Performance Evaluations of Micro-Climate Cooling Products

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Abstract (150)

Numerous occupations require routine exposures to extreme heat conditions posing significant risks to workers. Cooling vests are one intervention to prevent heat injuries and illnesses in these environments. A three phase project was performed in a thermally controlled environment to evaluate cooling effectiveness of three commercially available cooling vests, HeatShield, AirVest and IsoTherm. Phase I utilized thermal manikins to quantify cooling time using established protocols. Phase II quantified the time required for heart rate and core body temperature to return to normal (both with and without a cooling vest during recovery) following heat exposure. Phase III evaluated core body temperature and heart rate of participants during exercise protocols while wearing a fire fighter's ensemble. Major findings of this study revealed 1) the HeatShield and IsoTherm vests provided cooling for approximately 21 minutes, 2) although recovery times were significantly shorter when both cooling vests were used, the AirVest resulted in the shortest recovery times, and 3) core body temperatures were kept lowest for the AirVest and HeatShield while other physiological measures did not differ. The overall findings of this project support the use of micro-climate cooling products for persons working in extreme thermal conditions.

Keywords: cooling vest, heat stress, thermal manikins, heat exposure protocol

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1. Introduction

A number of occupations require routine exposures to extreme temperature conditions, such as fire fighters; hazardous materials handlers; forestry, agricultural, construction, and military personnel; and others. Persons performing job tasks in these extreme environments are at risk for the development of heat related injuries and illnesses. Additionally, a number of athletic training camps are positioned in extreme temperature and humidity conditions, and the increase in the number of heat related incidents have prompted concerns.

Many studies have shown that heat stress has a negative effect on performance (both physical and cognitive) (e.g., Bennet et. al, 1995; Pilcher and Nadler, 2002, 2003). Not limiting exposures to heat stress or improving conditions after reaching signs of physiological fatigue is dangerous and unnecessary. Monitoring human performance during exposure to extreme thermal conditions is important for establishing safety standards (Hankcock and Vasmatzidis, 1998). Micro-climate cooling products, such as commercially available gel or ice water based vests, have been developed to reduce the risk of heat stress and heat related injuries and illnesses by reducing core body temperature and heart rate either during or following work in hot environments (Bennett et al, 1995; Chen et al, 1997). However, few published studies exist on the effectiveness of these vests. Moreover, a number of those vests studied were designed for specific applications (typically military operations) and therefore are not available to the general public.

Thus, the overall goal of this study was to evaluate cooling effectiveness of three commercially available micro-climate cooling products during various exercise protocols. Specifically, the objectives were to: (1) determine the cooling capacity performance of three commercially available micro-climate cooling vests using thermal manikins (TMs), (2) evaluate recovery rates associated with two ClimaTech Safety cooling vests following heat exposure while performing light exercise, and (3) provide performance assessment data (quantitative physiological response assessments and qualitative comfort and usability assessments) on human subjects wearing three commercially available cooling vests while performing light exercise. The TMs provided a no risk method (no human subjects) for assessing product performance that can be easily replicated. However, human performance testing is needed to obtain crucial information on (a) the effects of wearing the products, as the TMs do not respond as a human would to the same stress, and (b) on the ability of persons to use the device without interfering with job task performance or introducing other risks (such as musculoskeletal discomfort/disorders). The project was completed in three phases, each phase associated with a single objective.

2. Phase I: Thermal Manikin Cooling Capacity Assessment

2.1 Methodology

Two ClimaTech Safety micro-climate cooling vests and a competitor product were tested under controlled conditions at the Natick Soldier Center, Natick, MA to determine the cooling capacity using Thermal Manikins (TMs). The vests tested included ClimaTech Safety's HeatShield (gel vest) and AirVest (continuous compressed air supply), and Bullard's IsoTherm (ice pack vest). TMs are ten-zone, heated aluminum manikins designed based on the anthropometric dimensions of the 50th percentile male and are available for use by the US Army Natik Soldier Center (a division of the National Protection Center) for testing of personal protective equipment.

For each vest, two trials were performed to assess the reliability of the vest under extreme conditions. The ambient environmental conditions were set to a temperature of 35^{o}C, 40% relative humidity, and 0.9 m$\cdot$sec^{-1} wind speed. The TM was provided with electrical current until reaching an equilibrium temperature (baseline) "skin" temperature of 35^{o}C, then fitted with the appropriate vest. A Joint Lightweight Integrated Suit Technology (JSLIST) MOPP IV overgarment was then fitted over the TM. The power required to maintain the TM equilibrium temperature was recorded at 1-minute intervals over one complete exhaustive cycle of the HeatShield and IsoTherm, and for one hour for the AirVest (as cooling time is continuous).

2.2 Data Analysis

Cooling capacity (measured in watts) was calculated as the power input to the TM and averaged over the first hour. Cooling capacity was calculated by multiplying the cooling rate by the cooling duration. The cooling rate and duration of cooling was recorded and compared to previous data obtained on other vests tested under identical conditions (Masadi et al., 1991). Cooling measures were limited to those in which over 100 watts of cooling were provided by the vests. Previous research has shown that cooling capacities less than this value are not effective at reducing core body temperatures, though persons may report sensations of cooling (Natick Soldier Center, 2003).

2.3 Results

Cooling time of both the HeatShield and the IsoTherm were identical, though the HeatShield provided more cooling capacity (Table 1, Figures 1 and 2). It is of interest to note that the IsoTherm vest exhausted its cooling mechanism (ice packs) before it reached the minimum cooling value (100 watts). TM testing results on the AirVest indicate that at 30% and 80% relative humidity, cooling capacity is 312 and 359 Watts respectively, though the cooling time is unlimited as it uses a compressed air supply.

