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Suzanne Schneider, Robert Roberg, Stephen Verney, Fabiano Amorim, Paulette

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University of New Mexico, Dept. HPPD, MSC 0402610, Albuquerque, NM 87131-0001

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13. ABSTRACT (Maximum 200 words)

Military personnel often must work in hot environments, increasing the risk of hyperthermia. Our purpose was to evaluate a new rapid thermal exchange device (RTX) in slowing the development of hyperthermia and associated symptoms to 3 other conditions [hand immersed in water bath (WB), water-perfused vest (VEST), and a no-cooling condition (NC)] in subjects exercising in a hot environment (42°C, 30% rh) wearing summer fatigues, a backpack and body armor. Ten subjects (age 25±3 yrs; weight 74±6 kg) performed 4 heat stress tests in a counter-balanced order (NC / RTX / WB / VEST). The protocol consisted of two bouts of treadmill walking (at 50% VO2max), separated by a 41-min cooling and rehydration period. The time to reach a pre-determined rectal temperature (Tr) in the 1st and 2nd bouts were not different among RTX (mean ± SD; 52±14 and 42±12 min respectively), NC (49±13 and 41±14 min respectively), and WB (54±14 and 55±20 min respectively), but was longer for the VEST (85±30, and 65±12 min respectively) in both bouts ($p<0.05$). The Trslope (°C/min) was significantly lower for VEST in the 1st and 2nd bouts versus the other conditions ($p<0.05$). HR was not different at 10, 20 and 30 minutes of exercise in the 1st bout among RTX, NC, and WB, but was lower for VEST in the 1st bout ($p<0.05$). HR was not different among conditions in the 2nd bout. Therefore, the RTX (unit B) was not effective in slowing the development of hyperthermia in the present protocol. Aspects related to hand vasoconstriction and the severe work/heat stress conditions possibly prevented the expected heat extraction.

14. SUBJECT TERMS

heat stress, hand cooling, body temperature, exercise, walking, cognitive function, muscle endurance.

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Effect of Palm Cooling with Negative Pressure on Heat balance during exercise in a hot, Dry Environment

Principal Investigator:

Suzanne Schneider, Ph.D.

Department Physical Performance and Development

Mail code 04-2610

University of New Mexico

Albuquerque, NM – 87131

Phone: (505) 277-3795

E-mail: sschneid@unm.edu

Co-Investigators :

Rob Robergs, Ph.D., Director Exercise Sciences Lab, UNM

Steve Verney, Ph.D., Dept. Psychology, UNM

Fabiano Amorim, M.S. and Paulette Yamada, M.S., Doctoral candidates UNM

Background

The human thermoregulatory system normally maintains body temperature within safe limits during heat exposure or while exercising. However, in extreme conditions the thermoregulatory system is unable to dissipate enough heat to balance heat gained, resulting in hyperthermia, decreases in performance, and, in extreme cases heat illness and death (Sawka and Wenger, 1988). It is estimated that 240 deaths occur annually in the U.S. related to heat illnesses (Clapp 2001).

Frequently military personnel are at risk of hyperthermia. Exertional heat illness continues to be a major problem for the military, resulting in significant morbidity and mortality among U.S. soldiers in hot weather (Gardner 96). Regional and whole body cooling approaches have been studied, using cooling vests (Shapiro 82; Vallerand 91; Ku 00; Nishihara 02), air or water-cooled garments (Nunneley 70; Cheuvront 03), or various methods of pre- and post-cooling (Mitchell 03, Nunneley 70). Most of these methods require heavy equipment, batteries or power, and may be impractical for use in a field environment.

Regional cooling often is viewed as more practical in a field situation. A variety of cooling vests have been developed with cooling provided using chilled water, air, gel, ice, and other coolants (Muir 99). Although effective, disadvantages of vest cooling are that they are worn under clothing and protective garments making them difficult to adjust and take on and off. Ice vests melt rapidly in hot environments, providing only temporary relief. The theoretical maximal cooling capacity for the air-cooled and liquid-cooled vests used in the study of Vallerand et al (91) were 487 and 459 W, respectively.

The hands, feet and face are effective regions for heat exchange and therefore frequently targeted for cooling. These regions are highly vascularized, but at first were not used because it was thought that exposure to cold would cause vasoconstriction, reducing heat exchange. Blood flow to the palm and sole are controlled by arteriovenous anastomoses, small blood vessels with thick muscular walls that constrict in response to nervous input, local cold, and local vasoactive agents. Particularly in response to a falling core temperature, these blood vessels constrict to reduce heat loss through the hands and feet. It has been debated, how much a local cold exposure may trigger this vasoconstrictor response. Livingstone et al (89) were one of the first to evaluate heat loss in exercising and resting humans by immersing their hands in cold water from 10 to 30^{o}C. Surprisingly they found that the colder the water, the greater the heat loss. They concluded that vasoconstriction did not impede heat loss in these subjects.

Tipton et al (93) reviewed hand immersion as a method of cooling and rewarming. They summarized 3 studies that used hand water immersion with bath temperatures from 10 to 30 ^{o}C. They reported that in subjects with a core temperature of 37.2^{o}C, immersing a hand in cold water reduced hand blood flow to less than 1 ml/100mL tissue and provided little whole body cooling. However, the cooling effect varied depending on the core temperature of the subjects. With a core temperature of 38^{o}C, core temperature was reduced by about 0.5^{o}C in 20 minutes. With a core temperature of 38.5^{o}C, core temperature was reduced in proportion to the temperature of the water; 0.7^{o}C with water of 30^{o}C, 1.2^{o}C with water of 20^{o}C, and 1.5^{o}C with water of 10^{o}C. From this review is it evident that hand cooling can be an effective method to reduce body temperature in hyperthermic individuals. The theoretical maximal cooling capacity for heat extraction from the hands was listed as 124 to 198 W in the review by Tipton et al (93).

A new cooling device, the Rapid Thermal Extraction Device (RTX) made by AVAcore Inc., of Palo Alto, CA, has been proposed to prevent hyperthermia by removing body heat from the hand by maintaining blood flow during cooling (Hsu 2005). This device utilizes the combined application of negative pressure and a heat sink to the palm to increase heat exchange between the circulating blood and the external environment. The negative pressure distends the subcutaneous venous plexuses to increase local blood flow, while the cold sink extracts heat from the circulating blood. The cooled blood is delivered directly to the body core via venous return. The inventors claim that using this equipment during exercise in the heat would increase endurance time and allow faster recovery (Grahn 05; Hsu 05). Furthermore, they propose it would be easy to implement in remote environments, since it can be small, lightweight and portable.

When male triathletes used this device for cooling while cycling for an hour in a heated room (32°C, 24% rh), they had a 0.6°C smaller rise in tympanic temperature compared to when they cycled without cooling. When similar subjects performed a 30 km time trial, they were able to complete this distance in 61 $\pm$ 2 min compared to 65 $\pm$ 3 min without cooling ($P < 0.01$) (Hsu 05). In another study (Grahn et al, 2005), endurance times were longer (46 vs. 32 min) for 18 subjects when they walked on a treadmill in a hot environment (40°C) until their heart rate reached 90% HR_{max} and the rate of rise of esophageal temperature was reduced by 30%. Foot cooling using an AVAcore device also has been shown to reduce the rise in heart rate and tympanic temperature in spinal cord injured patients performing 45 minutes of arm exercise (66% VO_{2max}) in a hot (32°C, 26% rh) room (Hagobian 2004).

Therefore, the present study was an independent evaluation of the AVAcore Technology rapid thermal exchange device (RTX). We evaluated its ability to slow the development of hyperthermia and to extend exercise endurance in 10 subjects while performing two prolonged mild exercise (walking at 50% VO_{2max}) bouts in a hot, dry environment (42°C, 30% rh). Body heat exchange, heart rate response, thermal sensation, muscle endurance, and cognitive function were evaluated using a counter-balanced, repeated-measures design. Each subject's responses were compared when using the RTX, to a no-cool condition, to a condition where cooling was provided by water immersion of the hand, and to cooling with a water-perfused vest.

Hypotheses tested in this study:

- Under the condition of combined heat and exercise stress in this study, **without cooling** the core temperature and heart rate will rise rapidly and the subjects will soon report high levels of thermal discomfort. After 40 minutes of rest and rehydration, muscular endurance will be reduced, and cognitive function will be impaired. Upon resuming exercise, their core temperature will reach 39.0°C in a short period of time.

- **When using the RTX system**, a functionally significant amount of heat will be removed from the body, allowing a slower rise in core temperature and heart rate and a delayed onset of thermal discomfort. After 40 minutes of rest and rehydration, subjects will have a faster fall in heart rate and core temperature and less impairment in muscle endurance and cognitive function as compared to the control (no-cool) condition. Upon resuming exercise, they will be able to walk significantly longer compared to the no-cool condition until their core temperature reaches 39^{o}C.

- **When immersing the hand in cool water** (same temperature as the RTX), a smaller amount of heat will be removed from the body compared to the RTX condition because of a lack of sustained venodilation induced by the negative pressure of the RTX device. The rise in core temperature, heart rate, and ratings of thermal discomfort will be lower than the no-cool condition but significantly greater than with the RTX. After 40 min of rest and rehydration, muscle endurance and cognitive function will be impaired. Upon resuming exercise, endurance time will be longer than the no-cool condition, but significantly shorter than the RTX condition.

- **When using the cooling vest**, heat will be removed from the body resulting in a slower rise in core temperature, heart rate, and an improvement in thermal sensation and cognitive function compared to the no-cool condition. After 40 min of rest and rehydration, there will be a small decrease in muscle endurance and cognitive function. At this point we cannot predict whether the RTX system will produce better cooling than the water-cooled vest or a faster recovery and better endurance during the second heat test. However, the RTX by cooling from the inside out (by cooling venous blood), might produce different thermal sensations and physiological responses compared to a cooling vest, which cools from the outside-in.

We will compare the effectiveness of the three cooling conditions (RTX , hand water bath, and cooling vest) to each other and to the control, no-cool condition using the following standard "bench mark" physiological criteria: core temperature (T_{core}) at set time intervals and delta T_{core}/time; heart rate (HR) at set time intervals and delta HR/time;

endurance time during the first and second heat exposure bouts; and heat extracted (W) during the cooling conditions, if possible. We also will compare the changes in cognitive function and muscle endurance during the four heat stress test (HST) conditions.

Importance of this study for DARPA and the Army:

We designed this study to directly apply to current military conditions. The subjects recruited were similar in age, body mass, and fitness as military recruits. Indeed, we included volunteers from the university ROTC. The subjects wore summer Army battle dress uniforms while exercising in the heat. *(They did not wear boot or helmets because this might cause blisters and limit our ability to measure heat tolerance in these volunteers not accustomed to such gear).* The environmental conditions were selected such that the effective heat stress is similar to average summer temperatures in Iraq, where the average ambient temperature in July and August is about 45^{o}C and 20% rh (www.southtravels.com/middleeast/iraq/weather.html).

This study compared a current Army personal cooling system (the "Air Warrior" cooling vest) to the RTX device. The two cooling systems were compared under conditions where soldiers would need personal cooling (walking briskly in the heat).

The Army requested we include a comparison with the hand immersed in cool water—using the same water temperature as that used in the RTX device (A container to immerse a hand in chilled water could be implemented more cheaply in a crew vehicle for example, than equipping the vehicle with RTX systems). Therefore, it is important to document the efficiency of the RTX device compared to cheaper cooling methods.

We talked with the manufacturer of the RTX and studied previous publications and data using this device (Grahn 05; Grahn 98; Hsu 05; Hogobian 04). The most attractive aspect of this cooling system is that it cools the venous blood returning to the core and thus provides a rapid fall in deep body temperature. Most military activities involve repeated heat exposures, and a rapid recovery could be crucial. Therefore, we included a recovery and second heat bout in our protocol to determine whether the RTX system provides a more effective return-to-action after only 40 min of recovery compared to the cooling water bath and cooling vest.

The findings of this study could have immediate applications. One outcome may be to place RTX systems in the field in Iraq or Afghanistan to provide more rapid cooling of possible heat-stress casualties. A second application could be to implement the RTX during stationary heat exposures, such as in tanks, helicopters, or other combat vehicles. A third application may be to use the device as tested in this study; for continuous personal cooling in ambulatory subjects.

The physical data provided in this study describing the rate of heat retention in soldiers wearing body armor and the needed heat extraction to prevent over-heating can be used to model future cooling devices.

Material and Methods

We recruited 12 healthy volunteers to participate in this study.

The number of subjects was based on a power analysis using data from Cheuvront et al. (2003): comparing the "continuous whole body cooling group" and the "no-cool group." In their paper, five heat acclimated men exercised for 80 min in a warm environment (30^{o}C) wearing impermeable clothing with or without cooling. Without cooling, the average rise in rectal temperature was 1.7 $\pm$ 0.3^{o}C, while, with cooling the average rise was reduced to 0.5 $\pm$ 0. ^{o}C. If, we predict that the RTX device will be only 30-40% as effective as a whole body-cooling suit due to a smaller surface area for heat exchange, then the rise in rectal temperature with the RTX should be approximately 1.3^{o}C. Using the standard deviations from Cheuvront's data and a hypothesized 0.4^{o}C difference in rise of body temperature between the no-cool and RTX-cooled conditions, 10 subjects would be sufficient to detect a significant difference (alpha value of 0.05 and a power of 0.8). Therefore, we recruited 12 subjects in case one or two subjects did not complete the study. Indeed, two subjects did not complete the study.

The inclusion criteria for this study were:

- Healthy, non-smoker
- Between the ages of 18 and 35 years
- $VO_{2max} \geq 35$ for women and ≥ 40 ml/kg/min for men, as determined in our lab using a graded, treadmill protocol.
- Moderately active lifestyle (exercise vigorously at least 30 min, 3 times a week) determined using a physical activity questionnaire (Heyward 02)
- Body Mass Index (BMI) between 15 and 25 kg/m^2, with exception for weight lifters where % body fat was used to assess fatness

Subject age, BMI and fitness were selected to be similar to those of young Army recruits (Vogel et al., 1986; Quesada et al, 2000). Female subjects would have "normal menstrual cycles, or, be taking a monophasic oral contraceptive with consistent hormonal intake for 3 weeks of their menstrual cycle. HST for all subjects were performed at the same time of day to reduce changes related to circadian variation.

The study was conducted at the University of New Mexico, in the Exercise Physiology Laboratory, which contains a 12 x 14 ft environmentally-controlled room (temperature $\pm$ 1^{o}C and $\pm$ 2% RH), a biochemistry laboratory, the required testing equipment for human thermoregulatory studies, and personnel experienced in human exercise and environmental stress studies. Volunteers were reimbursed at a rate of $10.00/hour for screening and experimental trials.

Subject screening

The present study was approved by the UNM Health Science Center Institutional Review Board. Subjects were first briefed about the study and provided written informed consent. Subjects were screened using a medical history questionnaire, an activity questionnaire, and the Physical Activity Readiness Questionnaire (PAR-Q) (in appendices from Heyward 02). A blood sample was obtained to determine lipid profile (total cholesterol, high and low density cholesterol) and fasting blood glucose. Volunteers were excluded if they had two or more cardiovascular disease risk factors, as determined by the most recent American College of Sports Medicine guidelines (2006).

Baseline Measurements:

A VO_{2max} test was performed in a thermoneutral environment (19-22ºC and 30% RH), using a continuous, graded treadmill protocol. The subject first warmed-up and then ran at two submaximal treadmill speeds (with no grade) and two treadmill grades (with constant speed). From this information linear regression equations were developed and used to determine the work settings used during heat stress tests. The subject then rested 5-10 minutes and then began the VO_2max determination. Treadmill speed and grade were increased in one-minute stages (protocol specific for each subject based on warm up) until voluntary exhaustion. The maximal aerobic capacity (VO_{2max}) was determined as the highest VO_2 attained during a 30 sec period where the VO_2 reached a plateau (increased less than 150 ml) with further increase in exercise intensity. Maximal heart rate was determined during this interval.

Weight and height were obtained using a precision scale (accuracy ± 50g) and a stadiometer for calculation of body mass index, or BMI (kg/m^2). *Body fat* was measured in each subject using Lange skinfold calipers and the gender-specific, sum of three skinfold equations of Jackson and Pollack (Heyward 06).

Upper body strength was assessed by measuring the 1 repetition max (1-RM) for a supine bench press exercise. Subjects first warmed-up by completing 5-10 reps at 50% of their estimated 1-RM. Following a 1-min rest, the subject performed 3-5 bench press repetitions at 70% of the estimated 1-RM. He/she then rested 3 minutes before attempting the next weight increment. This was repeated until he/she could not complete 1 lift with proper form. Using this procedure, the 1-RM was obtained within 3-5 trials. This whole test was repeated on separate days to confirm the 1-RM value (confirmed if the weight matched within 5%).

Emotional Status, Environmental Systems Questionnaire, and Cognitive Function Tests were performed during the baseline period and during the 1st and 10th days of heat acclimation.

These tests were administered at the same time of day, in the same posture, and with a similar lighting level.

Overall study protocol

After screening, the volunteers were familiarized with the testing environment by undergoing a 10-day heat acclimation protocol. Next, four HST were performed in a counter-balanced order (see table below). One HST test was performed without cooling. Another test was performed with the left hand placed in the RTX cooling device in a manner consistent with instructions from the manufacturer. Another test was performed with the left hand immersed in cool water (temperature similar to the RTX). Another test was performed while wearing the "air warrior" cooling vest.

Counter-balanced Testing Order

Subject	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**
1	1st	2nd	3rd	4th
2	2nd	3rd	4th	1st
3	3rd	4th	1st	2nd
4	4th	1st	2nd	3rd
5	1st	2nd	3rd	4th
6	2nd	3rd	4th	1st
7	3rd	4th	1st	2nd
8	4th	1st	2nd	3rd
9	1st	2nd	3rd	4th
10	2nd	3rd	4th	1st
11	3rd	4th	1st	2nd
12	4th	1st	2nd	3rd

Heat acclimation protocol

The heat acclimation protocol (HAP) consisted of 10 days of treadmill walking at 56% VO_{2max} for 100 minutes (two, 50-min sessions with a 15 min rest between sessions) in a hot, dry environment (42ºC and 30% rh). Heat acclimation was confirmed by comparing sweat rate, core temperature and HR between the first and the last HAP days. During HAP, subjects were allowed to drink water *ad libitum.* Core temperature (using a telemetry pill) and HR were monitored continuously. Total sweat loss was calculated from the change in nude body weight before and after each session, corrected for water ingestion and urine output.

Heat Stress tests (HST)

The volunteers were advised to refrain from vigorous exercise, caffeine and alcoholic beverages for at least 24 hours before each HST. On each experimental day, the subjects drank 500 mL of water two hours before arrival to the laboratory. They also drank 200 mL of bottled water when they arrived. If they were still dehydrated, from measurements of urine specific gravity and osmolality, they were given additional water to drink until urine specific gravity was less than 1.030 and osmolality was less than 600 mosmol/kg.

Before each HST, we obtained a nude body weight and the subject then dressed in a standard Army summer battle dress uniform. The subject next entered the environmental chamber equilibrated at 42^{o}C, 30% RH, and an air flow of 1.8 m/sec. They stood quietly on the treadmill for 15 minutes while cooling and measurement equipment were attached. At the end of this baseline period, a resting blood sample, HR and thermal measurements were obtained. The exercise bout began as the subject started walking on the treadmill and the cooling equipment (during cooling conditions) was activated.

Each HST (see figure below) consisted of two bouts of treadmill walking separated by a 41-min cooling and rehydration period. Each exercise bout started with a 5-min warm-up of walking at 0% grade at 3.5 mph. The treadmill speed and grade were then increased to 3.5 to 4.2 mph, 0 to 4% grade while they walked wearing a backpack with 0-25% body weight. The combination of speed, grade and backpack weight were chosen to produce a work rate that required approximately 50% of each subject's VO_{2max}.

To obtain the targeted 50% VO_{2max} work rate, subjects walked on the treadmill while wearing a backpack with weight up to 25% body weight and with the grade of the treadmill set to induce the required level of strain. Their backpacks contained weights and water *bottles equilibrated to the temperature of the chamber. Using this approach, we could obtain the desired work level (50% VO_{2max}), while providing a treadmill speed representative of an Army patrol and a treadmill grade that would not induce leg muscular fatigue and muscle cramps.*

EXERCISE BOUT 1

Each subject walked under the above conditions until their core temperature (pill or rectal) reached 38.5^{o}C. A venous blood sample (5 mL) was obtained from an antecubital vein immediately upon reaching the targeted core temperature. Cognitive function tests (group A) were started while subjects walked on the treadmill after 25 min. Oxygen consumption was measured after approximately 10-20 minutes of walking. Continuous measurement of core temperature, skin temperatures and HR were obtained. Walking was terminated earlier, if subject's experienced symptoms of exertional heat illness (severe nausea, light-headedness, ataxia or confusion) or upon subject request.

