.

The inability of thermal convergence and HS to affect tolerance time suggests other factors are important to heat exposure. In our study, all control subjects ($n = 9$) unable to complete the protocol complained of dizziness, light-headedness, an tingling sensations in their arms and hands. P_a was monitored during recovery and all subjects had lower P_a than pre-exposure values. Thus, our findings suggest that factors other than HS and/or thermal convergence contribute to heat intolerance.

In our study, the six-pack vest had a greater impact on reducing HS than the four-pack vest during the second hour of heat exposure. The lower T_{re} and T_{sk} with the six-pack vest during the second hour of heat exposure suggests a greater transfer of heat from the body. The available surface cooling area of the four-pack vest (1449 cm^2) is 52%of the six-pack (2795 cm^2), while the weight of coolant in the four-pack vest (1.8 kg) is 39% of the six-pack vest (4.6 kg). The greater surface area and cooling capacity (heat of fusion of 268 $J . g^{-1}$) of the six-pack vest probably contributed to the lower T_{re} and T_{sk} associated with the six-pack vest.

Effect of cool vests on f_c

Lower f_c accompanied rest and exercise during the vest conditions compared to the control condition. This suggests that the cool vests maintained cardiac output and blood flow to active muscle and skin, and thus, facilitated conduction of heat from the body core to the skin for dissipation to the environment (Nadel et al. 1979; Rowell 1983).

Conclusion

In conclusion, four-pack and six-pack cool vests reduced HS during rest and exercise in a warm/humid environment. The cool vests were associated with significantly smaller increases in T_{re}, T_{sk}, HS, and f_c compared to wearing no vest. During the first 60 min of heat exposure, physiological responses were similar for the four-pack and six-pack vests, while during the second 60 min of heat exposure the six-pack vest had a greater impact on reducing HS than the four-pack vest. These findings suggest that the six-pack cool vest would be more effective countermeasures to HS strain for personnel involved in damage control operations lasting longer than 60 min in a warm/humid environment.

Acknowledgements Supported by the Naval Medical Research and Development Command, Department of the Navy, under work Unit NO. 63706N M0096-004-6301. The views expressed in this paper are those of the authors and do not reflect official policy or position of the Department of the Navy, the Department of Defense, or the U.S. Government. Approved for public release, distribution unlimited.

References

Banto G, Braun D (1992) Heat Strain during at-sea helicopter operations and the effect of passive microclimate cooling. Aviat Space Environ Med 63:881–885

Bennett B, Hagan R, Banta G, Williams F (1992) Physiological responses during shipboard firefighting. Aviat Space Environ Med 63:68

Carpenter T (1964) Tables, factors, an formulas for computing respiratory exchange and biological transformations of energy. Carnegie Institution of Washington Publication 303C, Washington, D.C.

Craig FN, Garren HW, Frankel H, Blevins WV (1954) Heat load and voluntary tolerance time. J Appl Physiol 6:634–644

Duncan H, Gardner G, Barnard R (1979) Physiological responses of men working in fire fighting equipment in the heat. Erogonomics 22:521–527

Eichna LW, Park CR, Nelson N, Horvath SM, Palmas ED (1950) Thermal regulation during acclimatization in a hot, dry (desert type) environment. Am J Physiol 163:585–597

Henane R, Bittel R, Viret R, Morine S (1979) Thermal strain resulting from protective clothing of an armored vehicle crew in warm conditions. Aviat Space Environ Med 50:599–603

Hodgdon JA, Beckett MB (1984) Prediction of percent body fat for U.S. Navy men from body circumferences and height. Naval Health Research Center Technical Repot 11

Janik C, Avellini B, Pimental N (1987) Microclimate cooling systems: shipboard evaluation of commercial models. NCTRF Tech Rep 163

Kaufman WC (1963) Human tolerance limits for some thermal environments of Aerospace. Aerospace Med 34:889–896

Muza S, Pimental N, Cosimini H, Sawka M (1988) Portable, ambient air microclimate cooling in simulated desert and tropic conditions. Aviat Space Environ Med 59:553–558

Nadel E, Cafarelli E, Roberts M, Wenger C (1979) Circulatory regulation during exercise in different ambient temperatures. J Appl Physiol 46:430–437

Nunneley S, Antunano M, Bomalaski S (1992) Thermal convergence fails to predict heat tolerance limits. Aviat Space Environ Med 63:886–890

Pandolf K, Gloldman R (1978) Convergence of skin and rectal temperatures as a criterion for heat tolerance. Aviat Space Environ Med 49:1095–1101

Pimental N, Avellini B, Banderet L (1991) Comparison of heat stress when the Navy fire fighters ensemble is worn in various configurations. Navy Clothing and Textile Research Facility and U.S. Army Research Institute of Environmental Medicine. Technical report no. NCTRF 192

Ramanathan N (1964) A new weighing system for mean surface temperatures of the human body. J Appl Physiol 21: 1757–1762

Romet T, Frim J (1987) Physiological responses to fire fighting activities. Eur J Appl Physiol 56: 633–638

Rowell L (1983) Cardiovascular aspect of human thermo-regulation. Circ Res 52: 367–379

Shvartz E, Benor D (1972) Heat strain in hot and humid environments. Aerospace Med 43: 852–855

Speckman K, Allan A, Sawka M, Young A, Muza S, Pandolf K (1988) Perspectives in microclimate cooling involving protective clothing in hot environments. Int J Ind Ergon 3: 121–147

Stolwijk J, Hardy J (1966) Partitional calorimetric studies of responses of man to thermal transients. J Appl physiol 21: 967–977

Terrian D, Nunneley S (1983) A laboratory comparison of portable cooling systems for workers exposed to two levels of heat stress. USAFSAM Tech Rep 83–14