3. Phase II: Recovery Rates Associated with ClimaTech Safety Cooling Vests

3.1 Methodology

3.1.1. Participants

Eight healthy fit male participants were recruited from a university population through advertisements placed throughout campus. Potential participants were provided with a verbal and written description of the project, its objectives and requirements for participation, and completed informed consent documents approved by the Institutional Review Board (IRB) prior to any experimentation. A medical history questionnaire suggested by the American College of Sports Medicine (2003) was used to screen participants for potential heart or blood conditions that would place the participants at undue risk during experimental protocols. Participants also completed a custom demographic questionnaire and a questionnaire to assess participant's habitual physical activity. Participation in the study was strictly voluntary and participants were compensated at a rate of $15 per testing session.

3.1.2 Dependent Variables

Three dependent variables were considered: recovery time, reduction in core body temperature, and reduction in heart rate. Recovery time was recorded as the amount of time required for the participant's core body temperature ***and*** heart rate to return to pre-exercise conditions following heat exposure. Pre-exercise conditions are defined as the body temperature and heart rate recorded following a resting period provided at the beginning of the testing session (further details are provided in section 3.1.6).

Reduction in core body temperature was calculated as the average reduction in core body temperature per minute over the recovery period. Core body temperature assessments were taken every minute during recovery using an infrared ear scanner (Omron Healthcare, Inc., Bannockburn, Illinois).

Reduction in heart rate was calculated as the average reduction in heart rate per minute over the recovery period. Heart rate assessment was continuous and was monitored on a computer throughout recovery using a Polar Heart Rate Monitor (S810).

3.1.3 Independent Variable

The independent variable for this phase was the vest (or recovery test) being performed. Each participant completed three trials to assess recovery rate: (1) recovery with no vest (Base), (2) recovery with either the HeatShield (HS) or AirVest (AIR), and (3) recovery with either the HeatShield (HS_{dhs}) or AirVest (AIR_{dhs}) following exposure while wearing a fully discharged HeatShield (i.e., provided no cooling during exposure). Participants were randomly assigned to AirVest or HeatShield trials, and all participants completed the Base condition for comparison purposes. Exposure to the recovery conditions was randomized across participants.

3.1.4 Heat Exposure Protocol

The previous night and the morning of testing, participants were instructed to consume 1-liter of a non-caffeinated beverage (at a minimum) to ensure normal hydration. The heat exposure protocol consisted of continuous walking on a motorized treadmill at 5 $km \cdot h^{-1}$ and 0% gradient. The ambient temperature in the environmentally controlled room was set at 35^{o}C with humidity and wind speed constant at 40% and 0.9 $m \cdot sec^{-1}$ respectively during heat exposure.

Participants were required to wear a standard fire fighters ensemble (jacket and pants) over a cotton shirt and shorts, while wearing tennis shoes. This ensemble was chosen to ensure standardization across participants, to minimize the amount of body heat that escaped during the test sessions, and to simulate a “worst case scenario”.

Core body temperature (T_{co}) was measured using infrared ear temperature scans at a sampling frequency of 500 Hz. Temperature assessments were recorded every 2 minutes during exercise and every minute during recovery. During assessments, participants were allowed to rest their hands on the handrails for stability. An experimenter "tugged" on the participants' ear upward and back to straighten the ear canal and improve reading consistency. A total of three scans were taken every assessment and the average was used as T_{co}. Heart rate (HR) was assessed continuously during exercise and recovery.

3.1.5 Maximum Heart Rate Assessment

A graded exercise test (GXT) was used to assess physical fitness level and estimate maximum heart rate. Maximum heart rate was used as a safety criterion for ending the experimental session (described below). The GXT was performed on a motorized treadmill using a modified Balke protocol. The Balke protocol specifies that after a 5-minute warm up period (5% gradient at $5 km \cdot h^{-1}$), the gradient is increased by 2.5% every 2 minutes until the participant fatigues (cannot continue). During the GXT, participants were not allowed to use the treadmill handles at any time and were verbally encouraged to continue the test until exhaustion. Heart rate was continuously monitored (S810 Polar Heart Rate Monitor) and maximum heart rate (HR_{max}) was recorded.

3.1.6 Procedure

Upon arrival participants completed the consent forms, the medical screening, personal demographics, and physical activity questionnaires. Participants scheduled a time for the completion of the GXT. Recovery test sessions were scheduled not less than 48 hours and no more than 2 weeks apart.

At each test session, participants were fitted with all data collection equipment and asked to rest in a seated position in a thermally neutral environment for 5 minutes, after which resting heart rate and core body temperature were recorded. A minimum of two resting heart rates were taken: one at the end of the 5 minute rest period and one a minute later. If the two values were less than 3 bpm apart, the participant began exercise; otherwise additional heart rates were collected until two consecutive readings were within 3 bpm. After being fitted with the appropriate vest and the ensemble, the participants entered the environmentally controlled room and remained seated for an additional 20 minutes to become acclimated to the environmental conditions. Participants began exercising and continued until either 1 hour was expended or until reaching one of the following three safety criteria:

1. T_{co} reached 39^{o}C,
2. HR reached 85% of individual maximum as determined through the GXT test,
3. or the participant experienced any adverse symptomology (dizziness, nausea, weakness, chills, absence of sweat) or reported that they could not continue.

After completion of the exercise protocol in the experimental environment, participants were immediately placed in a thermally neutral room, the ensemble was removed, and the participants were fitted with the appropriate recovery vest, if appropriate. During recovery, the participant remained seated until their heart rate ***and*** core body temperature values returned to pre-exercise conditions.