RECOVERY PERIOD

The subjects then removed their back pack and sat quietly for 41 minutes in the heat chamber, drank bottled water (15 mL/kg body mass, at a temperature of 15-17^{o}C) at a set rate (25% of the total volume every 5 minutes). After approximately 10 min of cooling and rehydration, subjects began to perform cognitive function tests (group B). These tests took 20 min to complete. They next lay down for the supine bench press muscle endurance test (less than two minutes). They then stood, put on their back pack and were weighed again before moving back to the treadmill to start the second exercise bout.

Cooling was applied during the recovery period, but was briefly disconnected two times. At the end of the first exercise bout and after the blood draw, cooling was removed for about one minute while the subject was weighed and moved from the treadmill to a seated position to perform the cognitive tests. At the end of the cognitive tests, cooling was removed for about three minutes as subjects performed the muscle endurance test, reweighed, and returned to the treadmill before the second exercise bout.

EXERCISE BOUT 2

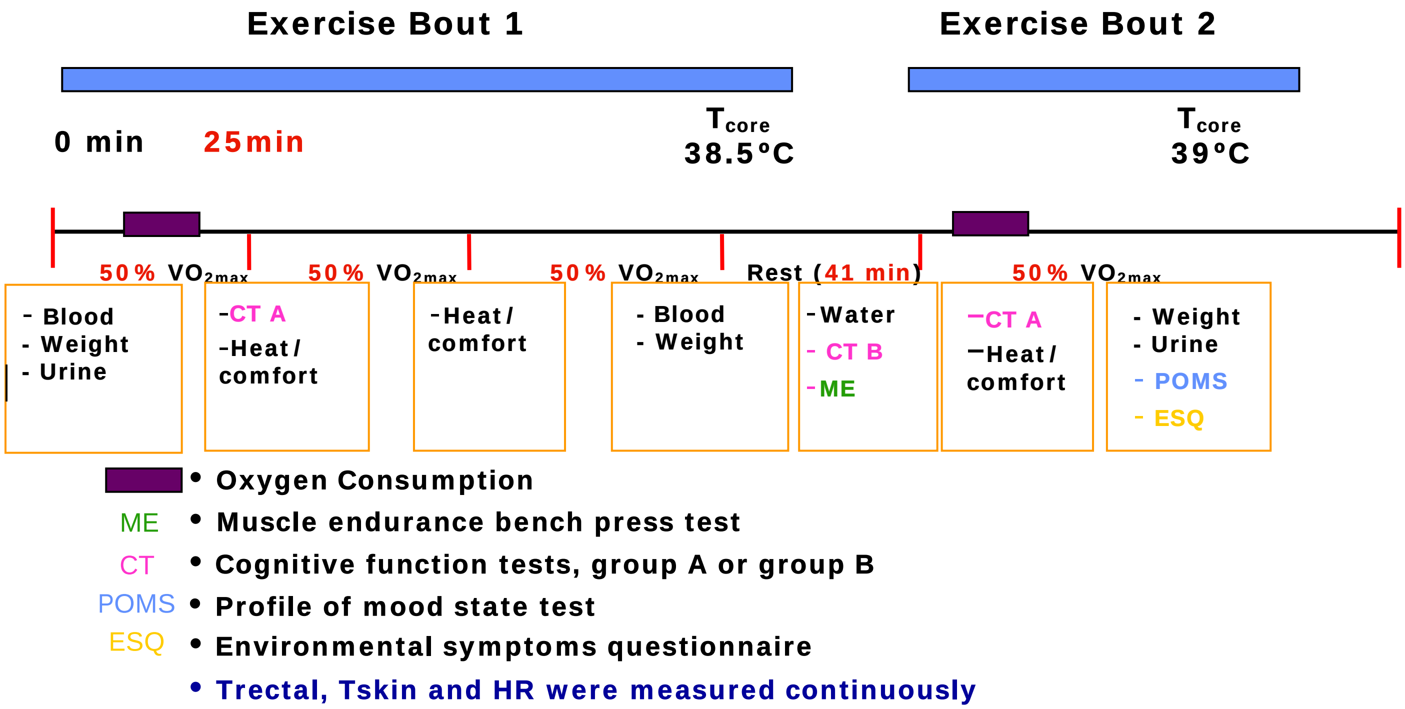
After 41 min of rest/rehydration, the subjects returned to the treadmill and walked under the same conditions until their Tcore reached 39^{o}C, HR exceeded 95% HRmax, they experienced symptoms of exertional heat illness, or subject request. Immediately upon reaching the termination criteria, the subject left the chamber, towel dried and obtained a nude weight. They then completed a Profile of Mood State (POMS) emotional status test and the Environmental Symptoms Questionnaire (ESQ) in a quiet room.

This HST protocol allowed us to compare the rate of body heating during the first walking condition to assess the ability of the three cooling conditions to slow the onset of hyperthermia. The second walking bout was necessary to assess the ability of each cooling method to reduce heat strain and promote recovery. Comparing the endurance time after rest/rehydration with cooling was an important aspect of this study because of claims that the RTX system provides faster internal cooling, greatly enhancing intermittent work endurance compared to other cooling systems. Also, intermittent walk/rest cycles are more representative of a soldier's normal activity.

Each HST was administered in counter-balanced order with a minimum of three days between tests. If more than 4 days occurred between HST tests, an additional heat acclimation day would be performed before continuing with HSTs. *This happened when one subject (subject 7 became ill, and one extra heat acclimation session was performed to maintain his state of heat acclimation before his final HSTs could be performed. Subject 11 also performed one additional heat acclimation session to maintain his heat acclimation status before performing one of his "extra" HST; see results section about extra RTX tests at different temperatures.*

Noise and lighting were matched within the chamber during each HST as much as possible. For example, the cooling unit for the cooling vest (the MCU) produced about 50 db of noise, and so was positioned outside of the environmental room during HST where the noise was not audible to the subjects.

Heat Stress Test Protocol



Cooling Equipment:

AVAcore RTX, Unit B Model

Several versions of the RTX exist. The system used for this evaluation was the commercially available "coffeepot" or Unit B version. It consists of a hard shell container with tubing and quick-connect fittings to attach to an ice-water thermos. A water pump in the RTX pulses chilled water into a metal cone. The subject lightly places their hand around the cone without gripping and thermocouples within the cone measure water and hand temperatures. A ratchet-like membrane with numbered settings can be twisted to seal around the wrist. A vacuum pump automatically turns off and on to maintain a negative pressure of approximately 24 inches of water around the hand. A digital display from the top of the RTX provides continuous readouts of the cone temperature, hand temperature, vacuum pressure and watts of power used by the device.

"Air" Warrior Cooling Vest

Air Warrior Cooling Vests were supplied to our laboratory by the United States Army

Research Institute of Environmental Medicine (USARIEM). We had three sizes: large, medium and small. For our use, the vests were perfused with water, which was chilled by an electrolytic cooler, termed the Multiple-use Cooling Unit (MCU). The MCU chills water which is pumped at a rate of approximately 0.4 to 0.7 liters/min through tubing and quick release fittings to the vest. The temperature of the water perfusing the suit under our environmental conditions was 15-16^{o}C. The water temperature could not be controlled in this system, other than by altering the flow rate. During all tests, we used the MCU with the flow rate at the maximal level.

Water bath Cooling Set-up

For the water bath, the goal was to develop a hand cooling system that could be cheaply and easily applied in the field. For this purpose we used a thermos, which in the field could be filled with chilled water. For our purposes however, we needed to match the temperature used in the RTX trials. Therefore, a copper tubing coil was inserted in the thermos and chilled water was pumped through the tubing to regulate the water bath temperature. The water was chilled and pumped using a commercially available cooling unit (a Thermocube, Model 300-400-U-A chiller, Total Thermal Solutions Comp, Pleasant Valley, NY). The flow rate through this system was 1.9 liters/min and water bath temperature could be controlled within 1^{o}C.

Specific measurements:

Hydration status was assessed when subjects arrived in the lab from the urine specific gravity (by refractometry) and osmolality (by freezing point depression). If subjects were deemed dehydrated, they were given additional water to drink and reassessed after 20 minutes. During the HST, the rate of dehydration was assessed from the changes in hematocrit, hemoglobin concentration (Dill and Costill 1974), plasma osmolality, urine changes, and body weight loss.

Cardiovascular and metabolic measurements. During all HST, heart rate was obtained and recorded with a telemetric heart rate monitor (Polar, model 810i HR watch, Oy, Finland). Breath-by-breath metabolic data were collected with a fast-response turbine flow meter (K.L. Engineering Model S-430, Van Nuys, CA) and oxygen consumption and carbon dioxide concentrations were measured with oxygen and carbon dioxide electronic gas analyzers (AEI Technologies, Model S-3A and Model CD-3H, Pittsburgh, PA). Data acquisition was performed with custom developed software (Labview – National Instruments). The values were recorded during both exercise bouts of each HST. Values were used to calculate heat production.

Thermoregulatory Measurements:

Core Temperature. During HST, we had planned to use both pill (Vitasense Model VSM100M, Minimitter Company, Inc., Bend, OR) and rectal sensors (Model 491B, Cincinnati Subzero Products, Inc., Cinc. OH), but this was done only for the first two subjects. We soon discovered that this new telemetry pill system was not as reliable as telemetry systems we have used in the past. The pill readings occasionally began erratic, and would suddenly increase or decrease while the rectal temperature remained stable. Because of the high cost of the pills ($50/each) and the unreliability of the data, we opted to only use the rectal temperature measurement for the remaining HST. *For subject comfort, we continued to use the pill during HAP, as we could extrapolate between stable measurements to estimate Tcore.*

Skin Temperatures (T_{sk}) were measured continuously at 8 sites using uncovered thermistors (Model EUS-U-UL5-0, Grant Instr., Cambridge Ltd) and stored with the rectal thermistor data in a data logger (Squirrel data logger, Model 2020, Grant Instr., Cambridge Ltd). Mean skin temperature was calculated using modified Hardy and DuBois formulas (Hardy 1938) as seen below for the four HST conditions. Since it was impractical to measure foot temperature, the lower leg temperature was substituted for this site in each condition. Lower forearm temperature was substituted for hand temperature site in no-cool and vest tests. For RTX tests, the RTX measured palm temperature, so this temperature was used as the estimate of half of "weighed"area for hand temperature in the Hardy and DuBois formula. For water bath tests, the water bath temperature was used as the estimate of temperature for the hand. We realize these hand temperature estimates are not exact and will introduce some a amount of error in the mean skin temperature formula. We found it impossible to keep a thermistor attached to the hand during our tests due to limited accessibility in some cooling conditions, excessive movement and sweating. The formulas used to calculate mean T_{sk} were as follows:

For no-cool and vest tests:

Mean $T_{sk} = (T_{forehead} \text{ x } 0.07) + (T_{arm} \text{ x } 0.14) + (T_{left\ forearm} \text{ x } 0.025) + (T_{right\ forearm} \text{ x } 0.025) + (T_{calf} \text{ x } 0.20) + (T_{thigh} \text{ x } 0.19) + (T_{chest} \text{ x } 0.18) + T_{back} \text{ x } 0.17)$.

For water bath tests:

Mean $T_{sk} = (T_{forhead} \text{ x } 0.07) + (T_{arm} \text{ x } 0.14) + (T_{water\ temp} \text{ x } 0.025) + (T_{right\ forearm} \text{ x } 0.025) + (T_{calf} \text{ x } 0.20) + (T_{thigh} \text{ x } 0.19) + (T_{chest} \text{ x } 0.18) + T_{back} \text{ x } 0.17)$.

For RTX tests:

Mean $T_{sk} = (T_{forhead} \text{ x } 0.07) + (T_{arm} \text{ x } 0.14) + (T_{left\ hand\ from\ RTX} \text{ x } 0.0125) + (T_{right\ forearm} \text{ x } 0.025) + T_{left\ forearm} \text{ x } 0.0125) + (T_{calf} \text{ x } 0.20) + (T_{thigh} \text{ x } 0.19) + (T_{chest} \text{ x } 0.18) + T_{back} \text{ x } 0.17)$.

Mean body temperature (T_b) was calculated from the T_{core} and mean T_{sk} as:

$T_b = x\ T_{core} + (1 - x) \text{ mean } T_{sk}$

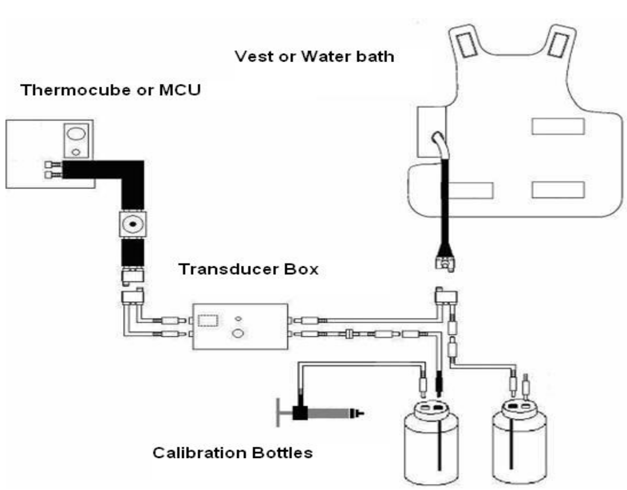
where x = 0.8, the appropriate weighting factor for a hot environment (Houdas and Ring 1982).

Total sweat loss was calculated as the difference in nude body mass between before and after exercise, corrected for urine output and fluid intake. This value represents the rate of dehydration but is not a measure of the evaporative sweat rate, as the weight loss is not corrected for respiratory water loss or water collected in clothing.

Environmental heat stress Wet bulb, dry bulb, globe temperature and WBGT were recorded every 5 minutes from a WBGT data monitor (Metrosonics, Model 3600, Oconomowoc, WI) and wind speed was measured with a wind anemometer (Smart Sensor Anemometer) at waist level for a subject on the treadmill.

Heat Extraction measurements Water bath inlet and outlet temperature and flow rate were measured to calculate heat extraction during water bath and vest HST. We attempted to obtain the same measurements during RTX trials, but this was not possible. The RTX was not designed for continuous flow operation and could not sustain the high pressures produced by the thermocube chiller. Heat extraction was able to be obtained for only a few minutes from one subject before the RTX unit was broken (the water-tight seals gave way). During RTX tests, hand temperature, vacuum pressure (in inches of water) and water temperature were recorded every 5 minutes from the RTX readout.

A diagram of the heat extraction system and the set-up for calibrating the flow readings is shown on this page. We used the measurement and calibration system provided by USARIEM for the Air Warrior vest for both the vest and water bath. A transducer box containing thermocouples to measure the water-in and water-out temperatures and a flow meter were connected between the cooling system (vest or water bath) and the MCU. Digital output from the MCU was sent to a desktop computer which contained software also provided by USARIEM which then calculated the watts of heat extracted and recorded the data in one



minute intervals. For calibration, the water outflow was collected in a plastic bottle over a period of 200 seconds. The bottle was weighed before and after the collection period to calibrate the flow sensor in the transducer box. Calibrations were performed for the vest and the water bath system each week during the study.

Body Heat balance was calculated for the first exercise bout of each HST using standard partitional calorimetry equations with adjustments for clothing Clo factors (provided by USARIEM for the summer battle uniform with body armor). A partial calorimetry spreadsheet (Atkins and Thompson, 00) was modified for our test conditions and used for the heat balance calculations.

Subjective heat and comfort rating were reported using scales modified from Fox and DuBois (1993) as recently reported by Mitchell et al (2003). The volunteer was asked to rate their comfort using a scale from 1 (comfortable) to 5 (intolerable) and their thermal sensation from 1 (very cold) to 9 (very hot). Subjects were asked to rate their comfort and thermal sensations using these scales at 30-min intervals during each HST.

Emotional status was assessed with the Profile of Mood States (POMS; McNair, et al, 1981) a widely used instrument designed to assess a variety of mood states. Respondents rated mood descriptors on a 5-point Likert type scale as to the extent of emotions they experienced during each HST. This self-report measure yields a global distress score, Total Mood Disturbance, as well as six statistically identified factors: Tension-Anxiety, Depression-Dejection, Vigor-Activity, Fatigue-Inertia, Anger-Hostility, and Confusion-Bewilderment. The short-form (POMS-SF; Curran, et al., 1995), which consists of 37 adjectives, was administered. The POMS-SF was administered during baseline, following the 1^{st} and 10^{th} day of the HAP, and at the end of each of the four HSTs. The test was administered in a quiet room with constant lighting.

The Environmental Symptoms Questionnaire (ESQ), version IV developed by R.F. Johnson in 1984 (Sampson 94), was administered after the 1^{st} and 10^{th} HAP, and at the end of each HST. Subjects were asked to fill out a questionnaire ranking the symptoms they felt during the HST. They rated their feelings on a scale from 0 (not at all) to 5 (extreme), for 22 questions that relate to symptoms of heat illnesses. For example, subjects were asked to rate their feeling of lightheadedness, headache, coordination, difficulty breathing, muscle cramps, stomach cramps, weakness, warmth, etc. This test has been used extensively in previous military investigations of heat exposures (see Sampson 94, Appendix C for a listing of such studies). This test was administered after the POMS test.

Cognitive Tests:

Cognitive functioning was assessed with a variety of well-studied neuropsychological tests tapping the constructs of executive functioning, working memory, and sustained attention. Tasks such as these that require higher cognitive functioning are more vulnerable to the effects of heat stress than are tasks focusing on automatic processing (e.g., simple reaction time; Hancock & Vasmatzidis, 2003). The cognitive tests (CT) were administered during baseline and during each of the four HSTs. Three tasks, the Simple and Choice Reaction Time tasks and the N-Back task (Group A), were administered while walking on the treadmill in a thermoneutral room during baseline, during the 1st and 10th heat acclimation days, and during each exercise bout of the HSTs. In order to better investigate the effects of heat stress and fatigue, these tasks were administered after 25 min during the first exercise bout and again, when core temperature reached 38.3 ^{o}C during the second exercise bout. Three additional tasks, the Trail Making Test, the Color Word Interference Test, and the Letter-Number Sequencing Test (Group B), were administered while seated during baseline and after 10-25 min into the rest/rehydration period of each HST.

The Simple and Choice Reaction Time tasks and the N-Back task (Group A) were computer administered. The Simple Reaction Time task consists of the measurement of reaction time through a keyboard press following the presentation of a simple stimulus (e.g., dot) on the computer screen. The Choice Reaction Time task consists of the measurement of reaction time (decision time and movement time) from a home key following the presentation of a particular stimulus (e.g., directional arrow) and the press of a corresponding key (e.g., arrow). The N-Back task consists of presenting numbers in a sequence and participants are asked to compare the current stimulus to a stimulus that was *n* positions back in the sequence. In this experiment there were 3-levels of cognitive load. In the minimum level condition, the 0-back condition, participants only had to keep in working memory one number throughout the entire experiment and verify whether the current stimulus is the same as this target stimulus. In the 1- and 2- back conditions, the memory set changed throughout the experiment. Participants press a button when the current stimulus matches a previously presented stimulus. In the 1-back condition the target is the previous number presented. In the 2-back condition the target is the number presented two positions back in the list. In these conditions, previous stimuli must be kept in working memory until a new stimulus is presented and a judgment can be made, then the working memory set must be updated with the newly presented stimulus.

Ten minutes into the rest and rehydration phase, the participants began 20 min of cognitive testing (Group B). The Trail Making Test and the Color Word Interference Test were administered from the Delis-Kaplan Executive Function System (D-KEFS; Delis, et al, 2001), a standardized system of cognitive functioning measures that are sensitive to changes in brain functioning. The Trail Making Test consists of connecting in order encircled numbers (Part I) and encircled numbers and letters (Part II, switching condition). The Color Word Interference Test consists of several conditions: a color naming trial (e.g., naming colors of colored XXXs), a word naming trial (color labeled words printed in black ink), an interference condition (naming color labeled words, e.g., "RED," typed in an incongruous color ink, e.g., blue ink), a contingency condition (e.g., naming the color labeled words if they are enclosed in a box), and a contingency naming shift condition (e.g., naming the color labeled words if they are enclosed in a box, otherwise naming the color). In each condition, a page is presented to the subject with a long list of items and the subject is instructed to read through the stimuli as fast as they can. The Letter-Number Sequencing Task is a subtest from the Wechsler Adult Intelligence Scale – 3rd edition (WAIS-III;

Wechsler, 1997) and consists of reading a combination of numbers and letters and then recalling the numbers first in ascending order and then the letters in ascending order. The string of letters and numbers increases linearly from two items until the participant is unable to correctly complete at least one of the three trials of a given span length.