3.1.7 Statistical Analysis

Appropriate descriptive statistics were computed for each dependent variable and normality tests (Shapiro-Wilk) were run prior to subsequent analyses. Repeated measures ANOVA was used to test for the main effect of recovery trial. Results were considered significant at α=0.10. This level of significance was chosen due to the small sample size. Tukey's HSD multiple comparison tests were used to identify specific differences between recovery conditions.

3.2 Results

Recovery times ranged from 15.5 min to 22.77 minutes (Table 2), core temperature reductions per minute ranged from 0.05 ^{o} min^{-1} to 0.11 ^{o} min^{-1}, and heart rate reductions per minute ranged from approximately 3 bmp to approximately 6 bpm (Table 2). Recovery time and core body temperature (T_{co}) reductions per minute were significant by recovery trial ($p = 0.08$ and $p=0.07$ respectively) (Table 2, Figures 3 and 4). Recovery time was shortest for the AirVest conditions, followed by the HeatShield Conditions, then by the base condition (no vest). The use of any cooling vest resulted in significantly shorter recovery times than recovery without the use of a cooling vest. Results also indicated that T_{co} was reduced the greatest in the AIR_{dhs} condition. T_{co} was reduced the least in the HS_{dhs} trial, and no statistically significant differences were found between the other conditions. No significant differences were found in heart rate (HR) reductions across the trials ($p=0.66$).

4. Phase III: Human Performance Testing and Usability Assessment

4.1 Methodology

4.1.1 Participants

The participants identified in Phase II also completed Phase III.

4.1.2 Dependent Variables

Several dependent variables were assessed including heart rate increases per minute (HR), core body temperature increases per minute (T_{co}), rate of perceived exertion (RPE) increases, maximum RPE rating, exercise duration (time), and subjective and usability ratings. HR was assessed continuously during the exercise protocol using the S810 Polar Heart Rate Monitor (PolarUSA, Lake Success, NY). T_{co} was assessed every other minute throughout the test session using three ear scans (as described earlier). Every 5 minutes participants were asked to provide an estimate of how hard they believed they were working using the Borg's Perceived Level of Exertion Scale (RPE) (which ranges from 0 indicating no effort to 10 indicating maximal effort). Participants were shown a copy of the scale and asked to orally rate their RPE. Exercise duration was defined as the length of time participants were able to perform the exercise (before reaching the safety criteria defined earlier or 1 hour) for each test session.

Following each testing condition, participants completed a short questionnaire asking them to subjectively rate the comfort and usability factors for each garment. Usability of the vests was assessed using nine questions regarding ease of donning, movement comfort, fit on the body and underneath the uniform, interference with exercise, adjustability, increase in work time, use of the vest daily, and overall vest performance. Participants used a 5-point scale ranging from 1 = strongly disagree to 5 = strongly agree to evaluate each question. Following the last testing session, participants were asked to force rank the vests from most preferred to least preferred.

4.1.3 Independent Variable

The independent variable was the vest worn during the exercise protocol. Each participant completed three trials in which the HeatShield, AirVest, and IsoTherm (Bullard) vests were each worn. Exposure to the vests was randomized across participants. Test sessions were scheduled not less than 48 hours and no more than 2 weeks apart.

4.1.4 Heat Exposure Protocol

The exposure protocol was identical to that described in Phase II, and is briefly summarized here. Participants performed continuous walking on a motorized treadmill at 5 $km \cdot h^{-1}$ and 0% gradient in an environmentally controlled room set at 35^{o}C with humidity and wind speed constant at 40% and 0.9 m$\cdot$sec^{-1}. Participants wore a standard fire fighters ensemble (jacket and pants) over a cotton shirt and shorts with tennis shoes.

4.1.5 Procedure

The same procedures were used in this phase as in Phase II. Upon arrival, participants were fitted with all data collection equipment and rested in a seated position in a thermally neutral room (ambient temperature 23^{o}C) for 5 minutes, after which resting heart rate and core body temperature were assessed. Participants then entered the environmentally controlled room and rested in a seated position for an additional 20 minutes. Afterwards, participants were fitted with a fully charged cooling vest and ensemble. Exercise began immediately and continued until one of the safety criteria (discussed previously) were met or until testing duration reached 1 hour.

After completing the test session, participants were escorted to a thermal neutral room to rest for an unspecified amount of time. After participants felt rested, they completed the 9-item usability questionnaire. On the last day of testing, participants ranked each of the three vests as 1, 2, or 3, where 1 = most preferred vest and 3 = least preferred vest.

4.1.6 Statistical Analysis

Appropriate descriptive statistics were computed for each dependent variable. HR, T_{co}, RPE, maximum RPE, exercise duration, and usability ratings were statistically analyzed using a repeated measures ANOVA. Tukey's HSD multiple comparison tests were used to identify specific differences between vest trials. Final ranking data were analyzed using Friedman's test. Findings were considered significant at α=0.10. A significance level of 0.10 was chosen due to the small sample size.

4.2 Results

4.2.1 Objective Measures

Only increases in core body temperature was significant by vest (p=0.09) (Table 3, Figure 5 and Figure 6). Both the AirVest and HeatShield had similar T_{co} mean values and resulted in significantly lower increases in core body temperature than the IsoTherm over the testing session. Heart rate increase (p=0.56), test duration (p=0.45), RPE (p=0.99), and maximum RPE rating (p=0.66) were not significant by vest type (Table 3).

4.2.2 Usability and Ranking Measures

Usability results are presented in Table 3. In general, the HeatShield and AirVest were rated superior to the IsoTherm for most questions. For vest donning, movement comfort, and fit underneath the uniform, the HeatShield and AirVest received significantly higher ratings than the IsoTherm, although ratings between the HeatShield and AirVest were not significant. Participants rated the body fit of the HeatShield significantly higher than the other two vests, and body fit of the AirVest significantly higher than the IsoTherm. The HeatShield was also rated highest in terms of daily usage over the other vests, with the IsoTherm receiving the second highest rating which was significantly higher than the AirVest rating. Participants did not perceive any differences between the vests in terms of interference with the exercise, adjustability, increased work time, or overall performance. The HeatShield was by far the most preferred cooling vest with 75% of the participants ranking it number 1. No differences were found in the mean rankings for the AirVest or Bullard.