Muscle endurance. Based on the baseline 1-RM data, a weight was determined (70% of the 1-RM) that resulted in fatigue in a cool room after 10-15 continuous repetitions. During two baseline days in a thermoneutral environment, muscle endurance tests using this 70% RM weight were performed to record the number of repetitions the subject could perform with this weight. This muscle endurance test was performed after the first bout of exercise during each HST after 25 min of recovery and rehydration.

Data Analysis and interpretation

The effectiveness of the cooling devices were assessed by using standard "bench mark" criteria that have been used in previous cooling investigations (Vallerand 1991). Such criteria include comparisons of T_{core} at set time intervals and delta T_{core}/time; heart rate at set time intervals and delta HR/time; the endurance time for the first and second heat exposure bouts; and heat extracted (W). We also compared the changes in cognitive function and muscle endurance between the four HST conditions.

The effect on recovery of the three cooling devices was assessed from measurements of the fall in HR and rectal temperature during the recovery and rehydration period. We also compared the HR, body temperature, and thermal assessment responses during the first and second exercise bouts to assess the degree of recovery provided during the rest and rehydration period.

Each variable was compared using a repeated measures ANOVA design to determine significant differences between the four test conditions (no cooling, water bath, vest and RTX). When a significant condition effect was determined for a given variable, a Tukey post-hoc test was performed. As we completed HST and found no obvious improvements from the RTX or water bath at 15^{o}C, we increased the cooling temperatures to 18 and then 22^{o}C. The first 3 subjects were studied with the RTX and water bath at 15^{o}C (subjects 1, 2, and 4), the next three subjects at 18^{o}C (subjects 5, 6, and 7), and the final 4 subjects were tested at 22^{o}C (subjects 9, 10, 11, and 12). Some subjects performed more than one RTX trial (see below). However, for comparisons between the four cooling conditions, only the first RTX trial was included. Thus, for each comparison between cooling conditions, 10 subjects were compared during the four cooling conditions (no cool, vest, water bath, RTX).

In addition three subjects (5, 10, and 11) performed more than one RTX trial to further address the sub-question of whether the cooling temperature affected the HST results. Thus five subjects (1, 2, 5, 10, and 11) were tested with RTX at 15^{o}C. Five subjects (5, 6, 7, 10, 11) were tested at 18^{o}C. Five subjects (5, 9, 10, 11, and 12) were tested at 22^{o}C.

Results

The study was completed in Albuquerque, New Mexico between the months of January (subject recruitment and screening began) and June of 2006. Albuquerque is located in a desert climate at an altitude of approximately 1500 meters.

Subjects Ten subjects completed the four cooling conditions in this study, eight men and two women. The two women were both taking monophasic contraceptives, and all HST were scheduled during the 3-wk interval of constant hormonal balance. The physical characteristics of these subjects are shown in the table below.

Subject	**Gender**	**Age (yrs)**	**Weight (kg)**	**Height (cm)**	**VO2max (ml/kg/min)**	**Body fat (%)**	**BMI (kg/m2)**
1	**M**	29	73.2	180	69.8	8.5	22.5
2	**M**	27	79.6	172	55.5	11.8	**27.1**
4	**M**	21	76.4	179	50.7	11.6	23.9

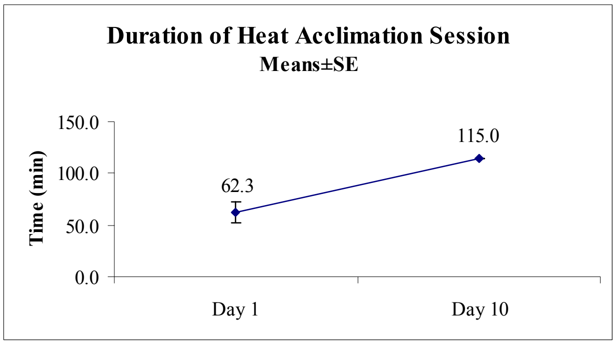
5	**M**	22	84.5	186	62.1	8.3	24.5
6	**M**	24	65.5	170	48.9	14.7	22.8
7	**M**	22	62.5	171	52.3	7.9	21.5
9	**F**	24	76.3	175	40.6	27.4	25.1
10	**M**	26	72.1	180	66.9	6.7	22.4
11	**M**	30	76.5	185	55.2	14.2	22.3
12	**F**	21	73.0	179	43.2	28.8	22.9
MEAN		**25**	**74.0**	**177.5**	**54.5**	**14.0**	**23.5**
STD		**3**	**6.4**	**5.8**	**9.5**	**7.9**	**1.7**
n		**10**	**10.0**	**10.0**	**10.0**	**10.0**	**10.0**

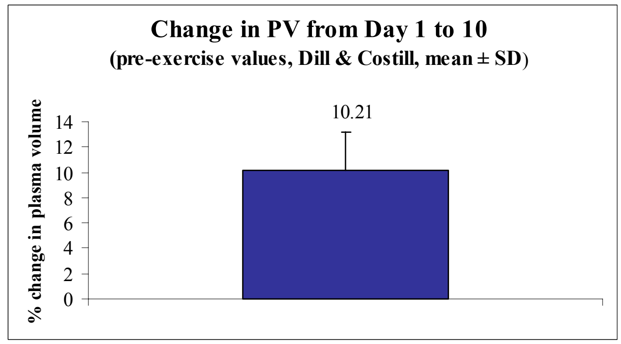
One subject (#2) did not meet our initial screening criteria of having a BMI less than 25 kg/m^2. However, this subject was a Marine with extensive resistive exercise training and his body fat value was well below average. He was accepted into the study since he was obviously not overweight, and would be representative of some Army recruits.

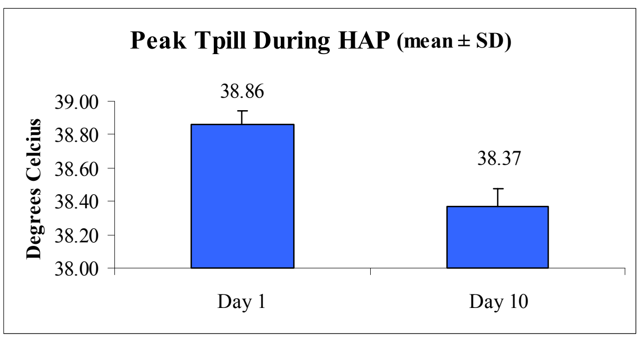
Hand Temperature Modification to Protocol The first three subjects were tested with the RTX and water bath temperature set at 15^{o}C and the results did not show an appreciable cooling effect. At this point, we reviewed the data with the manufacturers and with DARPA and it was suggested that our hand temperature was too low, causing the subjects to remain vasoconstricted. Therefore, we opted to test the next three subjects at 18^{o}C and the final four subjects at 22^{o}C (the temperature used in a previous positive study, Grahn et al., 05). We obtained permission from our IRB to make this change in protocol.

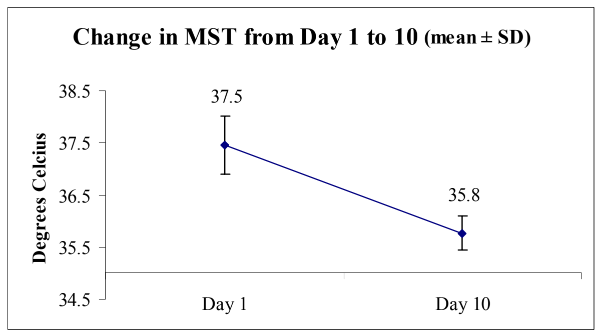
Additional Tests Additionally, three subjects agreed to perform extra RTX HSTs at varying hand temperature. One subject (Subject 5) performed two RTX tests at 15 and 18^{o}C. Two subjects (10 and 11) each performed 3 RTX tests; at 15, 18, and 22^{o}C. The extra RTX tests were performed after each subject had completed the original study design (no cool, vest, water bath, RTX).

Heat Acclimation The heat acclimation protocol was very successful, with each subject showing the classic signs of heat acclimation (see below). The duration each subject could exercise without symptoms or until Tpill reached 39°C increased, plasma volume expanded by an average of 10%, the final Tpill was reduced despite a longer exercise time, and mean skin temperature (MST) was reduced.









HST Ambient Conditions

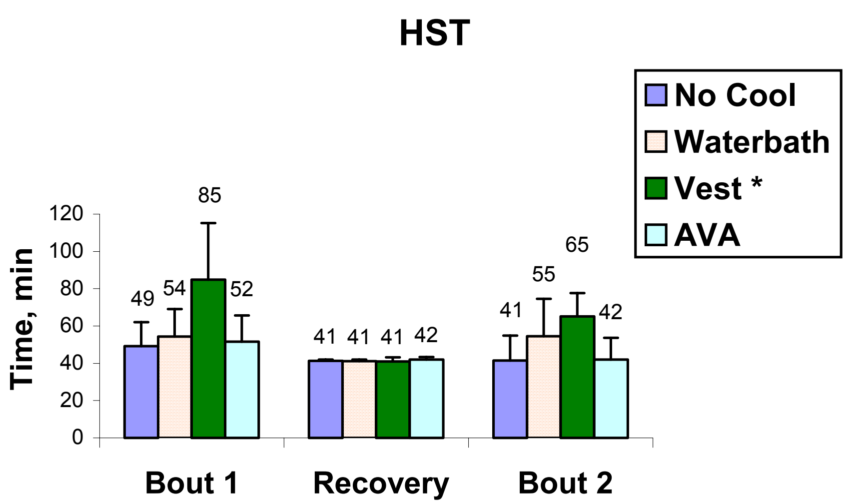
The environmental conditions during the HST are shown below.

Test	First Exercise Bout			Recovery Period			Second Exercise Bout		
	Tdry	RH	WBGT	Tdry	RH	WBGT	Tdry	RH	WBGT
No Cool	42.5	27.7	31.6	42.6	27.0	31.3	42.6	28.4	32.4
Vest	42.4	27.9	32.1	42.6	27.3	30.8	42.5	26.8	31.2
Water bath	42.4	27.7	31.3	42.6	27.2	31.9	42.5	29.0	31.9
AVA	42.4	27.7	30.1	42.6	27.7	30.3	42.5	28.1	30.3

The average dry bulb temperature was maintained within 0.2^{o}C throughout each test and was similar between testing conditions. Relative humidity increased slightly (about 1%) during each test and was similar between testing conditions. The average WBGT was maintained between 30 and 32.4^{o}C during the HST.

HST Times

The time was recorded for each phase of the HST: exercise bout 1, recovery, and exercise bout 2 (see figure below). There was a significant difference among the conditions ($P<0.01$); where vest cooling times were longer than the no-cool during the first and second exercise bouts. Water bath and RTX times were similar to no-cool. *(* symbol in the legend indicates a significant difference from no-cool; in the figure below for bout 1 and bout 2).*



Oxygen Consumption during HST

We initially planned for each subject to walk at an exercise level of 56% VO_{2max} during the exercise bouts. However, after the first HST in subjects 1 and 2 we found that the exercise time was too short in the no-cool condition to complete all desired measurements. We therefore modified the protocol to lower the target exercise level to 45-50% VO_{2max} for the remaining subjects. We were able to repeat the no-cool test in subject 1 and he finished the four HST at a slightly lower than targeted exercise level (averaged 40.7%). Subject 2 however, had already completed two tests which could not be repeated, therefore he completed his four tests at an average exercise level of 57% VO_{2max}. The treadmill speed, grade and backpack weight were identical for a given subject during the four HST. Therefore the mean oxygen consumption for each of the 10 subjects was similar across the four cooling conditions (see table below for the average VO_2 obtained during each HST).

Sub	**1**	**2**	**4**	**5**	**6**	**7**	**9**	**10**	**11**	**12**	**MEAN**
NC	39.2	50.3	39.4	47.6	52.6	45.2	50.5	46.6	55.6	51.6	**47.9**
VEST	36.6	57.6	37.8	43.1	50.8	53.8	46.4	49.6	59.4	45.6	**48.1**
WATER	42.0	66.1	36.4	37.8	49.5	41.8	48.4	47.6	54.7	47.3	**47.2**
AVA	45.1	54.6	38.2	45.4	49.5	50.9	53.8	42.4	54.4	47.6	**48.2**
MEAN	**40.7**	**57.1**	**38.0**	**43.5**	**50.6**	**47.9**	**49.7**	**46.5**	**56.0**	**48.0**	**47.8**

Reason for Terminating Exercise Bouts

Our criteria for terminating an exercise bout included attaining the target T_{core}, a heart rate > 95% of HR_{max}, severe symptoms of heat distress, or subject request. The targeted T_{core} for the first exercise bout was 38.5°C and 39.0°C for the second exercise bout. During the vest test for subject 7, the MCU failed near the beginning of the second exercise bout and the test was discontinued after approximately 7 minutes. During the vest test in subject 12, the second exercise bout was discontinued after 75 min when her T_{core} no longer increased with increasing exercise duration. The rectal probe position was checked at the end of the test and found to be positioned properly.

During the first exercise bout, most tests were terminated for core temperature or HR criteria, the only exceptions were 2 vest tests that were stopped for symptoms. Several of the subjects became nauseous and light headed immediately after stopping exercise, while standing for the post-bout 1 blood draw. This sickness usually went away very quickly after they were able to sit and start the recovery.

During the second exercise bout, many of the tests for the cooling conditions had to be terminated when symptoms occurred before the subject attained a core temperature of 39°C.

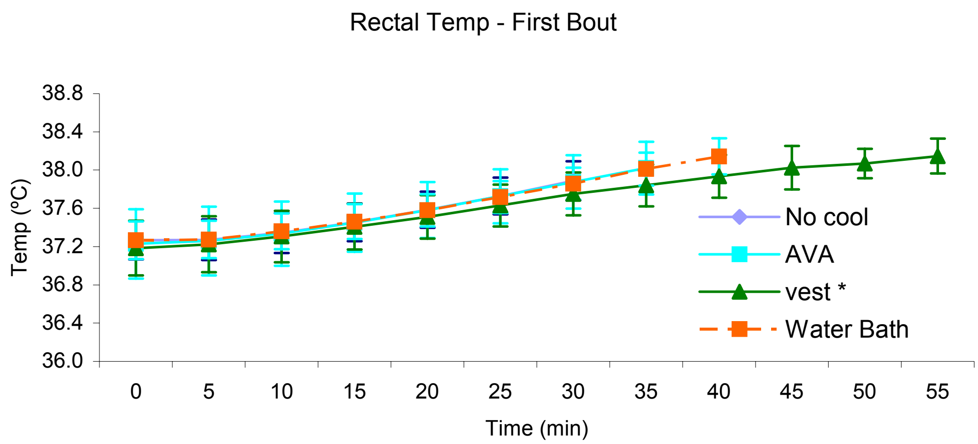
Interestingly, none of the no-cool tests were terminated for symptoms, but all subjects had to stop sooner upon reaching their HR or core temperature criteria.

	First Exercise Bout			
SUBJECT	NO COOL	VEST	WATER	AVA
1	Core	Core	Core	Core
2	Core	Core	Core	Core
4	Core	Core	Core	Core
5	Core	Core	Core	Core
6	HR	HR	HR	HR
7	Core	Symptoms	Core	Core
9	Core	Core	Core	Core
10	HR	Symptoms	Core	Core
11	Core	Core	Core	Core
12	Core	Core	Core	Core
	Second Exercise Bout			
	NO COOL	VEST	WATER	AVA
1	HR	Symptoms	HR	HR
2	HR	Symptoms	Symptoms	Symptoms
4	Core	Symptoms	Symptoms	Core
5	HR	Core	Core	Core
6	HR	HR	HR	HR
7	HR	Equip failure	Symptoms	Symptoms
9	Core	Core	Core	Core
10	HR	Symptoms	Symptoms	HR
11	Core	HR	HR	Core
12	HR	Plateau Core	Core	Symptoms

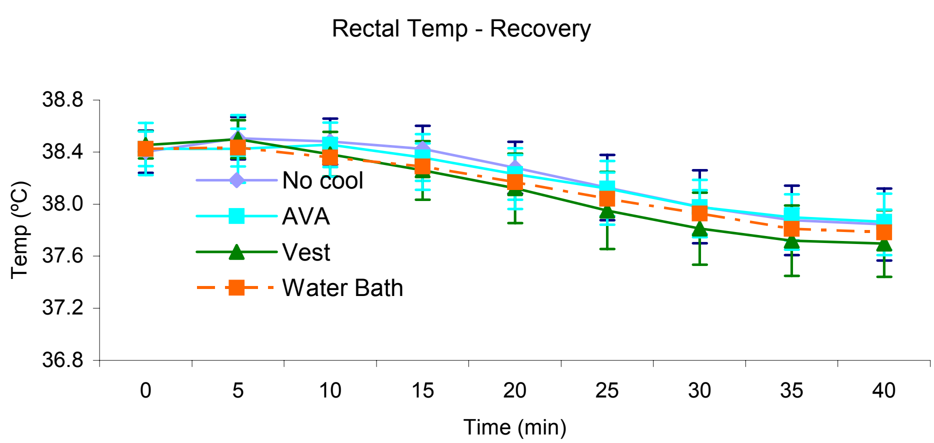
Rectal Temperature Response: Absolute values

The rectal temperatures (mean ± SD) during the four HST are shown below. Each symbol represents the mean for all subjects who completed the given time point. During bout 1, all 10 subjects completed 0 to 30 min of exercise. Thereafter, the "n" value decreases after 30 minutes as some subjects stopped exercise. For the recovery data, all ten subjects completed each time point. During bout 2, all subjects completed the first 25 minutes of exercise. An ANOVA was performed on the rectal temperature values, including only the time points with complete data sets and after the first 10 minutes in each exercise bout.

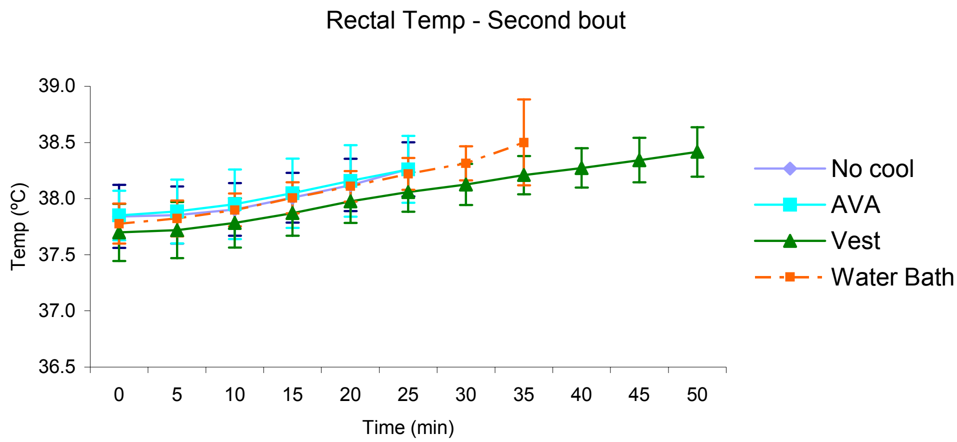
During exercise bout 1, a significant condition effect was found and rectal temperatures during the vest condition were significantly lower than the no-cool condition (during the first 30 minutes). RTX and water bath temperatures were not significantly different from no-cool.



No significant differences occurred in the rectal temperature responses between cooling conditions during the recovery period.



No significant differences occurred in the rectal temperature response between cooling conditions during the second exercise bout (during the first 25 min).



Delta Rectal Temperatures:

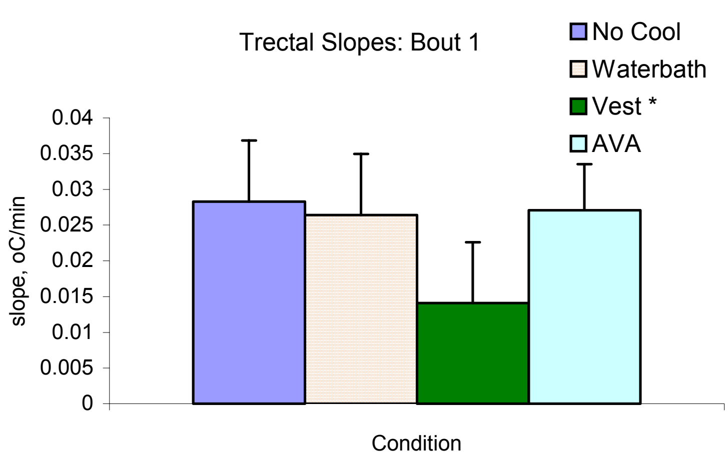
The change in rectal temperature was calculated between the beginning of each exercise bout and the final time point with complete data sets (30 min for bout 1, 25 min for bout 2). During the first exercise bout, no significant differences occurred between the no-cool condition and any of the cooling conditions. During recovery, the fall in rectal temperature was greater during the vest (-0.35°C) and water bath (-0.29°C) conditions compared to no-cool (-0.19°C). During the second exercise bout, the rise in rectal temperature was greater in the water bath condition (0.20°C) compared to no-cool (0.16°C). That is, after a greater fall in temperature during recovery, rectal temperature rose more quickly at the start of the second exercise bout.

Slope of the Rectal Temperature response:

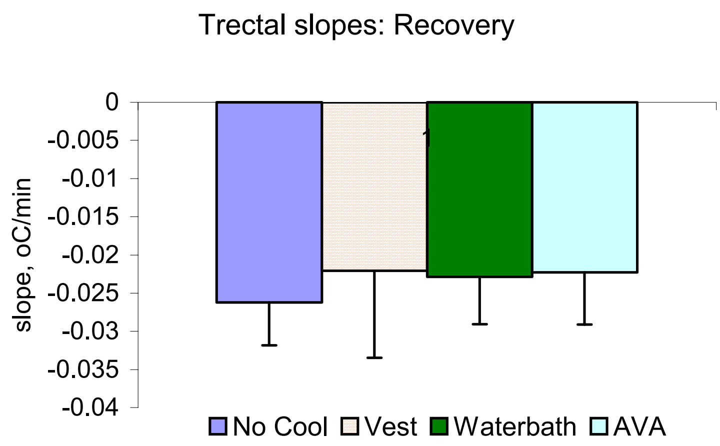
The comparisons of the absolute and delta rectal temperature data was compromised by the inability to analyze data from later time points, because of missing data as subjects stopped exercise. We feel a more valid comparison of the temperature response is to compare the slope of the rise in rectal temperature. However, even this comparison, is difficult, as the rise in core temperature with time was not always a liner relationship. Instead, the rise in rectal temperature was fairly linear and similar among cooling conditions during the first 20-30 minutes of an exercise bout. Once a cooling condition became effective, the rise in temperature slowed. Thus for example, many vest tests had a non-linear core temperature response, where the relationship appeared to have two slopes; an initial fast rise and a later slower rise.

The rectal temperature slopes were calculated as follows. We used a customized LabView program to manually view the slope of the rise in rectal temperature and to use a sliding cursor to select the data points to include in calculating the slope. In most of the exercise bouts and recovery period, the change in rectal temperature over time was a linear response, and the slopes were calculated for the first bout, recovery, and second bout. However, in some trials the slope was not linear, but biphasic being reduced about mid-way through the exercise or recovery period. In this case, two slopes were calculated and the average of the two slopes was used for the cooling condition comparison. For no-cool tests, average slopes were used for 0 first bouts, 1 recovery, and 2 second bouts. For vest tests, average slopes were found for 4 first bouts, 2 recovery, and 6 second bouts. For water bath tests, average slopes were found for 0 first bouts, 1 recovery, and 0 second bouts. For AVA tests, average slopes were found for 0 first bouts, 2 recovery, and 1 second bout. The mean ±SD for the slopes for all subjects are shown below.

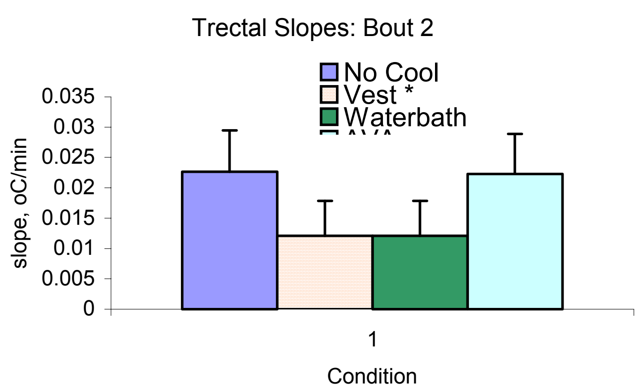
During the first exercise bout, the vest slope was significantly lower than the no-cool condition while water bath and AVA slopes were similar to no-cool.



No significant difference in slope occurred during recovery.

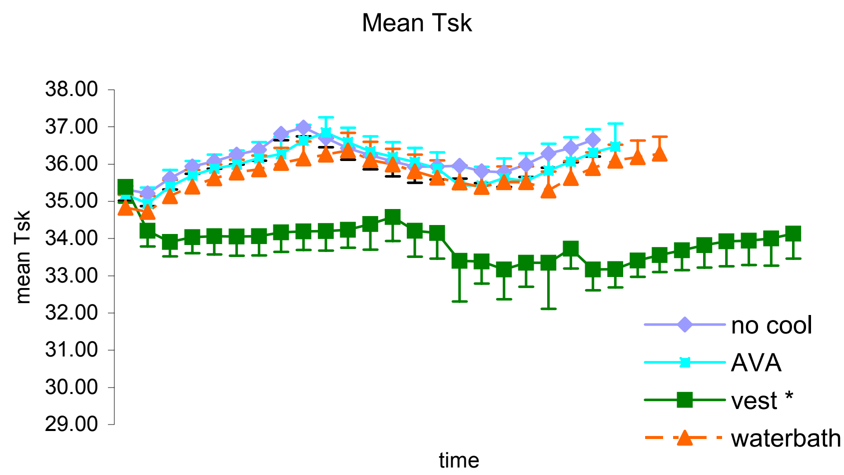


During the second exercise bout, the vest slope was significantly lower than no-cool while the water bath and AVA slopes were similar to no-cool.

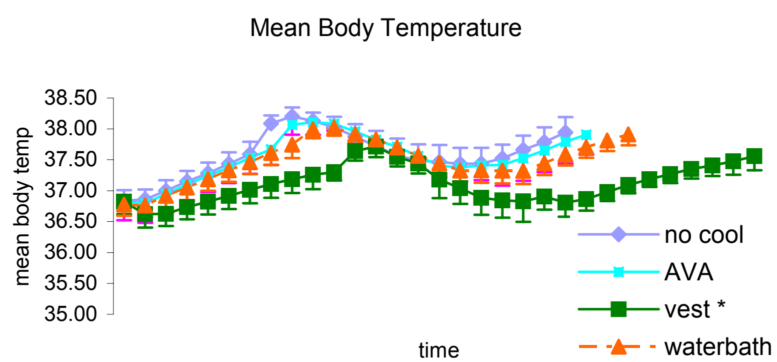


Mean skin and Mean Body Temperatures:

Mean skin temperature was calculated from the eight skin sites as described in the "methods" section. There was a significant difference between the cooling conditions, where the vest mean skin temperature was lower than the other conditions. The chest and back temperatures during the vest tests were lower (mean Tchest: no cool 37.24, vest 31.35, water bath 37.29, and AVA 37.09. Mean Tback: no cool 37.56, vest 30.42, water bath 37.58 and AVA 37.77).

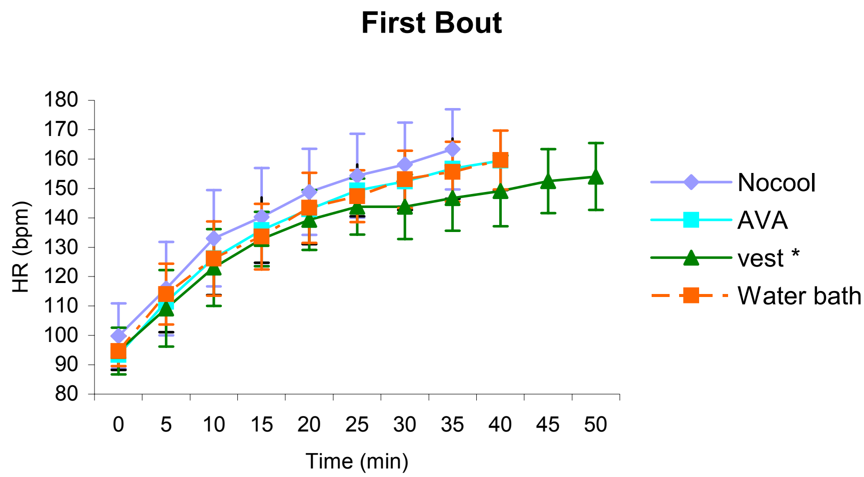


Mean body temperature, calculated as (0.8 x Tcore) + (0.2 x Tsk), also reflected the cooler chest and back temperatures in the vest compared to the other cooling conditions.

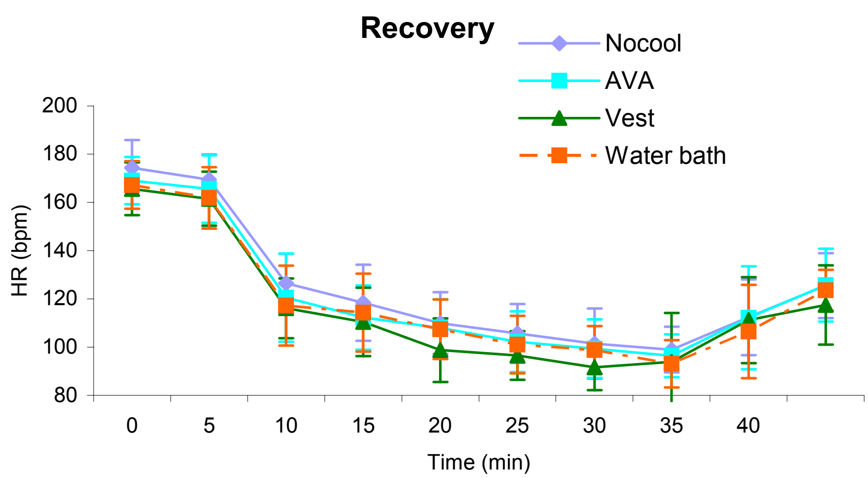


Heart Rates

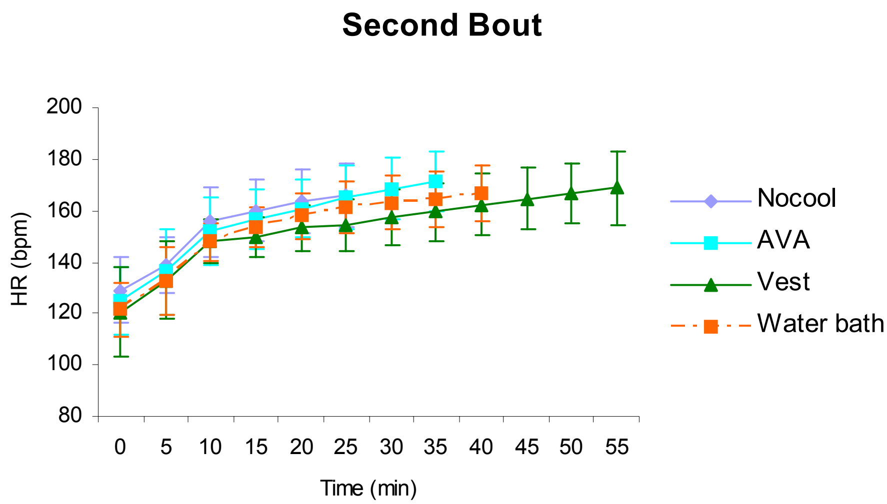
The absolute HR values were compared for only those time intervals where all 10 subjects were able to complete the exercise: first 30 minutes during bout 1 and first 25 minutes during bout 2 using a repeated measures ANOVA. During the first exercise bout there was a significant interaction effect (condition x time); the rise in HR was lower during the vest condition compared to the other test conditions. The HR during water bath and AVA tests were similar to no-cool.



No significant differences between conditions occurred in the HR during recovery.



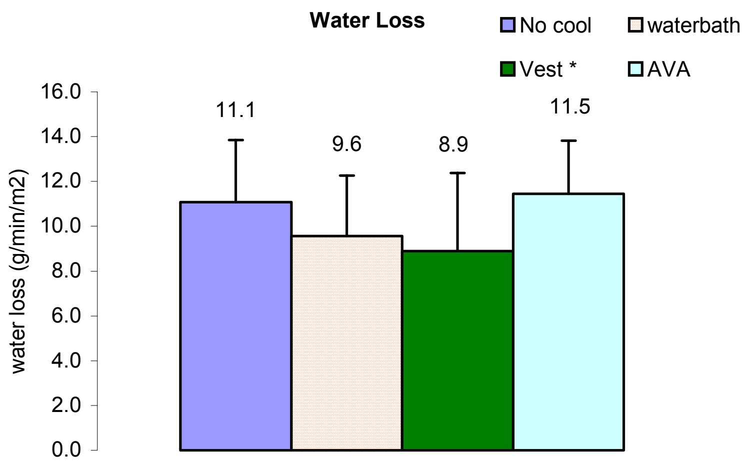
During the second exercise bout no significant differences occurred among the cooling conditions.



Delta HR values (between time 0 and 30 minutes during the first bout and 25 minutes during the second bout) were then calculated for the four cooling conditions. During the first bout, the delta HR was significantly less during the vest condition (52 ±15 bpm) compared to the no-cool condition (64 ± 10 bpm). No significant differences were seen from no-cool for the delta HR during water bath (63 ± 11 bpm) and RTX (63 ± 10 bpm) tests. During the second exercise bout the only significant difference between cooling conditions was between the vest (58 ± 12 bpm) and the RTX (72 ± 14 bpm) tests. The average delta HR during the no-cool test and water bath tests were 66 ± 11 and 67 ± 8 bpm, respectively.

Sweat loss

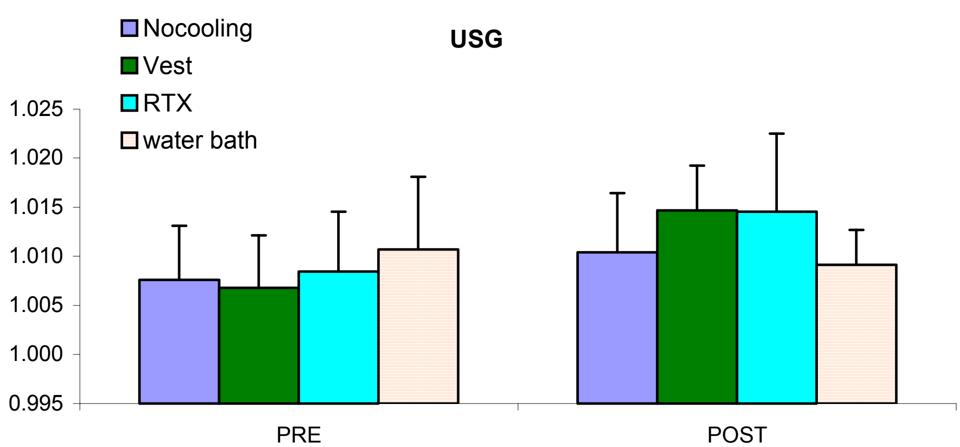
Each subject was asked to drink 15 mL/kg body weight of bottled water during the recovery period, but in a couple cases, the subject could not complete the entire volume. Nevertheless, the average water ingestion during the four HST were similar: no cool 1.11 ± 0.3 L; vest 1.24 ± 0.3 L; water bath 1.20 ± 0.4 L; and AVA 1.25 ± 0.2 L. At the end of the second exercise bout, all subjects had lost weight compared to their pre-exercise value. The following figure shows the rate of water loss during the HST. The change in nude body weight was corrected for fluid intake and urine loss during the tests.

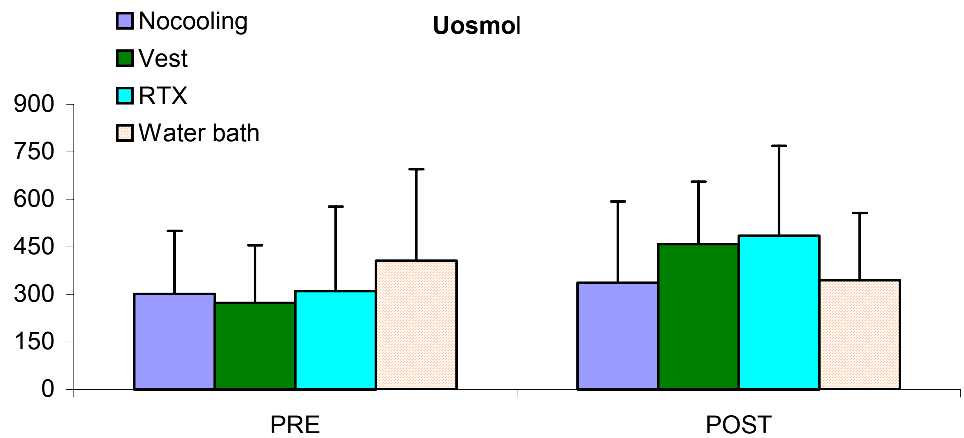


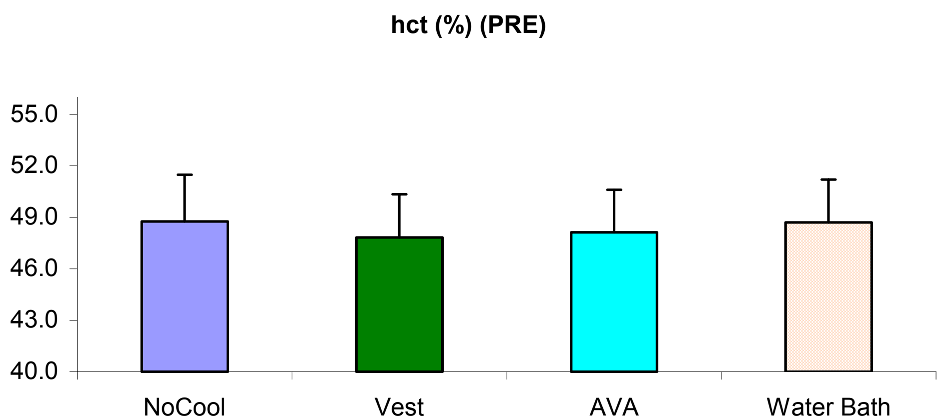
There was a significant difference between the cooling conditions. The rate of water loss during the vest condition was less than no-cool. The rate of water loss during the water bath and AVA tests were not significantly different from no-cool.

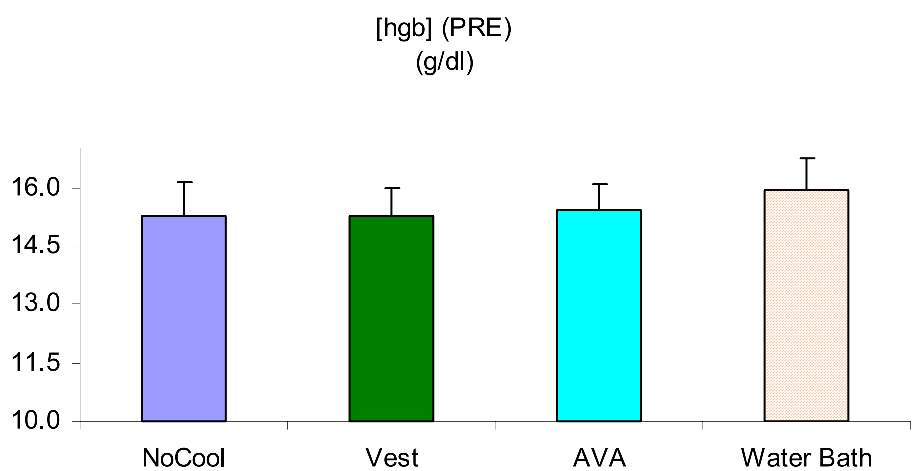
Biochemical Data

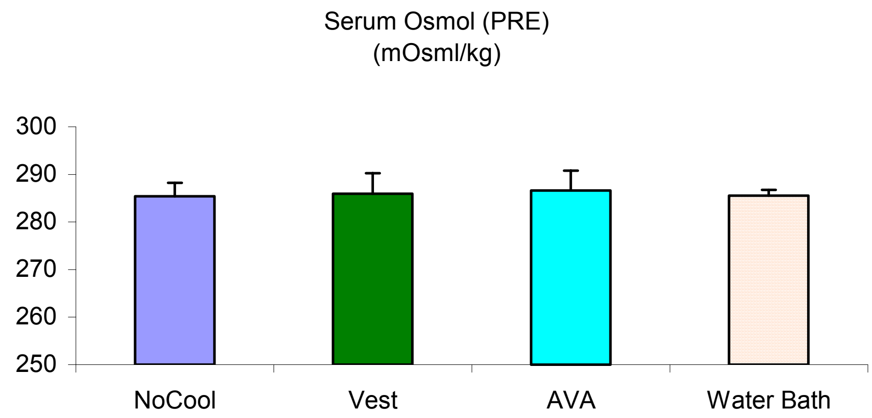
Hydration status for each subject was assessed before each HST by measuring urine specific gravity (USG) and osmolality. Values greater than 1.030 g/dL or 600 mosm/kg were considered signs of dehydration and subjects were required to drink water and rest before starting the baseline period. A venous blood sample was then obtained immediately before each subject began walking during each HST. The hydration status can be verified at this time by comparing pre-test serum osmolality values; where a value > 290 mOsm/kg would be considered dehydrated. The pre-HST urine and serum biochemical data are shown below.