5. Discussion and Conclusions

The objectives of this study were to: (1) determine the cooling capacity performance of three commercially available micro-climate cooling vests using thermal manikins (TMs), (2) evaluate recovery rates associated with two ClimaTech Safety cooling vests following heat exposure resulting from the performance of light exercise, and (3) provide performance assessment data (quantitative physiological response assessments and qualitative comfort and usability assessments) on human subjects wearing three commercially available cooling vests while performing light exercise. Results pertaining to objective 1, cooling capacity performance, indicated that it is expected that persons wearing the HeatShield or the IsoTherm vest will benefit from wearing these products for 21 minutes. After that time, while persons may still report sensations of cooling, the ability of the vests to keep core body temperatures within a safe range will be depleted. Other vests tested using the same protocols resulted in significantly longer cooling times (minimum of 40 minutes of effective cooling time) (Natick Soldier Center, 2003). These differences may be attributed to the cooling mechanisms (some use gel like those tested in this study while others use batteries to circulate water through the vests). It is also important to note that when comparing these findings to future results, the effective cooling time is associated with cooling capacities of greater than 100 watts, as capacities below this level have been shown to be ineffective at reducing core body temperature (Natick Soldier Center, 2003). Possible modifications to the design of the HeatShield and IsoTherm may be needed to increase the cooling time of the vest. For example, changing the design of the HeatShield from a bib-like design to a more enclosed or complete unit may promote conservation of cooling capacity of the vest.

Findings of the recovery rate phase provide support for the use of micro-climate cooling products to help persons return to pre-exercise physiological levels under extreme thermal conditions. Reductions in core body temperatures were found to return to normal levels much faster when any cooling vest was used. Heart rate (HR) reductions were not effected by the use of a cooling vest during recovery. This finding was expected, as the majority of heart rate reductions should be related to the cessation of exercise. These findings support those found by Constable et al. (1987) who also found that using cooling vest during rest periods reduced physiological strain. However, Constable (1990) warns of accelerated fatigue associated with using cooling vest during rest periods, which was not considered in the current study.

Only core body temperature increases were significant across vests for the human performance testing, with the AirVest and HeatShield resulting in significantly lower increases in core body temperature over the test duration. This finding supports the use of micro-climate cooling products during work tasks in extreme temperatures to reduce the effects of the environment on the human operator, as has been found in previous studies (Konz, 1984; Shapiro et al., 1982). With a reduced core body temperature, persons should be able to work for longer periods of time without experiencing undue stress or suffering from a heat related injury or illness. Again, HR increases were not expected to differ significantly given that the exercise remained consistent across vests and the weight and style of the vests were very similar. This same rationale is used to explain the lack of significance in rates of perceived exertion. Given the similarities, it was expected that participants would not perceive differences in the workload experienced.

Usability of the AirVest and HeatShield were, in general, superior to the IsoTherm vest. A major criticism of the IsoTherm vest was the bulkiness and discomfort associated with the initial use of the ice packs. Efforts were made to ensure the ice packs were frozen flat without odd angles or protrusions. However, the frozen ice packs were still uncomfortable for the participants. The major criticism of all the vests was the weight. Each of the vests weighed approximately <10 lbs when fully charged. Participants expressed concerns about using any vest for prolonged periods of time. A psychophysical study would need to be performed on experienced workers to determine if the weight of the vest would in fact result in significant increases in energy expenditure and affect perceived work durations.

Overall, the findings of this project support the use of micro-climate cooling products for persons working in extreme thermal conditions. Potential benefits for the recovery of persons following exposure to extreme conditions are promising in terms of reducing core body temperatures to normal levels in shortened periods of time. Vest redesign considerations may improve the performance of the vests in terms of cooling time. However, the current design is perceived by persons to be comfortable and conducive to extended wear.

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Table 1. Cooling capacity values using the TMs

Vest	**Cooling Capacity**	**Cooling Time**
HeatShield	152 Watts	21 minutes
IsoTherm	139 Watts	21 minutes
AirVest	312, 359 Watts*	Unlimited

* Values represent cooling capacity at 30% and 80% relative humidity respectively

Table 2. Descriptive statistics for the recovery trials. Values are mean (standard deviation). Superscripts represent Tukey's groupings.

Vest Trial	**Recovery time (min)**	**T_{co} reduction (^{o}F)**	**HR reduction (bpm)***
HS	20.41 (2.71)^{A}	0.07 (0.01)^{B}	3.08 (0.91)
HS_{dhs}	17.71 (2.58)^{A}	0.05 (0.01)^{C}	3.74 (0.84)
AIR	15.65 (3.17)^{B}	0.07 (0.02)^{B}	3.86 (1.16)
AIR_{dhs}	15.33 (3.62)^{B}	0.12 (0.02)^{A}	5.94 (1.40)
Base	22.77 (2.56)^{C}	0.05 (0.01)^{B}	3.07 (0.84)

*HR was not significant, therefore no Tukey's groupings are presented

Table 3. Descriptive statistics for the human performance trials. Values are mean (standard deviation). Superscripts represent Tukey's groupings.