Uosmol
Nocooling
Vest
RTX
Water bath
900
750
600
450
300
150
0
PRE
POST

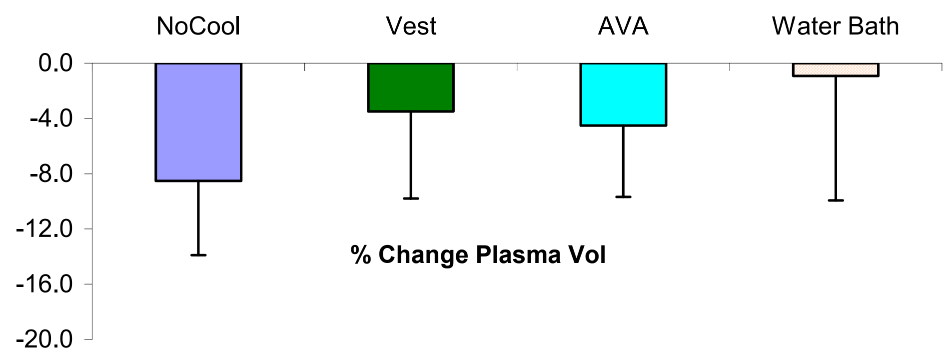

hct (%) (PRE)
55.0
52.0
49.0
46.0
43.0
40.0
NoCool
Vest
AVA
Water Bath


[hgb] (PRE)
(g/dl)
16.0
14.5
13.0
11.5
10.0
NoCool
Vest
AVA
Water Bath



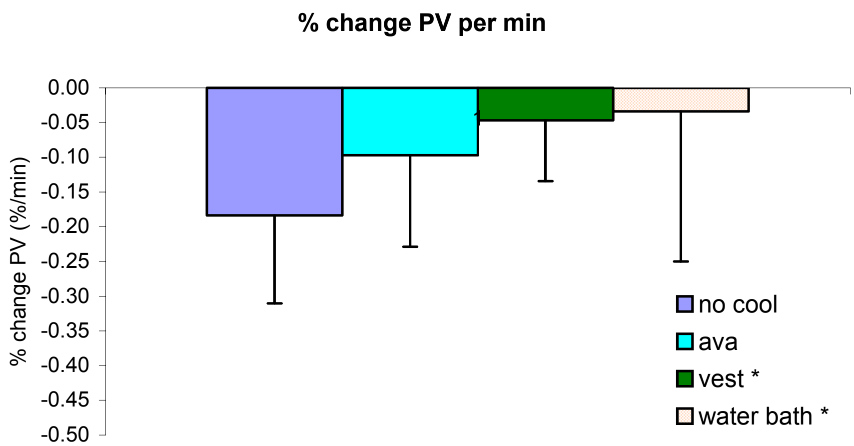
From the pre-HST urine data, the subjects during water bath tests may have arrived in a slightly less hydrated condition. However, from the pre-HST blood data, by the start of the HST the subjects in each group were in a similar state of hydration.

Blood samples also were obtained immediately upon attaining the termination criteria during the first heat stress bout to assess the rate of dehydration during each cooling condition. This sample was drawn while the subject stood still on the treadmill and before drinking. From hematocrit and hemoglobin data, the relative change in plasma volume between the beginning and end of each HST was calculated (Dill and Costill 74).



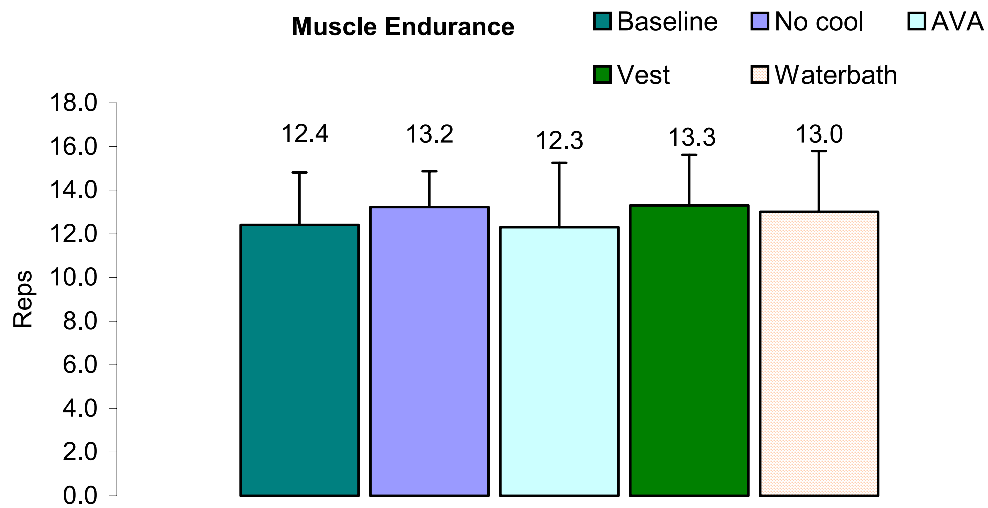
During each HST, the subjects hemoconcentrated and lost plasma volume. The only significant difference was there was a smaller relative change in PV in the water bath compared to the no-cool condition. The changes in plasma volume are not an index of the **rate** of dehydration however, as the exercise durations were not equal.

When the % change in plasma volume was corrected for the differing exercise bout times, the rate of plasma volume loss between conditions was significant; the rate of loss was smaller compared to no-cool in the vest and water bath conditions and similar to no-cool in the RTX condition.



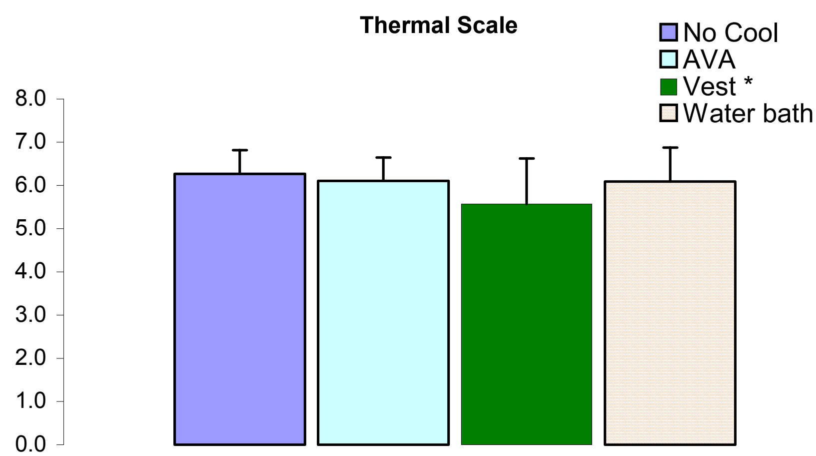
Muscle Endurance

Muscle endurance was measured near the end of the recovery period by having each subject perform as many supine bench press repetitions as possible in time with a metronome. Failure to complete a lift in the correct tempo would indicate test termination. No significant difference from the baseline, themoneutral condition occurred during any of the HST.



Thermal Sensation and Comfort Scales

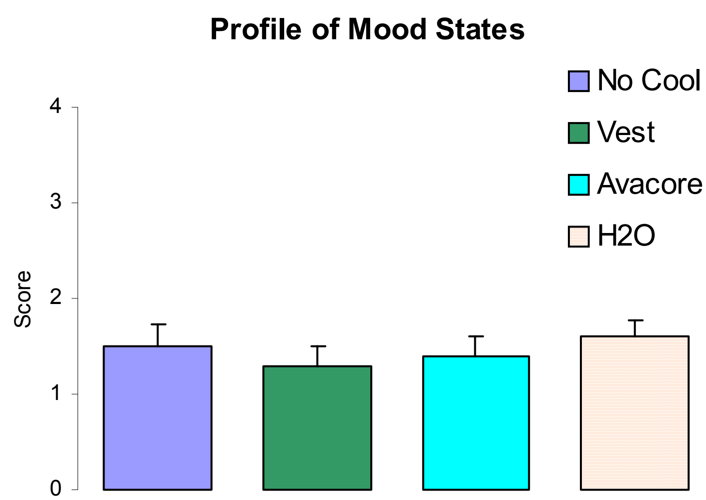
Subjects were asked to rate their thermal sensation at 30 min intervals during each HST. Ratings were from 1 to 9; where 1 was very cold, 4 was thermoneutral, and 9 was unbearably hot. The average rating during a HST, not including the first 15 min, was determined as an overall rating of thermal discomfort. The mean thermal comfort during vest tests was significantly lower than no-cool. Water bath and AVA test thermal ratings were similar to no-cool.

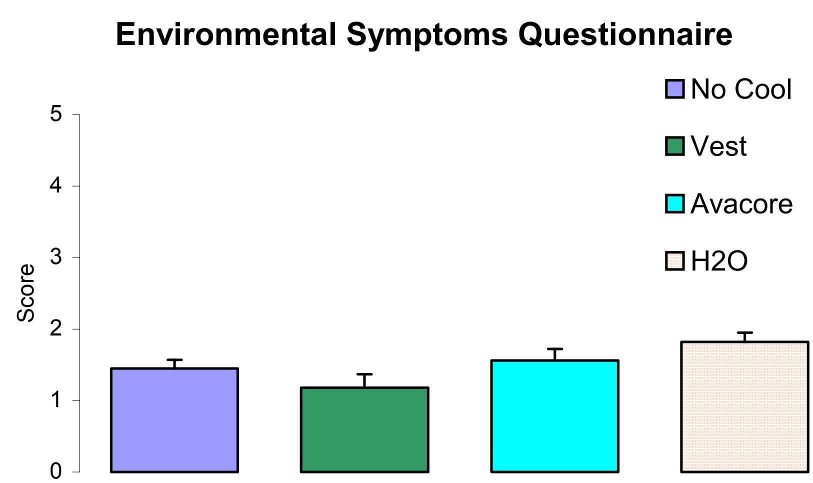


An overall comfort score also was obtained at 30 min intervals during each HST. Ratings extended from 1 to 5, where 1 was comfortable, 3 was uncomfortable, and 5 was intolerable. There were no significant differences in comfort scores between the HST conditions.

Physical and Emotional Symptoms (ESQ and POMS)

At the end of each heat stress condition, participants were asked to complete two questionnaires concerning physical and emotional symptoms, the Environmental Symptoms Questionnaire (ESQ) and the Profile of Mood States (POMS), respectively. The ESQ is comprised of physical symptoms such as lightheadedness, dizziness, and cramps. Ratings were from 0 to 5; where 0 indicated the participant had not experience that symptom, "not at all," and 5 indicated the symptom was "extreme." No significant differences were found among the heat stress conditions on the Environmental Symptoms Questionnaire (ESQ) total scores. Overall, participants indicated relatively little physical distress during heat stress testing.



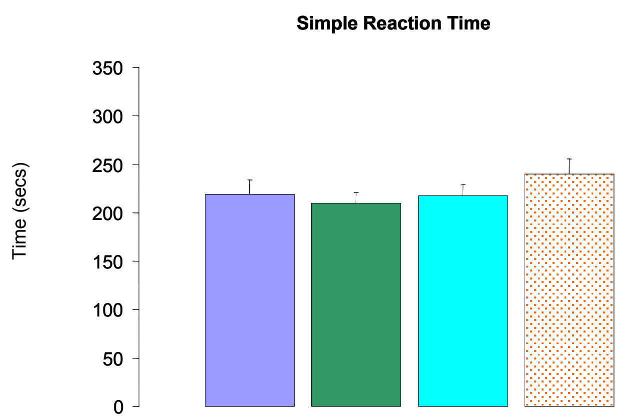


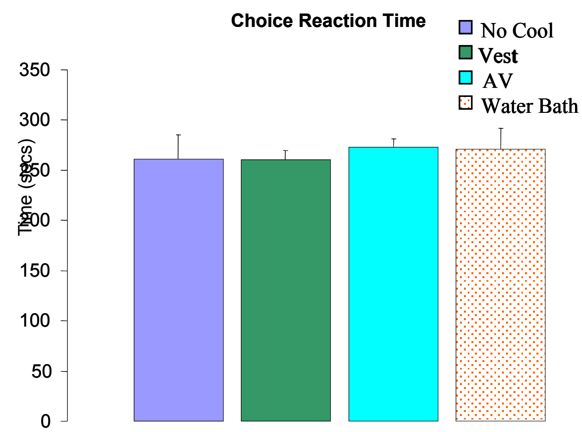
Participants also completed the Profile of Mood States (POMS) at the end of each heat stress condition. The POMS is comprised of questions concerning current emotional symptoms experienced. Ratings are listed from 0 to 4; where 0 indicates the participant has not experienced that emotion, "strongly disagree," and 4 indicates the participant has strongly experienced that emotion, "strongly agree." No significant differences among the heat stress conditions were found for the POMS total scores. The POMS also provides six subscales of specific emotions: depression, vigor, anger, tensions, confusion, and fatigue. No significant differences were found for any of these subscales across the four heat stress conditions. Similar to the ESQ results, participants appeared to not experience strong negative emotions following heat stress testing.

Cognitive Test Results

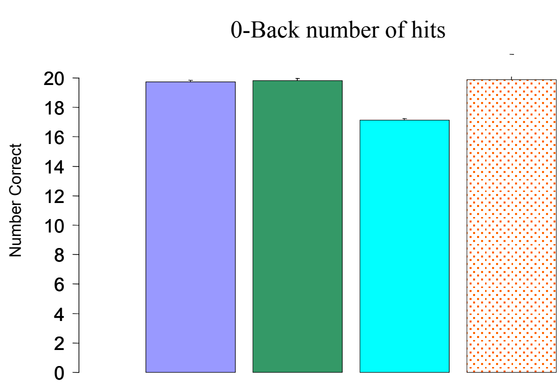
Cognitive testing was administered in two batteries at two different time points during heat stress testing. Cognitive tests A (CTA) consisted of computerized tests during the heat stress bout 1 while participants were engaged in treadmill exercise. Some participants also received CTA during bout 2. Cognitive tests B (CTB) consisted of standardized neuropsychological tests administered 10 minutes into the rest and rehydration period following bout 1.

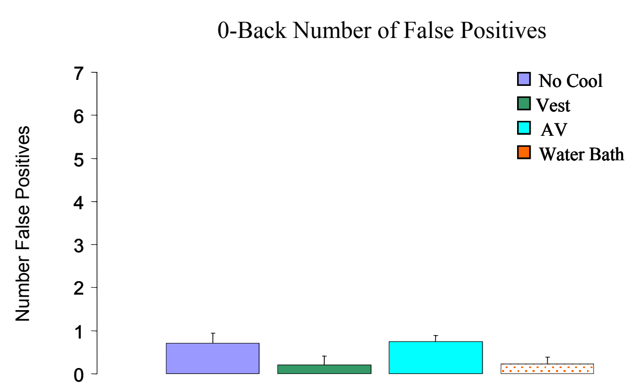
CTA consisted of three computerized tests tapping into sustained attention and working memory domains: simple reaction time, choice reaction time, and n-back tasks. Working memory is an executive functioning domain that requires an individual to hold and manipulate information in the temporary memory store. The simple reaction time task consisted pressing a button following the onset of an up arrow stimulus on the computer screen (figure below, left panel). Consistent with the hypotheses, no differences were found among the four heat stress conditions on this low cognitive demand attention task. The choice reaction time task consisted of a directed arrow stimulus (left, up, right arrows) and an appropriate button press response. Similar to the simple reaction time task, no differences were found among the heat stress conditions on this attention task (figure below, right panel). Participants appeared to maintain attention during the exercise portion of the heat stress test.



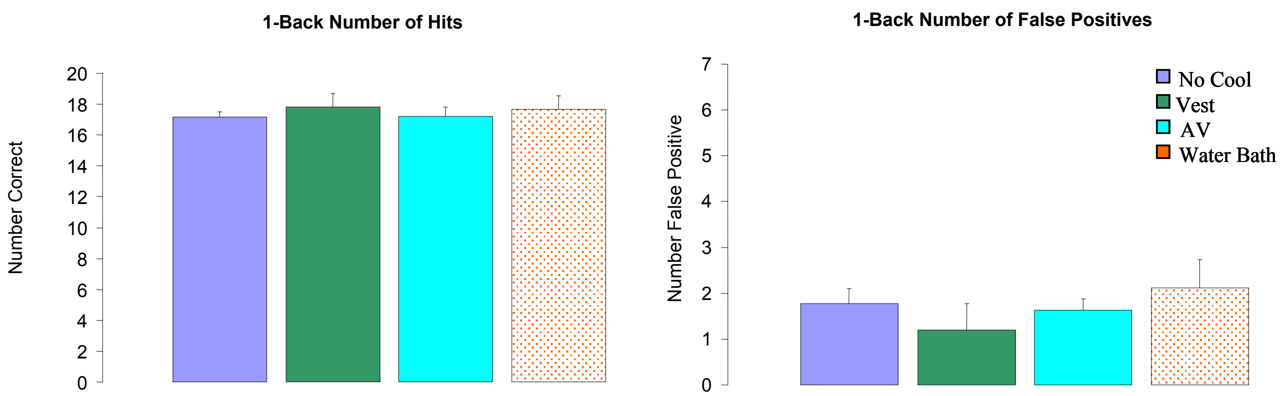


A more challenging computerized task was also included in the CTA battery, the n-back task with three conditions for different levels of complexity. The first subtest, the 0-back task, was a sustained attention task with a number appearing on the computer screen every second. The task consisted of a button press only to a ‘0’ in the sequence on the screen. The figure below presents the number correct, ‘hits’ (out of 20 possible; left panel) and the number of false positive (pressing to a non-target stimulus; right panel) for the four heat stress conditions on the 0-back task. No significant differences were found for either the number of hits or false positives during the 0-back task for the four heat stress conditions. In this easiest version of the n-back task tapping into sustained attention, participants performed close to perfect in hits and averaged less than one false positive per test. These results suggest that participants were able to maintain attention during the three-minute task with a constant stream of stimuli.

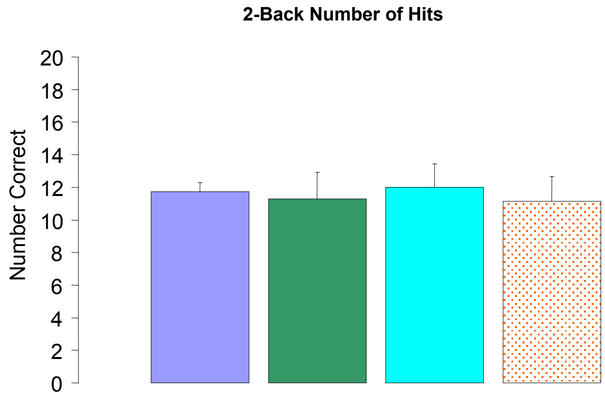


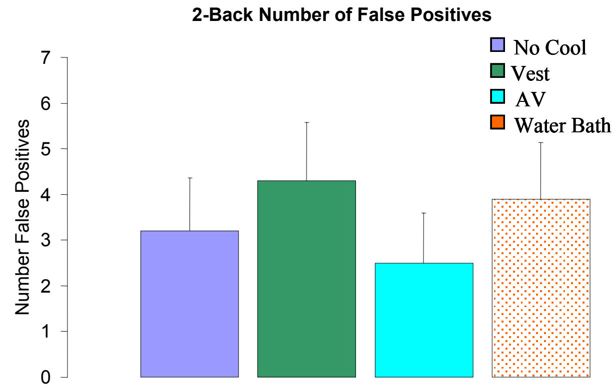


The second trial of the n-back task added a low level working memory component. The 1-back task also consisted of a stream of numbers at one-second intervals, but this task required participants to respond by button press to a number when it was the same as the previously presented number. The figure below presents the number of hits (left panel) and false positives (right panel) for the 1-back task for the four heat stress conditions. No significant differences were found for either the number of hits or false positives among the heat stress conditions. Participants performed well during this task correctly responding to 85% of the target stimuli with 1.7 false positive responding on average, although this is slightly lower in hits and higher in false positives compared to the 0-back task.