Vest	T_{co} increase (^{o}F)	Duration (min)	HR increase (bpm)	RPE increase	Max RPE
AirVest	0.03 (0.03)^{A}	29.75 (8.32)	4.02 (1.22)	0.05 (0.14)	3.09 (0.45)
HeatShield	0.03 (0.03)^{A}	27.88 (8.32)	4.07 (1.22)	0.04 (0.14)	2.85 (0.45)
IsoTherm	0.07 (0.03)^{B}	30.50 (8.32)	3.35 (1.22)	0.04 (0.14)	2.79 (0.45)

Table 4. Usability mean scores and final rankings. Values are mean (standard deviation). Superscripts represent Tukey's groupings.

Survey Item	HeatShield	AirVest	IsoTherm	p-value
1. It was easy to don the vest	4.50 (0.53)^{A}	4.25 (0.71)^{A}	3.38 (1.41)^{B}	**0.07**
2. I was able to move comfortably while wearing the vest	4.00 (0.53)^{A}	4.25 (0.71)^{A}	3.00 (1.20)^{B}	**0.02**
3. The vest fit my body well	4.38 (0.74)^{A}	4.00 (0.76)^{B}	3.13 (1.25)^{C}	**0.04**
4. The vest fit well underneath the uniform	4.50 (0.53)^{A}	4.25 (0.71)^{A}	3.25 (1.16)^{B}	**0.02**
5. The vest did not interfere with performing the exercise	4.25 (1.03)	4.00 (0.93)	3.25 (1.16)	0.16
6. Adjustability of the vest was sufficient	4.00 (0.76)	3.88 (0.64)	3.25 (1.04)	0.17
7. I feel I could work longer if I used the vest regularly	4.25 (0.46)	3.13 (1.46)	3.50 (0.93)	0.11
8. I would use this vest daily if it was available	4.13 (0.64)^{A}	2.88 (1.36)^{C}	3.13 (0.83)^{B}	**0.05**
9. I would rate the overall performance of this vest as (0=worst, 5=best)	4.13 (0.64)	3.38 (1.19)	3.25 (0.71)	0.12
Final Rank	1.38 (0.74)^{A}	2.38 (0.74)^{B}	2.25 (0.71)^{B}	**0.02**