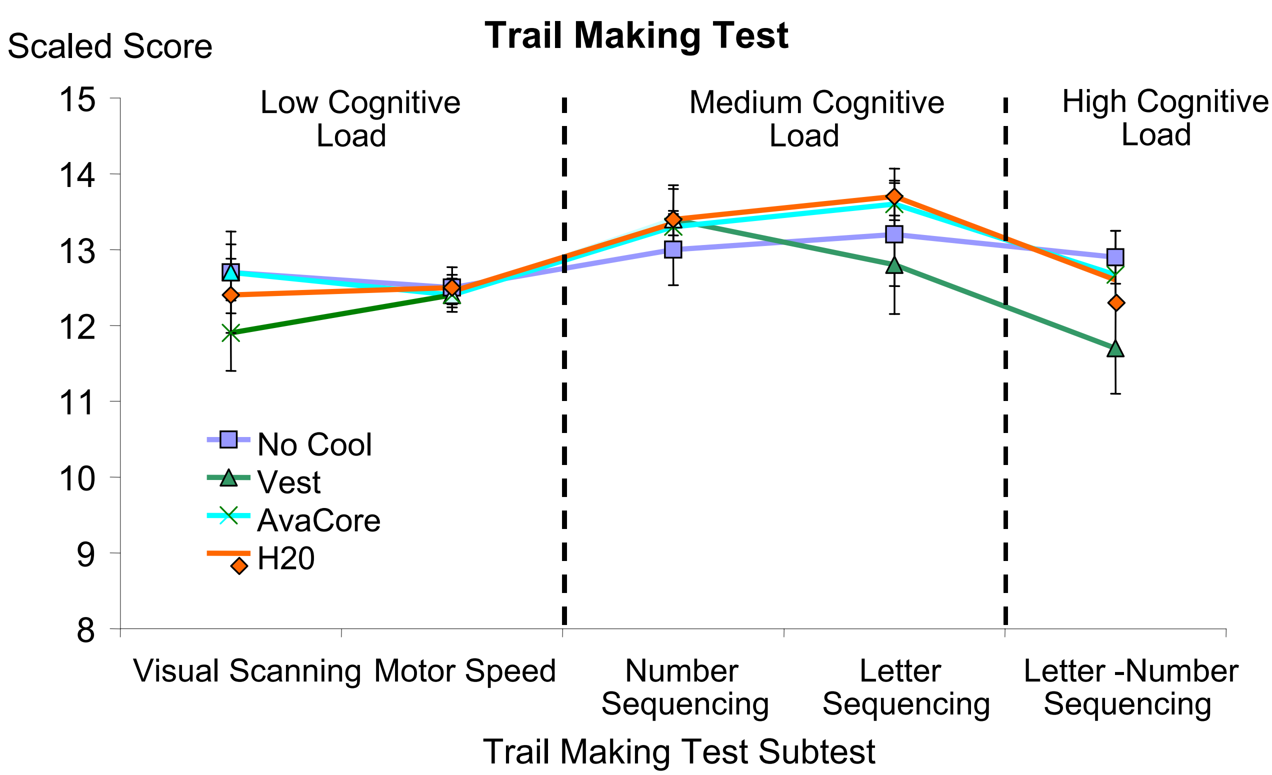
The third trial of the n-back task tapped into a higher level working memory load. The 2-back task required participants to respond by button press to a number when it was the same as a number that was presented two numbers previous. The figure below presents the number of hits (left panel) and false positives (right panel) for the 2-back task for the four heat stress conditions. No significant differences were found for either the number of hits or false positives among the heat stress conditions. Participants performed significantly lower during this task correctly responding to 55% of the target stimuli with a false positive rate of 3.5 on average. Participants were not able to perform adequately when cognitive demands were high in the heat stress environment.



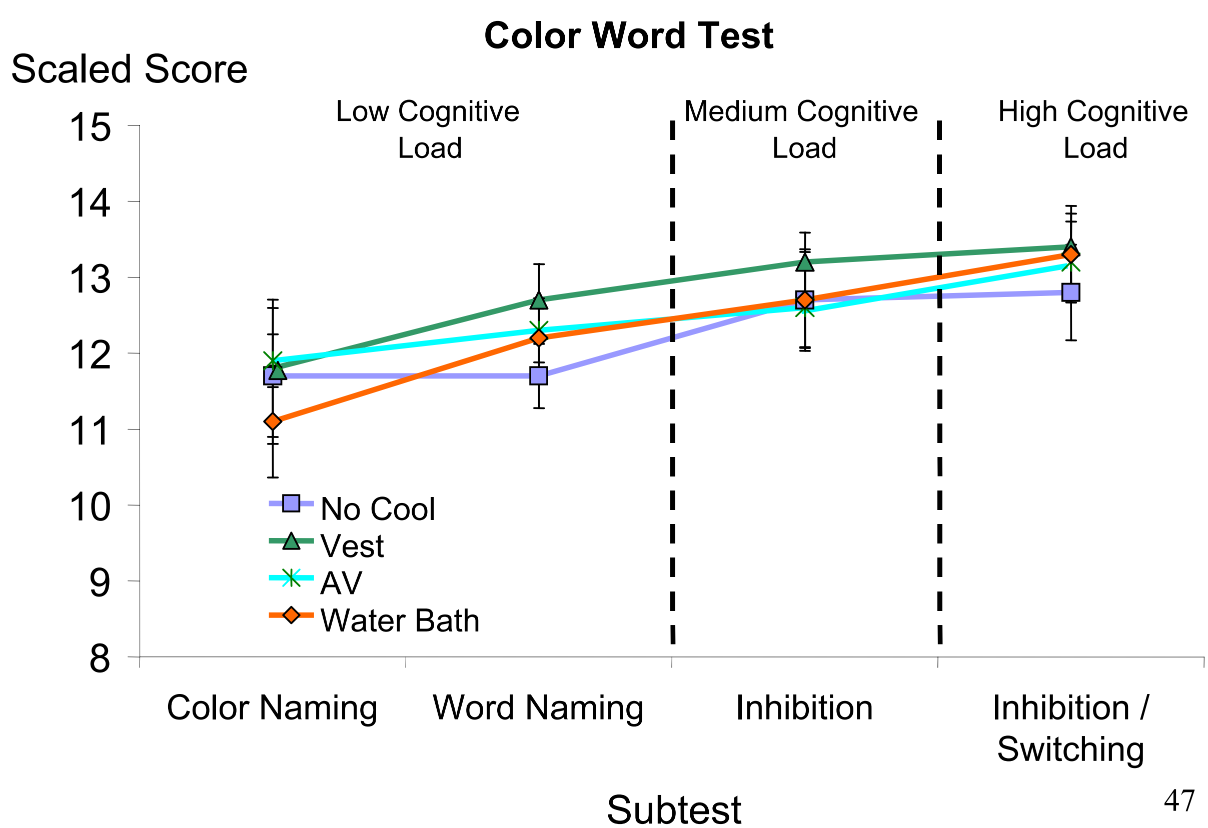


The CTB was administered approximately 10 minutes into the rest and rehydration period following exercise bout 1 while the participants remained in the heated environment. Three standardized neuropsychological tests tapping into executive functioning were completed in the CTB: the Trail Making Test (Delis-Kaplin Executive Functioning version, D-KEFS), the Color Word Test (D-KEFS version), and the Letter Number Sequencing test form the Wechsler Adult Intelligence Scale – 3rd edition (WAIS-III).

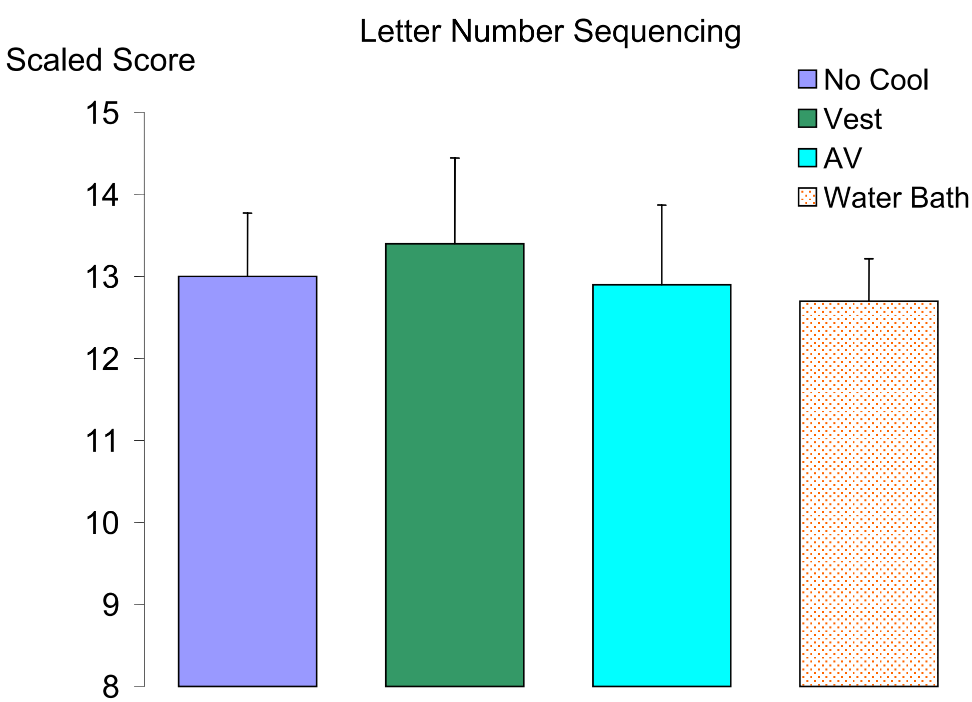
The D-KEFS version of the Trail Making Test (TMT) consists of five subtests isolating different domains used in the original TMT, an executive functioning test. The following figure presents results for the five TMT subtests for each of the heat stress conditions. The time to complete each subtest is recorded and then this time is translated into an age-corrected scaled score for each participant (with a mean of 10 and standard deviation of 3). Two of the subtests, Visual Scanning and Motor Speed, require relatively few cognitive resources to carry out the task and are labeled as “Low Cognitive Load” tests in the figure below. The TMT Visual Scanning subtest requires that participants identify and cross out a target number (i.e., ‘3’) in a large page of numbers and taps into a visual search and discrimination cognitive ability. The TMT Motor Sequencing subtest requires participants to draw a line following a printed dotted path from one target circle to another and taps into a motor sequencing cognitive ability. The next two tasks, TMT Number Sequencing and TMT Letter Sequencing, require more cognitive resources and are labeled as “Medium Cognitive Load” in the graph below. The TMT Number Sequencing subtest requires participants to draw a line as fast as they can between numbered targets in order, while the TMT Letter Sequencing task has letters as targeted stimuli that are to be connected in alphabetical order. The most difficult subtest is the TMT Letter-Number Sequencing task, labeled as "High Cognitive Load" in the graph below. This task requires participants to connect both numbered and lettered targets as fast as they can in a specific sequence alternating between one letter and one number (i.e., draw from 'A' to '1' then to 'B' to '2', etc.). No significant differences were found among the four heat stress conditions for any of the TMT subtests. Also, no significant differences were found between the subtests. Participants appeared to be able to perform above average (scaled scores ranging from 11.8 to 13.5) for all cognitive load levels on the TMT. However, practice effects likely contributed to these above average scores as the participants had completed the CTA at baseline and during the heat acclimation period.



The D-KEFS version of the Color Word test (CW) consists of four subtests isolating different cognitive domains used in the original Stroop Color Word test, an executive functioning test. The following figure presents results for the four CW subtests for each of the heat stress conditions. The time to complete each subtest is recorded and then this time is translated into an age-corrected scaled score for each participant. Two of the subtests, Color Naming and Word Naming, require relatively few cognitive resources to carry out the task and are labeled as "Low Cognitive Load" tests in the figure below. The CW Color Naming subtest requires participants to name blocks of colors as quickly as they can while the CW Word Naming subtest requires participants to name specific color names (e.g., "BLUE") as quickly as they can. The CW Inhibition task, similar to the original Stroop Color Word task, requires participants to name color words (e.g., "RED") as quickly as they can while ignoring the color of ink the word is printed in (e.g., "**RED**"). This task is more difficult than color naming or reading words; thus, CW Inhibition is labeled "Medium Cognitive Load" in the graph below. The D-KEFS version also adds a more demanding task, where participants are required to either name the color or read the word depending on a visual cue around the word (i.e., boxed). This subtest is labeled as "High Cognitive Load" in the graph below. No significant differences were found among the four heat stress conditions on any of the four CW subtests. Also, no significant differences were found between the subtests. Similar to the TMT, participants appeared to perform above average (scaled scores ranging from 11 to 13) for all cognitive loads on the CW. Again, practice effects likely contributed to these above average performances.

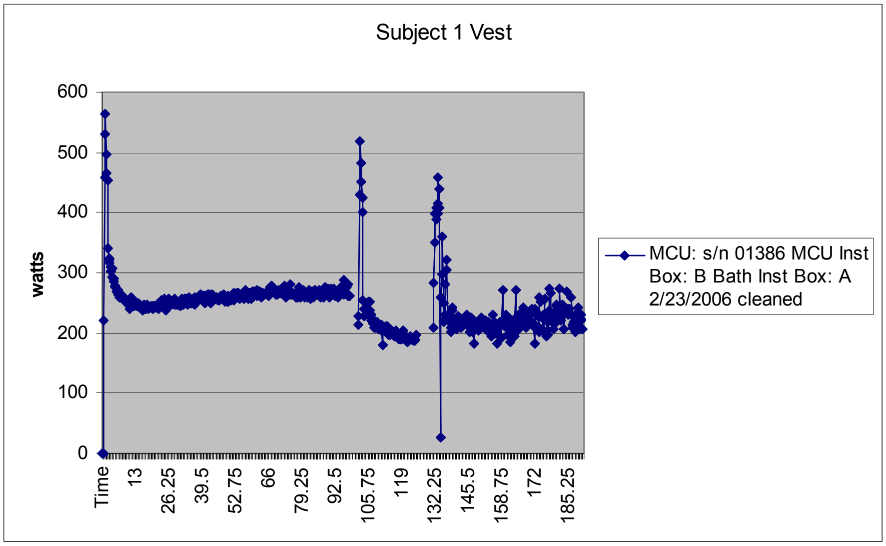


The third test of the CTB was the WAIS-III Letter-Number Sequencing test (LNS) of working memory. The following figure presents the LNS results for each of the heat stress conditions. The total point score on the CW is translated to an age-corrected scaled score as with the other neuropsychological tests. Participants are required to repeat a string of combined letters and numbers. However, the string is to be repeated back with the letters in alphabetical order first and then the numbers in order. For example, if the string stated was "L 4 J 2 C," the correct answer would be "C J L" and then "2 4." Results of this test are presented in the following graph. No significant differences were found among the four heat stress conditions on the Letter-Number Sequencing test. Participants performed above average with averaged scaled scores ranging from 12.7 to 13.4, although practice effects likely contributed to these performances.



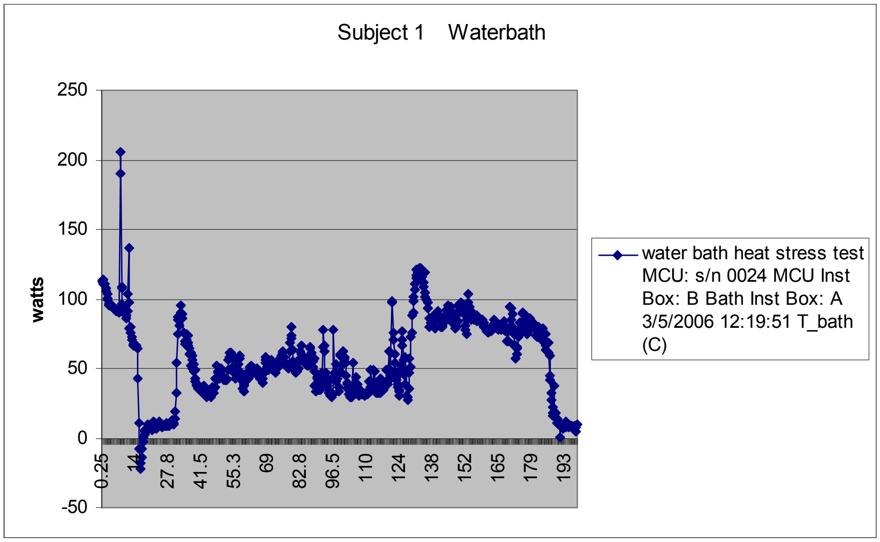
Heat Extraction

The watts of heat extracted during vest and water bath tests was quantified. Data from a typical vest test are shown below.

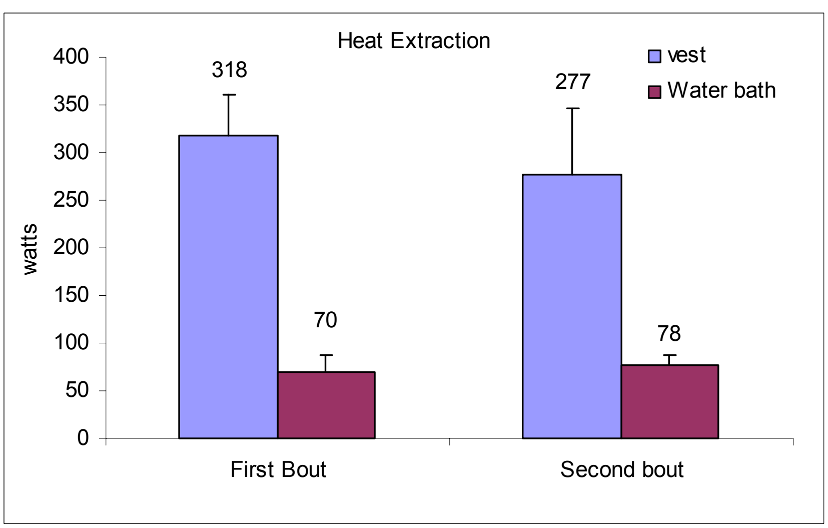


Vest cooling was turned on as the subject began walking in the first exercise bout. Heat extraction increased immediately as the chilled water perfused the tubing next to the subject's torso. Heat extraction immediately fell to a value around 250 watts and then gradually rose again as the subject warmed up with the exercise. The next big blip in the record represents when the cooling vest was disconnected from the cooling unit after about 10 minutes into the recovery period. The vest was disconnected so that the subject could move off the treadmill, weigh, and sit in a chair to begin cognitive tests. The disconnection lasted only about 1 minute and cooling was continued during the rehydration and cognitive testing which lasted approximately 20 minutes. At the end of cognitive testing, the vest was again disconnected (the next big blip in the record) so the subject could move to the bench press machine and perform the muscle endurance test. He then immediately stood and was weighed again, then returned to the treadmill to begin the second exercise bout. The cooling was again turned on as the second exercise bout began.

This record is typical of a vest test record. During the first bout the data are very clean but during the second bout the flow rate was more erratic and the heat extraction record was noisier. It is unclear why this happened during most tests but may have been due to introduction of bubbles into the system when the vest was disconnected and reconnected. Typically heat extraction was greater during the first exercise bout than the second bout. At the end of the test the subject left the chamber and removed the vest.