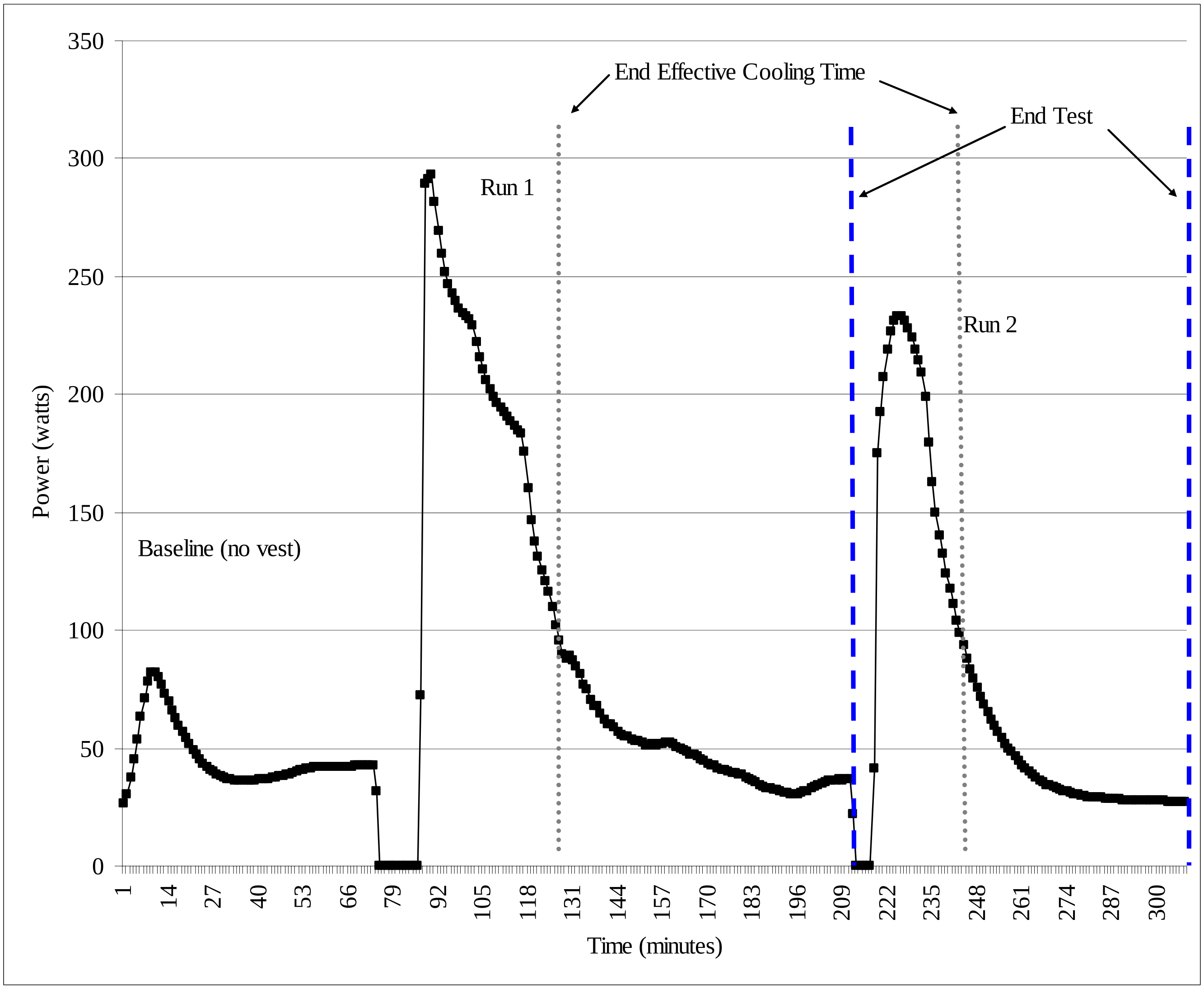

Figure 1. Heat Shield TM Test Results

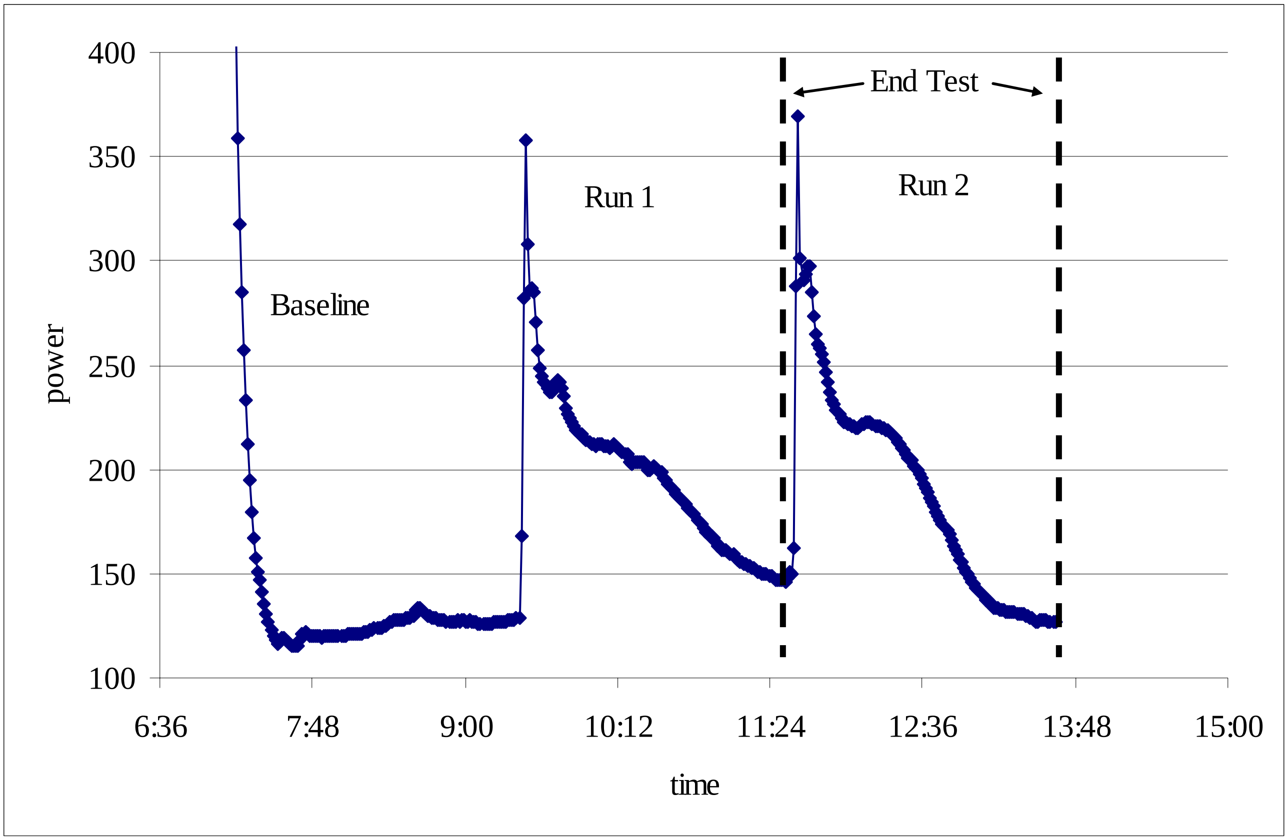

Figure 2. IsoTherm TM Test Results

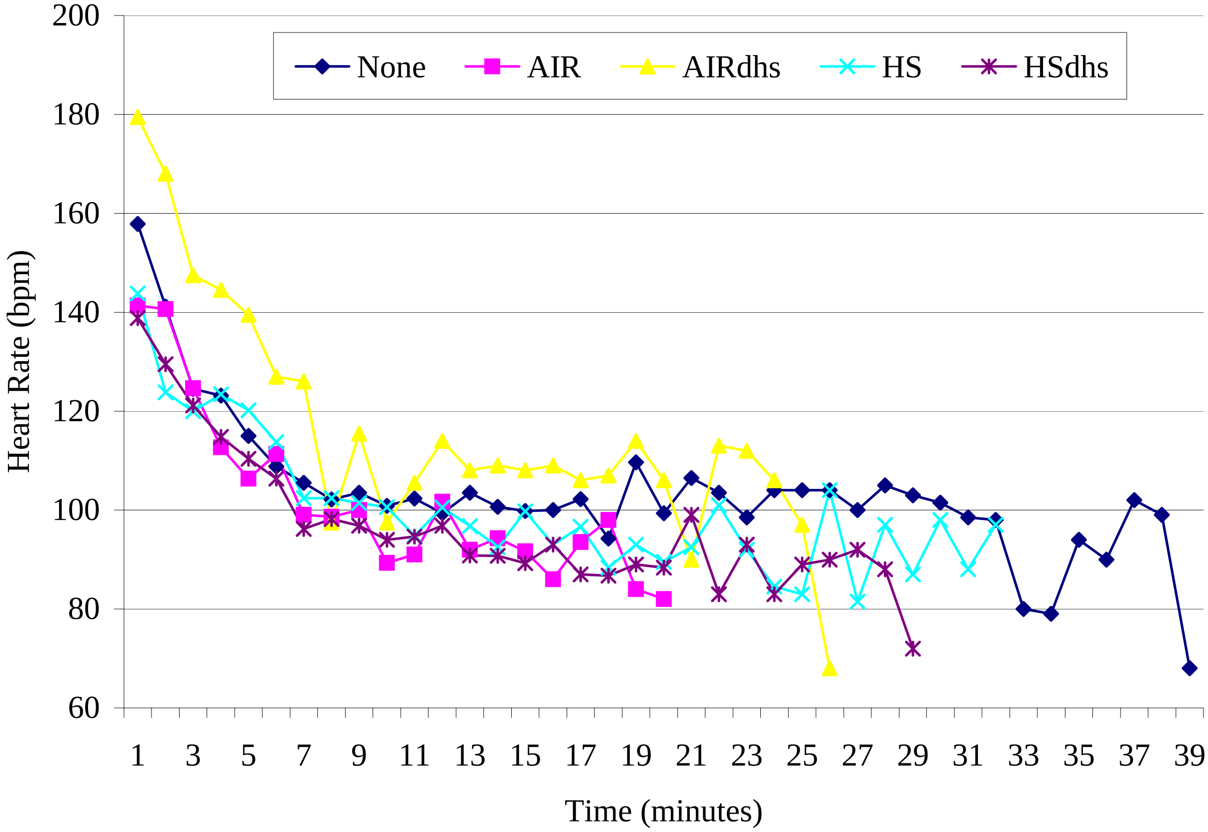

Figure 3. Mean decrease in heart rate by recovery trial.

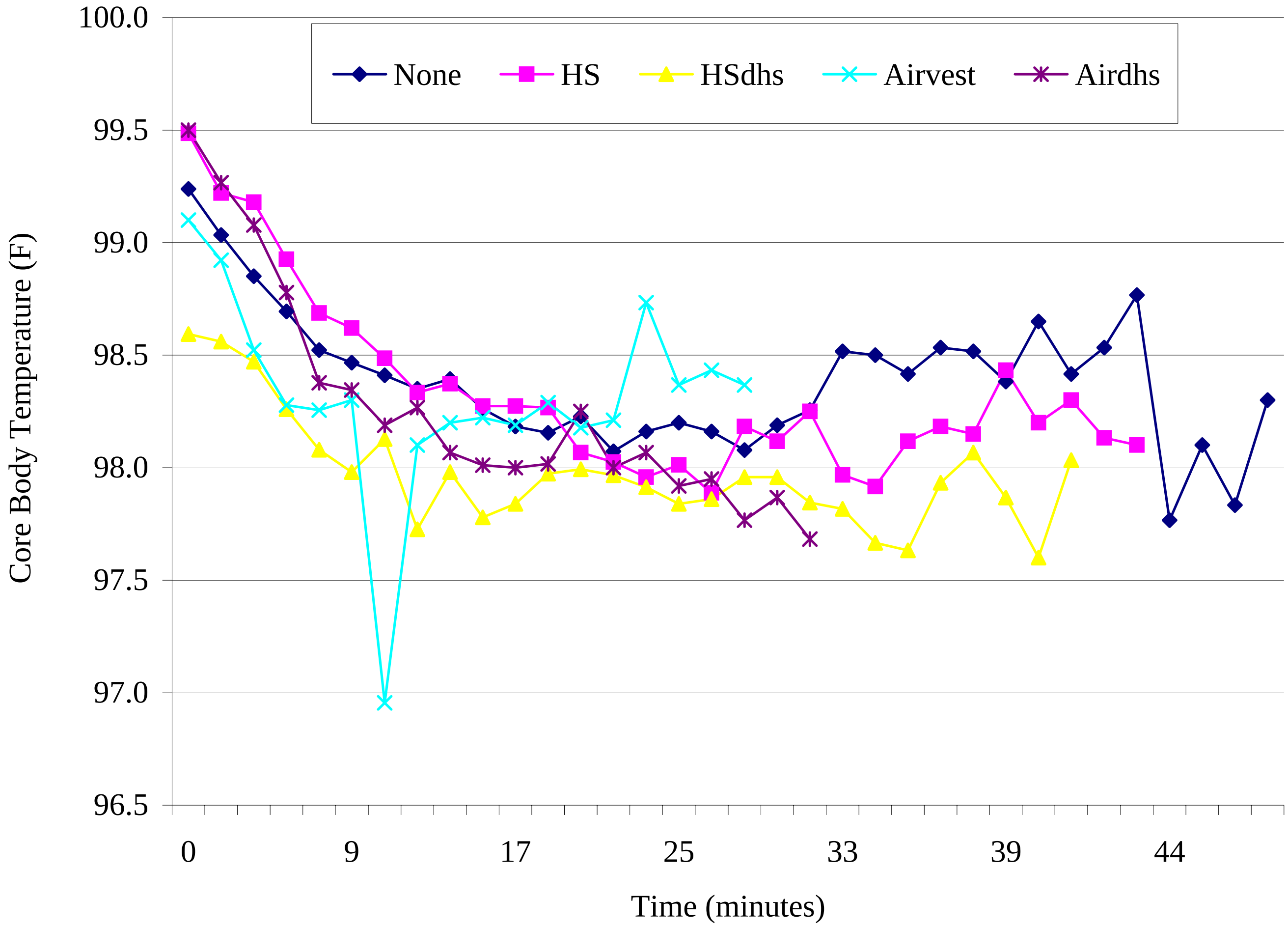

Figure 4. Mean decrease in core body temperature by recovery trial.