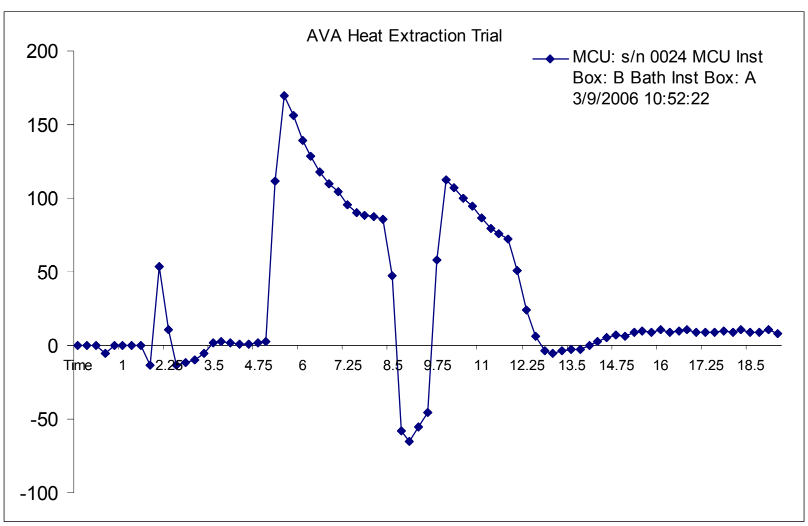


This next record is a typical water bath test also from subject #1. Again, cooling was turned on as the subject began walking for the first exercise bout. A large overshoot in cooling occurred during the first couple minutes. For this subject there was a false start and then a restart with a second, less pronounced overshoot. Water bath tests typically had more noise than the first vest test, maybe due to more bubbles in the system since we didn't "purge the system" as we did before vest tests. The cooling during the second bout usually was greater than during the first exercise bout, possibly due to the higher body temperatures. The cooling was disconnected during the same recovery intervals for all cooling conditions: including AVA tests. At the end of the test, the subject left the chamber and the water bath cooling system continued to run in the heat chamber for another 15-20 minutes to quantify the background heat extraction.



The heat extraction for all 10 subjects was averaged for the vest and water bath tests (see figure). Heat extraction during vest tests averaged around 300 watts and during water bath tests around 74 watts. The background heat extraction for the water bath tests was 12.6±3.6 watts before each test and 12.3±3.5 watts after each test.

We tried to develop a way to measure the background heat extraction for the vest. In one case we hung the vest from the treadmill railing and ran the cooling for approximately 45 minutes after one of the HST. Heat extraction under this condition without the subject wearing the vest settled at approximately 220 watts. However, this is not a good indication of what heat extraction would have been with the outer surface area of the vest covered with the body armor and the inner surface in contact with the subject. On another occasion we wrapped the vest around an exercise ball and applied the body armor around the outer surface of the vest. The heat extraction was approximately 100 watts. Again this is not a good simulation of what would happen with the vest worn by a subject. To estimate background heat extraction for the vest or any cooling system, USARIEM usually performs heated manikin tests to simulate the presence of a warm person inside the vest. Heat extraction was quantified for this exact vest system but with different clothing and without body armor over a range of ambient conditions (Army report 02). Extrapolating from this report to our ambient conditions, we would estimate that the background heat loss during our HST was around 60 watts. Thus the net heat extraction during vest tests would be approximately 300-60 = 240 watts and during the water bath tests was approximately 74 – 12 = 62 watts.

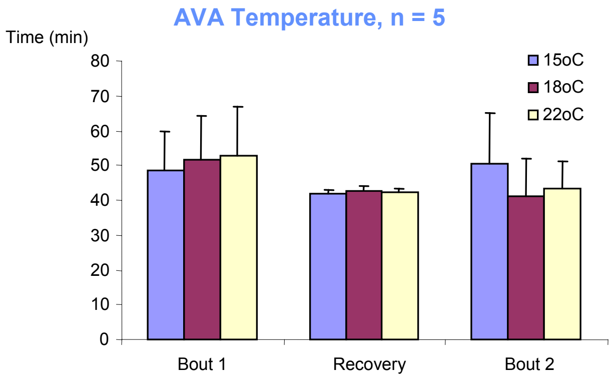


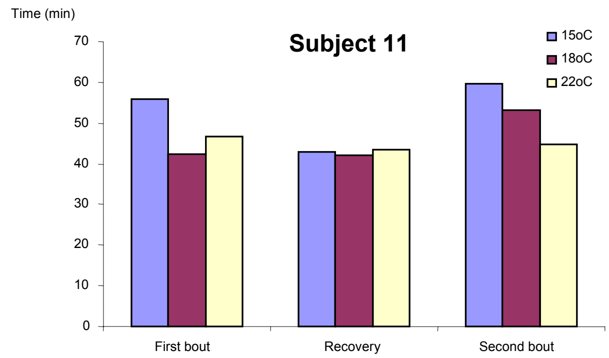
On one occasion we attempted to use the water bath perfusion system and the USARIEM measurement system to quantify the heat extraction of the RTX. The Thermocube was used to perfuse the RTX, by-passing the pulsatile pump in the RTX. The RTX was attached to subject #11 as he sat quietly in the heat chamber under similar conditions as a HST. Heat extraction immediately increased when cooling was turned on and then came down to around

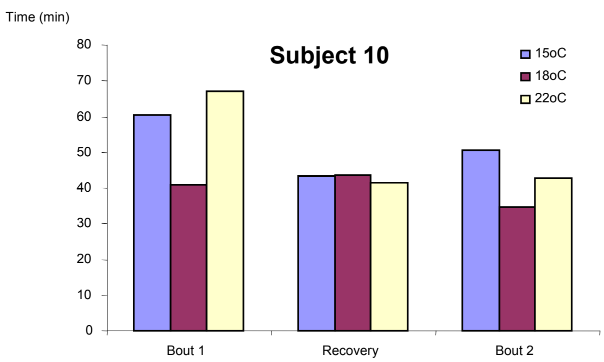
80 watts. We briefly removed his hand and then turned on the cooling again and heat extraction increased then returned to around 75 watts. He removed his hand and obtained a reading for the background heat extraction which leveled off around 10 watts. The next time we tried to use the RTX this way during a HST, the RTX began leaking. We returned the RTX to the manufacturer who repaired it and sent it back to us. We attempted again to use the RTX connected to the thermocube for a HST and again it began leaking. We concluded that the perfusion pressure was too high—the RTX was not designed to be used with this type of perfusion system. Therefore we were unable to quantify heat extraction during RTX tests.

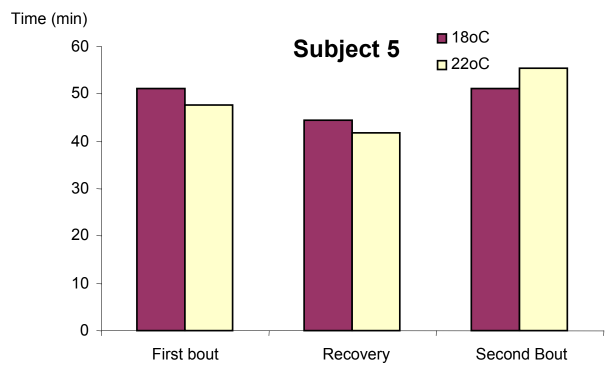
Effect of RTX temperature

At the beginning of this study we were recommended by the manufacturers to use an RTX temperature of 15^{o}C. After negative findings from the first three subjects, we suspected that the hand temperature was too cold, causing the hand to vasoconstrict and prevent optimal cooling. Therefore, we raised the perfusion temperature for both RTX and water bath tests on the next three subjects to 18^{o}C. These subjects also had negative results so we tested the final four subjects with a perfusion temperature of 22^{o}C. In addition, three subjects performed duplicate RTX tests at more than one hand temperature. Thus, we have pilot data to compare the effect of perfusion temperature on HST response. These data are preliminary as there are not enough data points to perform statistical comparisons or to draw conclusions.

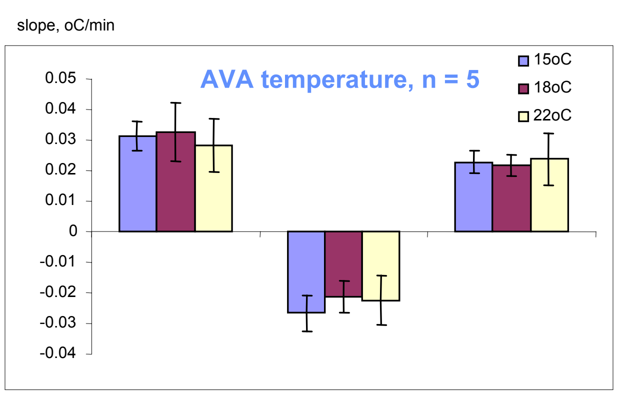


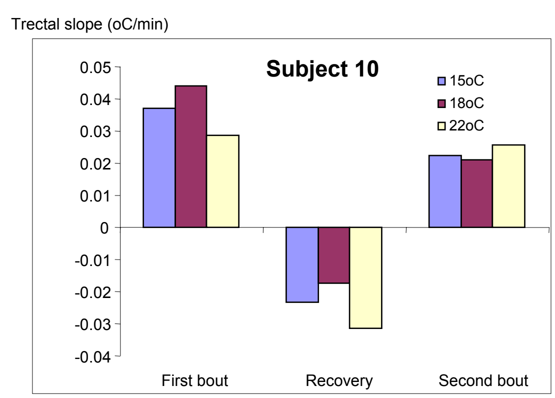


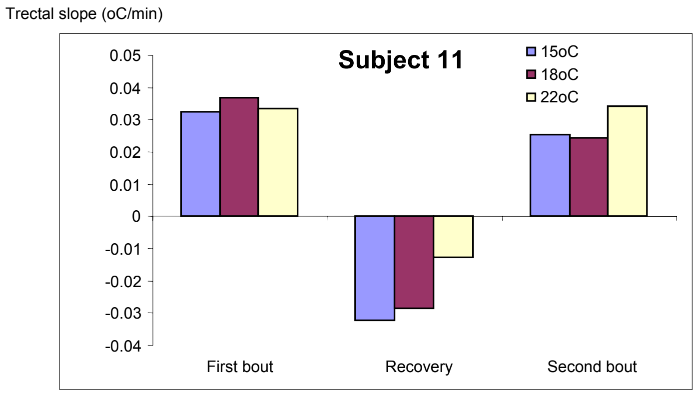


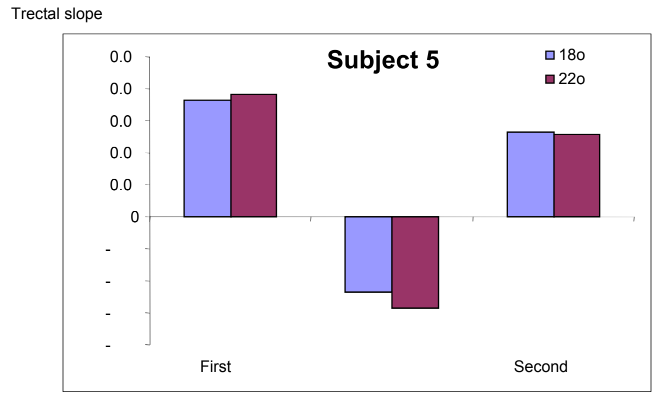


There was no consist trend in the HST data to suggest an effect of RTX temperature. From the mean data for 5 subjects, during the first exercise bout it appeared that the warmer the hand temp, the longer the duration. However this pattern was not maintained during the second exercise bout where the longest mean time occurred for the coldest temperature. No consist pattern was seen among the individual subject results.









Again, comparing the slope of the rectal temperature response for the HST tests at different hand temperatures, no consistent trend is evident to suggest that one hand temperature reduced the rise of core temperature more effectively than another.

Heat Balance Calculations

The table below represents the results for each factor in the heat balance equation determined using the data from this study entered into a community available spreadsheet: developed by Kerry Atkins and Martin Thomson and available on the sportsci.org. website. Some of the formulas in this spreadsheet were modified to represent the specific environmental and clothing conditions of this study. For example, a Clo factor for the summer uniform and body armor of 1.184 (provided by USARIEM) was used for all calculations. Heat balance was calculated for the first exercise bout only and does not include data from recovery or the second exercise bout. *(It would have been complicated to measure metabolic heat production during the recovery period in this protocol, so we limited the heat balance calculations to the first exercise bout only.)*

		M	H	S	K	R	C	Esk
		(W.m-2)	(W.m-2)	(W.m-2)	(W.m-2)	(W.m-2)	(W.m-2)	(W.m-2)
No Cool	*mean*	347.64	281.74	53.84	-132.58	-0.09	-105.40	111.36
	std	63.44	60.07	11.60	30.43	0.02	30.43	98.86
Vest	*mean*	350.11	284.37	*19.95	*-97.00	-0.11	*-130.28	100.15
	std	80.67	77.02	9.42	12.56	0.01	12.88	109.24

Water bath	*mean*	339.25	273.33	51.30	-134.16	-0.09	-99.04	68.73
	std	89.46	85.01	16.59	13.51	0.01	7.82	90.81
AVA	*mean*	344.09	278.29	55.70	-142.45	-0.08	-94.26	78.71
	std	68.44	64.22	13.42	13.49	0.01	7.76	119.94

In the table above, M, represents the metabolic free energy production and was calculated separately and entered into the spreadsheet using the following equation (Pandolf 77). This formula takes into account the weight in the backpack as well as the subject's weight, and the treadmill speed and grade.

$$M = 1.5w + 2.0(w+l)(l/w)^2 + n(w+l)[1.5v^2 + 0.35vg]$$

M = the metabolic rate (watts)

w = subject weight (kg)

l = load carried (kg)

v is walking speed (m/s)

g is grade (percentage)

n is the terrain factor (1 for treadmill walking)

M represents the total energy expenditure for each subject, including energy expended as heat (H) and for performing work (for example for the no cool condition, M-H=work, 348-282=66 w/m^2). The average body surface area for these subjects was 1.91m^2, therefore the average work performed was 126 watts. Since the treadmill speed and grade and backpack weight were the same for each HST, M did not differ significantly among the 4 conditions. The efficiency averaged 19% for no cool, RTX and AVA conditions and 20% for the vest condition. Therefore the heat production (H) also was similar for the 4 conditions.

S represents heat storage during each HST and this value is positive signifying that heat is being stored. Storage was significantly less during vest tests compared to no cool. S during RTX and water bath tests did not differ significantly from the no cool condition.

K represents conductive heat loss. In this spreadsheet it does not take into account the fact that during the cooling conditions, the surface of the skin is not in direct contact with the ambient air. For example during vest tests, the skin is in contact with the vest, not the surrounding air. During RTX and water bath tests, this calculation does not take into account that the hand skin is not in direct contact with the surrounding air, but rather is enclosed in the RTX or in contact with the water. Therefore, this calculation is not very meaningful or correct for these conditions. The negative value represents that heat is being gained from the environment to the surface of the skin. Significantly less heat is being gained during vest tests compared to no cool. No significant difference was measured between the water bath and RTX tests and no cool.

R represents the heat gained (since the value is negative) from the environment by radiation. This value was similar for the 4 cooling conditions. Heat was gained under our conditions similarly from the radiant heaters in the environmental chamber.

C represents the convective heat loss. Again this value is not correct or very meaningful in this study, since it represents the heat gained (again since the value is negative) from the environment to the surface of the skin not covered by the cooling systems. Most of the heat exchange in this study was provided by heat removal by the cooling systems. The results show that during the vest condition more heat would have been gained from the environment compared to the no cool condition. This result would obtained since the mean skin temperature during vest tests was lower than the other cooling conditions and so, a greater gradient from the ambient air to the skin surface would result in a theoretical greater heat gain. Again, this is not correct since the surface of the skin is not exposed to the ambient air.

Esk represents the total evaporative heat loss from the surface of the skin (heat transfer via skin diffusion and heat transfer via sweat evaporation). In this study it was calculated from the change in clothed body weight between the beginning and end of the first exercise bout and the ambient water vapor during the first bout. Total sweat loss would have been greater, as much sweat was trapped in the clothing. In our study it was unlikely that much sweat "dripped" on the ground, most would have been collected in the clothing.

Discussion

Major Findings

The purpose of this study was to evaluate the effectiveness of the RTX cooling system to slow the rise in body temperature and heart rate and extend work duration during exercise in a hot environment. The conditions chosen for this study represent severe conditions of internal (moderate exercise) and external (environmental) heat stress. In addition, the subjects wearing summer battle fatigues and body armor impeded heat loss, further challenging the capacity of the RTX to provide cooling. Under these thermal and exercise conditions, we found no improvement in physiological or psychological responses while subjects wore the RTX compared to a no-cooling condition. As a point of comparison, each subject also exercised while wearing a proven, operational cooling system: the "Air" Warrior cooling vest. The cooling vest extracted approximately 240 watts of body heat, an amount sufficient to slow the rise in core temperature and heart rate, reduce subjective ratings of thermal discomfort, and prolong endurance times. Immersing the hand in cold water failed to provide a significant benefit over the no-cool condition, removing only about 60 watts of body heat.

Fatigue during Exercise in a Hot Environment

The capacity for humans to perform even mild work is greatly influenced by the ambient conditions (Galloway 97). When the environmental and metabolic conditions exceed the capacity of the human body to dissipate heat, core temperature rises and endurance is negatively affected. Surprisingly we still don't understand exactly how core temperature affects fatigue, although this issue was recently reviewed by Cheung and Sleivert (04). Several authors suggest (Gonzalez-Alonso 99; Cheung 04; Nielsen 93) that heat-induced fatigue is linked to attaining a critical core temperature. Regardless of the starting core temperature or the rate of rise in core temperature, once this critical temperature (about 40^{o}C) is reached, the subject becomes fatigued and is unable to continue. One theory is that once brain temperature reaches this critical temperature, the central drive for exercise is reduced by a direct effect of temperature on motor control centers in the brain (Bruck 87; Nielsen 93). Thus, the subject stops working before serious cellular damage occurs (tissue damage begins at temperatures around 42^{o}C). Other theories speculate that fatigue is caused by effects from metabolic products produced by the exercising muscles, internal organs or central nervous system. The release of endotoxins or heat shock proteins, for example are thought to contribute to local or central fatigue (Hales 96). Peripheral theories of hyperthermic fatigue attribute fatigue to direct effects of hyperthermia on the contractile properties of the exercising muscle. Exceptions to the critical temperature rule include, fatigue in unfit or untrained subjects (Sawka 92), or conditions where heat loss from the skin is impeded and the thermal gradient from core to skin is reduced or reversed (Montain 94). Under such conditions, fatigue often occurs at a lower core temperature. For example, when subjects wear impermeable clothing fatigue and symptoms of heat exhaustion have been observed at core temperatures < 38^{o}C.

Heart rate increases proportionately with the rise in core temperature during exercise in the heat. Gonzalez-Alonzo et al (97) have shown that under conditions of similar skin blood flow, a 1^{o}C rise in esophageal temperature is accompanied by a 9±1 beat/min increase in heart rate and an 11±3 mL reduction in stroke volume. Initially, as core temperature rises heart rate increases, skin blood flow increases, and the ensuing redistribution of blood flow to the skin causes a fall in stroke volume. However, above a core temperature of approximately 38^{o}C, skin blood flow plateaus yet stroke volume continues to fall and heart rate increases in relation to the rise in core temperature. It has been proposed that this later rise in heart rate is due to thermal effects on the SA node or myocardium, to neurohumoral stimuli, to reduced cardiac filling time with increasing heart rate, or to other unknown factors (Gonzalez-Alonzo, 99).

Therefore, for trained and heat acclimated subjects, such as soldiers patrolling in Iraq in the summer, reducing the rate of rise in core temperature should extend the time to reach a critical core temperature, reduce cardiovascular and perceived strain, and extend work endurance.

Personal Cooling/Cooling Vest

Often in military operations a soldier must perform under very hot conditions where it is impractical to cool the environment surrounding him; for example in a helicopter, fighter, armored vehicle or while on ambulatory patrol. Personal cooling under these conditions should improve his effectiveness and reduce his risk of heat illness. Several approaches to personal cooling have been employed (Nunnelley 70). One effective approach has been to have a soldier wear a vest cooled with, ice, water or cool air. The US Army Natick Soldier Center has developed a cooling vest (the Air Warrior Microclimate Cooling Garment) that is being used by helicopter pilots and is currently being evaluated for deployment in armored vehicles (Edward Zambreski personnel communication). It consists of a vest (see picture in methods) with small diameter PVC tubing encapsulated between two layers of 100% cotton fabric. A chilled coolant (15^{o}C water in our study) is pumped through this tubing (at a rate of 0.4 to 0.7 L/min in our study) by a microclimate cooling unit (MCU). This "Air Warrior cooling vest" has been tested and certified to remove 180 watts of heat in a 125^{o}F, 14% RH environment (Army report 02). This is the cooling system we used as a "standard" benchmark to evaluate the effectiveness of the RTX device in the current study.