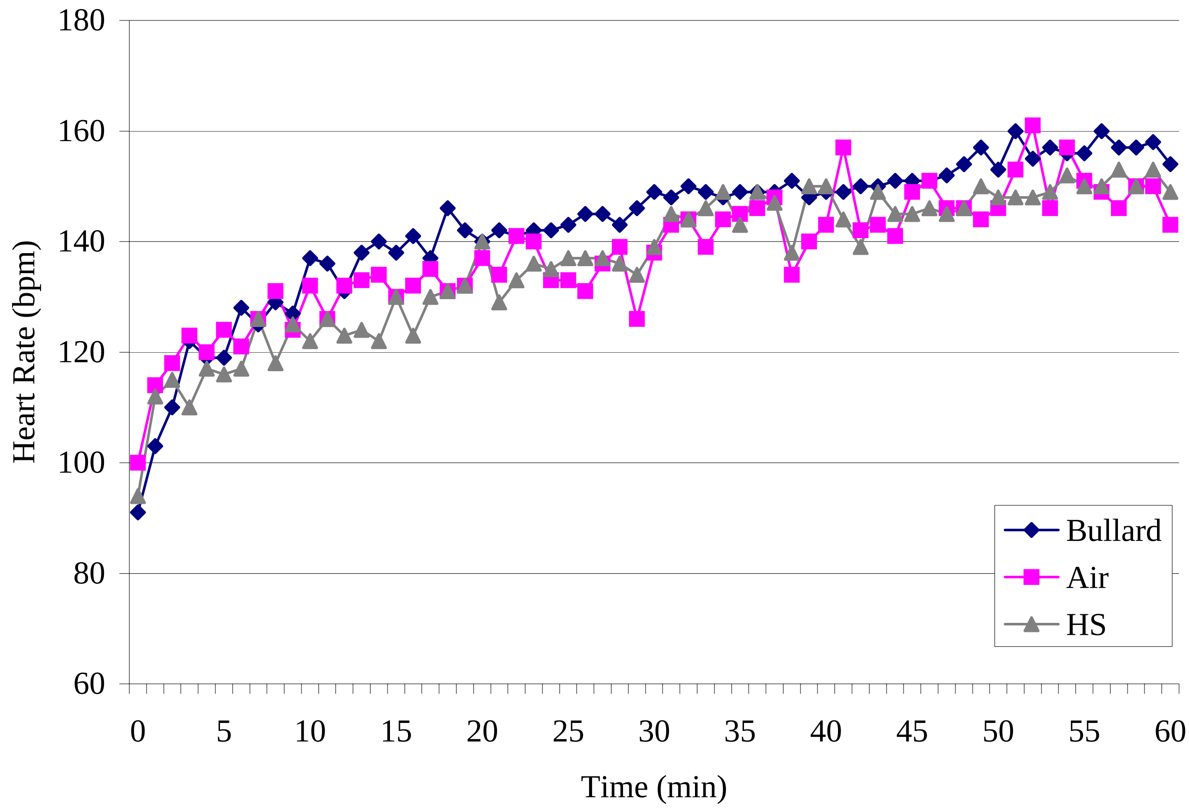

Figure 5. Mean increase in heart rate by vest type.

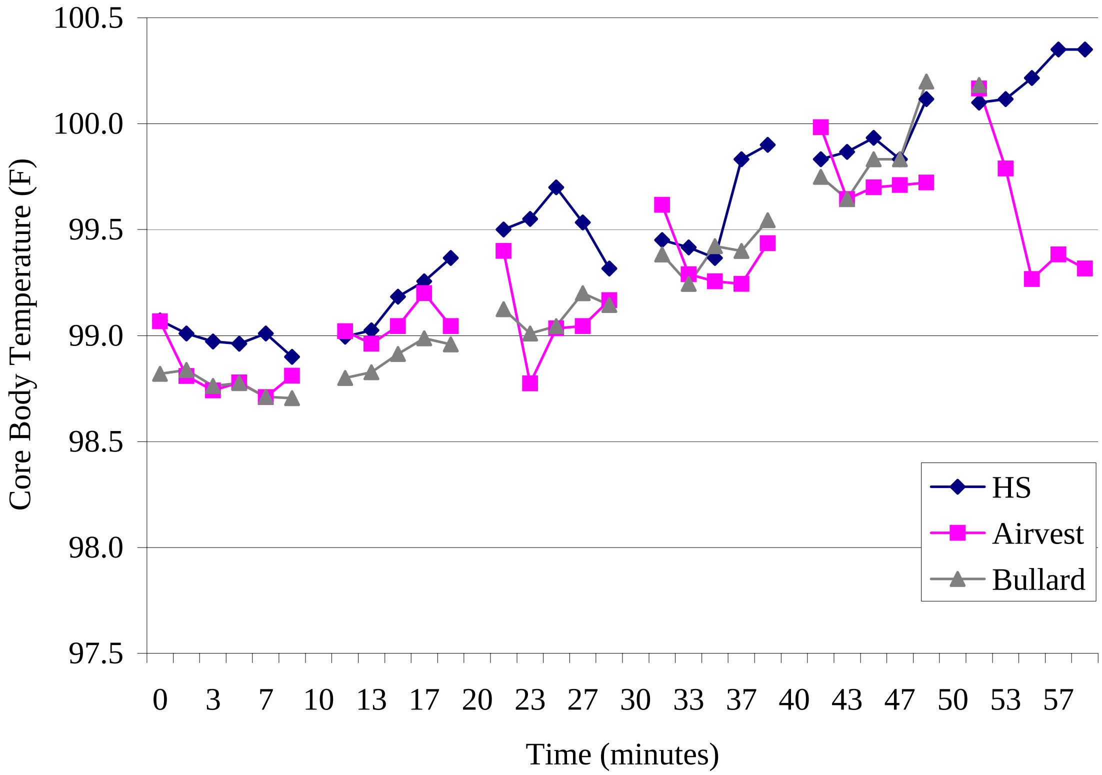

Figure 6. Mean increase in core body temperature by vest type.