Our results support the effectiveness of the Air Warrior cooling vest to provide effective personal cooling under the conditions of our study. There was a slower rate or rise in rectal temperature, lower heart rates, and lower ratings of subjective discomfort when our subjects wore this device compared to the no-cool condition. Both the first and second exercise bouts were significantly longer before our termination criteria were reached. However, a disadvantage of this vest cooling system is that it would be difficult to adapt to become a personal cooling device. The current MCU chiller is bulky and heavy (13 pounds). Also the vest is worn under the body armor, making it difficult to adjust or remove in the field. We understand that an ice-based vest is sometimes used by the military. But the vest/ice is bulky and the ice melts quickly making this system inefficient.

Hand Cooling and Development of the RTX

The new RTX technology may offer a plausible ambulatory personal cooling system. This concept was developed by Drs. Craig Heller and Dennis Grahn at Stanford University. It is based on the fact that some animals regulate their body temperature under extreme environmental conditions by using countercurrent heat exchange through specially adapted peripheral tissues (flippers in seals, feet and legs in wading birds for example). The peripheral tissues in these animals are endowed with a rich vascular supply under strong neural regulation that can modulate peripheral blood flow to regulate heat exchange with the environment. Humans have a similar vascular system in their face, hands and feet, where the opening and closing of arteriovenous anastomoses (AVAs) alters blood flow and heat exchange many-fold. Under cold conditions, these AVAs are closed minimizing blood flow to <1 mL/100 mL tissue. However, under conditions of high heat production (for example when jogging on a cold day), the AVAs open and increase hand blood flow to about 35 mL/100 mL tissue, allowing rapid heat loss to the environment (Tipton 93). The inventors of the RTX make use of this specialized peripheral vascular network to enhance personal cooling. The high vascular perfusion in the hands allows for greater heat exchange per cm^2 skin surface area compared to most body regions. Therefore, when used for personal cooling, less skin surface area would be required for a given heat exchange. Another advantage may be that the cooled blood is delivered back to the body through deep veins, thus directly cooling the body core, resulting in a faster fall in deep body temperature. Cooling a smaller body surface area may allow a smaller/lighter cooling system. Application to the hands rather than the torso would allow easier access for adjustment.

Cooling through the hands and arms during recovery from exercise has been shown to be effective in rapidly lowering body temperature in hyperthermic subjects (Tipton 93; Selkirk 04; Livingston 89; House 03; House 97; House 03; House 98). In a study by Alsopp and coworkers (91), a maximal cooling power of 197 W was calculated when subjects made hyperthermic by exercising in impermeable clothing (NBC clothing) immersed both hands in a 10^{o}C water bath. In a series of studies (Tipton 93; House 03), James House and co-workers of the British Royal Navy report that immersing the hands and forearms in cold water significantly extends heat tolerance time in firefighters and aircraft crew. They found that when core temperature is elevated, the colder the water used for immersion (down to 0-10^{o}C), the greater the rate of body cooling.

In the studies of hand cooling by these previous investigators, hand and arm cooling were applied during rest breaks between exercise bouts after the subjects already were hyperthermic. In the present study, and in the goal of providing an ambulatory cooling system, cooling would be provided during work to slow the rise in core temperature. With a normothermic core temperature (<38°C), the AVAs would be expected to constrict upon exposure to the cooling plate of the RTX. This would reduce hand blood flow, preventing a large amount of heat extraction. Therefore, only once body temperature exceeds some "threshold", should the AVAs open allowing for rapid heat exchange. This body temperature threshold may be variable between subjects and between environmental and exercise conditions. The RTX device applies mild negative pressure (24 inches of water in the present study) around the hand to help maintain capillary vasodilation once the AVAs have opened. (Dr. Grahn suggests that the negative pressure is not strong enough to draw open closed capillaries, personal communication). Further, we were cautioned by the RTX inventors at the start of this study to set the RTX temperature to 22°C to prevent or reduce the local vasoconstriction caused by contact of the hand with the RTX cooling bar. However, just before the start of the study, we were informed by Drs. Heller and Grahn that their recent pilot studies were showing that cooler RTX temperatures were more effective when subject's exercised in the heat, and they encouraged us to lower the RTX temperature to 15°C to obtain the best cooling response. Therefore we obtained a modification from our IRB and began to perform studies with hand temperatures as low as 15°C.

For the RTX to remove body heat, there is a delicate balance between the factors acting to distend the hand vessels and the opposing tendency to vasoconstrict. The rise in core temperature and local negative pressure act to keep the AVAs open, enhancing heat exchange. On the other hand, the cool bar of the RTX and psychological or physiological stress (provided by exercise or heat stress) will promote vasoconstriction. The vascular tone of the hand is controlled by autonomic nerves. Johnson and coworkers (95) recently reported that the back of the hand and fingers are innervated by both adrenergic nerves and by non-adrenergic active vasodilatory nerves. Alternately, the palm is innervated only by the adrenergic nervous system. Thus, at rest blood flow to the back of the hand is minimal, but as core temperature rises there is an initial increase in blood flow as adrenergic vasoconstrictor tone is released and a sudden, further rise in blood flow once the active vasodilatory nerves are activated. In the palm however, resting blood flow is much higher (4-5 times that of the hand dorsum). Then as core temperature rises and the AVAs open and palm blood flow increases, with possibly a greater blood flow per square cm compared to most other regions of the body. However, the adrenergic nervous system is sensitive to non-thermal constrictor reflexes. Constriction of finger blood flow for example is used in lie detector tests. What we don't know is whether palm blood flow also may be restricted during severe physiological stress, such as heavy exercise or heat stress, or whether hyperthermia would overcome this constrictor response. Our results suggest that the hand remained vasoconstricted throughout RTX tests and this may help to explain why we did not see a cooling response with the RTX.

In the previous cooling studies with the hands (Tipton 93; House 97, 98, 03, 03), the arms were immersed in cold water after the subjects had already exercised and raised their body temperatures. Their results may have differed from our results for two reasons. First, the hands may have been maximally dilated before cold water was applied for cooling. Once the palm is dilated the AVAs may be more resistant to adrenergic vasoconstriction. Second, whole hands and forearms were immersed in cool water. The active vasodilatory nerves may be less sensitive to local cold and therefore the blood vessels in the forearms and back of the hands may have remained open for heat exchange in their hyperthermic subjects.

Previous Studies with the RTX

Two publications reported that the RTX is effective in cooling the body during exercise in warm environments. In a series of studies, Grahn, Cao, and Heller (05) evaluated the RTX to reduce heat strain, lower heart rate and extend exercise endurance in subjects performing treadmill walking in a hot (40^{o}C) environment. They reported:

1) an RTX device similar to ours (dome unit), reduced the rate of rise in esophageal temperature and heart rate and extended exercise time (until subjects reached a heart rate of 90% of age-predicted HR_{max}) by 43%. The exercise intensity was adjusted (by altering treadmill slope) to produce the termination critieria within

20-45 min. The authors estimated the workload as a slope that was 60-65% of the slope at which subjects reached 90% HR_{max} during baseline VO_2max tests. It is difficult to know from this information the exact relative intensity (%VO_2max). However, from the endurance times and exercise conditions, we suspect the workload was approximately 40-50% VO_2max.

2) when subjects performed treadmill exercise (same intensity as above) with or without negative pressure, the RTX was not effective unless the negative pressure was applied. Work endurance was not extended with RTX cooling without negative pressure (time increased 11%, ns), while cooling with negative pressure significantly increased walking time (by 67%).
3) In a third experiment, subjects walked at varying exercise intensities (treadmill slopes) while RTX cooling was applied. In an exponential relationship, the harder the exercise intensity, the less the improvement in endurance time. This was explained by the authors this way: "One would expect the ability of the heat extraction device to increase endurance would depend on the intensity of the exercise. If the AVAs are fully open and the parameters of the heat extraction device are held constant, there should be a maximal attainable level of heat extraction. Therefore, as workload increases, that maximal level of heat extraction should be a lesser and lesser proportion of the total heat produced".

The second publication using the RTX (Hsu et al, 05) evaluated the ability of the RTX to slow the rise in core temperature (ear temperature) and lower heart rate in 8 male triathletes during constant load (~60%VO_2max) cycling exercise for 60 minutes in a warm environment (32^{o}C, 24%RH). RTX cooling attenuated the increase in core temperature (1.2 vs. 1.8^{o}C), while reducing mean oxygen consumption and blood lactate. Curiously, cooling did not lower heart rate. In a second study in this same report, 8 male triathletes performed a 30-km cycling time trial with and without cooling with the RTX. Completion time was 6±1% faster when using the RTX compared to no cooling and the cycling speed was 14±5% higher during the final 20% of the exercise.

Why Didn't We See Improvements with the RTX?

The exercise and heat stress protocol used in this investigation was designed in collaboration with scientists from the US Army Environmental Research Institute of Environmental Medicine (to insure military applicability) and the RTX developers (to ensure correct implementation of the RTX). Based on the previous reports, it is surprising our results did not confirm the effectiveness of the RTX. There are some specific differences in protocol that may explain our different results.

The most likely explanation for our lack of significant cooling benefit from the RTX may be related to the stressful conditions in our study. In the paper by Grahn et al (05), in their third study they reported that the effectiveness of the RTX decreases in an exponential manner with increasing exercise intensity. The exercise/heat stress conditions in our study most likely were more severe than those in the study by Grahn et al (05). This may have caused the AVAs in the palms to remain vasoconstricted (see explanation above about the effect of physiological stress on the adrenergic nervous response of the palm) throughout our heat stress tests. Our exercise intensity was similar to that of the study of Hsu and coworkers (05). However our environmental conditions were much more severe and heat stress would be further amplified in our study because of the interference of heat loss caused by the body armor. Therefore, again the greater physiological strain may have induced and maintained a palm vasoconstrictor response in our subjects during exercise and the recovery interval between exercise bouts.

We also considered that perhaps the core temperature measurement site could explain our differing results. We exclude this possibility based on preliminary findings reported to us by Drs. Grahn and Heller that they perform tests using both rectal and esophageal temperature and consistently find lower core temperatures using the RTX in both measurement sites. If the RTX does cool primarily the blood in deep veins returning to the body, it is possible that the esophageal site would reflect a sooner fall in core temperature. Rectal temperature typically has a lag time of approximately 20 minutes compared to the esophageal measurement site. However, with the exercise duration of the RTX tests, 52 and 42 min average durations for the first and second exercise bouts, we would expect to see a reduction in rectal temperature if the RTX removed a significant amount of body heat.

Another possibility for our different results may be related to preheating the hand. Dr. Heller mentioned to us that his technician also failed to find positive results from the RTX when they first began their studies. After a while, he learned how to appropriately prepare the subjects and instrument them with the RTX so that he consistently got good results. Dr. Heller mentioned that his technician has the subjects sit with their hands in hot (42^{o}C) water for about 10 minutes before putting their hand in the RTX. It is possible that local heating may maximally dilate the vessels in the hand, and this local heating may sustain an increased blood flow during the early stages of exercise until core temperature rises above the vasodilatory threshold. It is also possible that if the hand is pre-dilated, it is easier for the negative pressure in the RTX to maintain the AVAs in a dilated state then to assist their dilation when constricted. In our studies, we believe the hand was constricted as the subjects began to exercise. With the imposed stress of the exercise, it may be harder to induce vasodilation, and so the palm remained constricted throughout our tests. To test this theory, we would like to repeat our protocol in a few subjects while measuring palm perfusion, with and without hand preheating.

Although we used similar RTX temperatures (the 18 and 22^{o}C tests) as used in the previous published RTX studies (Grahn 05; Hsu 05), it is possible that the hand temperatures were too cold to allow palm vasodilation under the exercise conditions of our study. We may have found better results if we used a warmer RTX temperature. After our initial 3 subjects, when we failed to see positive results at 15^{o}C, we increased the RTX temperature to 18^{o}C for the next three subjects and to 22^{o}C for the final four subjects. Although there are not enough subjects at each RTX temperature to perform statistical comparisons, there were no obvious differences in the results at these three temperatures. It is possible that if we increase the RTX temperature further, vasodilation may occur. However, the higher the hand temperature, the lower the gradient for heat exchange from the hand to the RTX bar. Therefore, it is unclear whether a higher RTX temperature could remove sufficient heat to provide a significant cooling effect, even if the hand did vasodilate.

Possibly differences in subject characteristics could explain differing results with the RTX. The subjects in our study were each heat acclimated but the studies were performed during the winter months in a fairly cold environment (Albuquerque from January to May). The lower ambient temperatures may have caused our subjects to have a higher constrictor tone than the California-acclimated subjects near San Diego, CA (Grahn 05; Hsu 05).

It is also possible that our inability to demonstrate body cooling with the RTX was due to the RTX unit used in our study. We were sent two of the coffeepot (Unit B) versions of the RTX and Drs. Heller and Grahn visited our laboratory to instruct us in its' proper use. It is tricky to use this device, as there is a ratchet-like seal that encloses the wrist. If the seal is too tight, it may interfere with blood flow return from the hand, reducing heat exchange. Although we followed the instructions, and tightened the seal only tight enough to maintain a vacuum around the hand, we did not measure hand blood flow to confirm that the seal was not interfering with hand perfusion.

How much heat must the RTX remove to be Effective?

We attempted to estimate the watts of heat removed during the heat stress tests in this study. We were unable to quantify heat extraction by the RTX, because the RTX version (coffeepot design) we were evaluating could not sustain the high pressure from the thermocube perfusion pump. We can roughly estimate the heat removal provided by the RTX if we examine the heat extraction provided by the water bath, since it produced similar physiological responses during the heat stress tests. The average heat production during the control, no-cool tests was 282 watts per m^2 body surface area (1.9 m^2), or approximately 536W. The water bath removed approximately 60 W of heat, or only 11% of heat production. This amount of body heat extraction produced no noticeable improvement in any of our physiological or psychological measurements.

Examining the color of the hand during our heat stress tests, we noted there never was any evidence of palm vasodilation during either RTX or water bath tests. The palm remained a "blanched" white color at the end of the first and second exercise bouts, even when core temperature was elevated to 38.5 to 39°C. This is surprising considering the results of House (House 03; House et al 97; House et al 03; House 98) and others (Livingstone et al 89) where they reported cooling the hands and forearms lowered body temperature even when the hands and forearms were placed in 0-10°C water. A possible explanation for the suspected persistent vasoconstriction in our study during exercise may have been the severe heat and exercise conditions. However, it is particularly surprising that the palm did not vasodilate during the rest and rehydration interval between exercise bouts. During this interval, perhaps the fall in body temperatures with the cessation of exercise prevented the hands from vasodilating.

During vest tests, again we can only estimate the amount of heat extraction provided by the vest, since we could not quantify the background heat removal. (Background heat removal is heat absorbed from the environment, rather than removed from the subject). To quantify the background heat removal, controlled manikin tests would be required with a manikin heated to temperatures similar to our subjects and environmental temperatures and clothing similar to our subjects. From Army reports, we can only extrapolate that the amount of background heat removal (from data modeled for similar environmental conditions in soldiers wearing summer uniforms without body armor) would be approximately 60 W. Therefore our best estimate of the body heat removal for the vest in these tests was approximately 240 W, or 240W/536 W = about 48% of the heat production. This level of heat removal was sufficient to slow the rate of heat storage from approximately 54 watts in the no-cool tests to about 20 watts in the vest tests. These numbers provide a rough estimate of the quantity of heat removal that would be required from a personal ambulatory cooling system to be effective under heat and exercise stress conditions similar to those in the present study.

The vest was approximately 13% less effective during the second exercise bout compared to the first exercise bout (318 vs 277 watts). This reduction in cooling most likely was related to bubbles induced in the MCU system when we disconnected the vest during the recovery period to allow the subject to move off the treadmill. Even with this reduction in cooling, vest endurance times still were longer during the second exercise bout. During vest tests, average heart rate and rectal temperature were similar to no-cool during the first 25 minutes of the second exercise bout. This most likely was related to the bi-phasic character of the vest cooling curves (seen more often in vest tests than other cooling tests). Thus, as the subject becomes more hyperthermic, cooling becomes more effective. This effect probably would be apparent with any cooling system that removes sufficient body heat. *This information is useful for future tests of cooling systems; the tests must be long enough with core temperatures elevated, and the measurement system sensitive and fast enough to detect the cooling effect.*

Cognitive Function with the RTX

Participants reported little physical or emotional distress following the heat stress conditions as indicated on the Environmental Symptoms Questionnaire (ESQ; Sampson, 1994) and the Profile of Mood States (POMS; McNair, et al, 1981, Curran, et al., 1995). Despite being pushed to physical limits in a heated environment, participants in this study were not adversely affected by physical and emotional symptoms. In addition, these results suggest that this physically demanding testing was completed in a safe manner. It is also possible that social desirability effects influenced the manner in which participants responded. That is, participants may have under-reported their physical and emotional symptoms in a conscious or unconscious effort to make themselves appear more physically and mentally healthy.

A computerized testing battery (CTA) was administered during the first exercise bout when the body core temperature reached 38^{o}C. Participants responded quickly and accurately on two attention tasks requiring few cognitive resources, a simple and a choice reaction time task. Consistent with the literature (see a review in Hancock & Vasmatzidis, 2003), tasks of low cognitive load appeared to not be affected in the heat and physical stress environment. A working memory task was also administered in CTA, the n-back task with three cognitive loads, 0-, 1-, and 2-back tasks. During the 0-back task of sustained attention but no working memory demands, participants performed close to ceiling level with relatively few errors. As the task demands increased during the 1- and 2-back conditions, performance decreased significantly and the number of errors increased, as expected. No differences among the heat stress conditions were found on any of the CTA tasks suggesting that the different body cooling techniques did not differentially affect cognitive performance in the heat and exercise stress environment. The CTA tasks were also administered during exercise bout 2. The results from these sessions were similar to the bout 1 results; thus, they were not presented here.

Neuropsychological tests of executive functioning were administered during the rest and rehydration period. Two of the tests, the Delis-Kaplan Executive Functioning (D-KEFS; Delis, et al, 2001) versions of the Trail Making and Color Word Tests, included several subtests that isolate different cognitive components of the overall tasks and provide low, medium, and high cognitive loads across the test. Not only were no significant differences found among the heat stress conditions, no differences were found across the scaled scores for the different subtests. Similarly, there were no differences on the WAIS-III Letter-Number Sequencing test (Wechsler, 1997) of working memory among the heat stress conditions. Scaled scores provide an age-corrected normative value for each test and subtest. In contrast to our hypotheses, participants performed above average on all subtests in the heat and exercise stress environment relative to the normative scores. In contrast to the literature (Hancock & Vasmatzidis, 2003), the challenging physical demands placed on participants did not appear to adversely affect their ability to perform various cognitive tasks even when cognitive load demands were at a high level. Practice effects may have greatly impeded the lack of findings on the neuropsychological tests because prior to performing in the heat stress conditions, the participants had performed these tests in the baseline and heat acclimation periods. However, the prior learning also likely equalized performance across the four heat stress conditions, which was necessary to examine these conditions. Further studies are needed to understand the effect of heat and exercise tests on cognitive functioning.

Conducting cognitive testing in the heat and exercise environment proved challenging and several limitations of this study are important in understanding the results. First, this study was designed to investigate the physiological effects of different body cooling systems in a heat and exercise stress environment. Therefore, assessing cognitive functioning in this environment was constrained to the parameters set forth in the physiological aims of this study. As such, the sample size was small for an effective cognitive functioning analysis.

Individual difference variation in cognitive functioning usually requires more power to see the effect of an outside influence such as heat and exercise stress. However, the stringent methodology set forth in this study such as individualizing exercise load was also needed to better understand differential body cooling effects. This issue illustrates the difficulty in weighing parameters and subsequent trade-offs in designing a comprehensive study. In addition to the small sample size, several obstacles were encountered resulting in significant missing data for various tests throughout the cognitive testing, but especially in the computerized CTA battery. A platform for the computer was constructed for the treadmills, but extra caution was needed in administration because of the exercise motion, the hot environment, and the significant moisture from participant sweating. In addition, testing was terminated early when participants had reached their body core target temperature. Administration and technical difficulties were encountered often and missing data became problematic in analyses. While the computerized and neuropsychological tests were chosen to provide an investigation of a variety of cognitive functioning domains and cognitive load levels, brief assessment periods, environmental testing constraints, and learning/practice effects may also have hindered the ability to reliably and validly assess true cognitive functioning impairment in the stress environment. Thus, there may be significant heat and exercise stress effects on cognitive functioning that could not be detected in this study.

Muscular Endurance Results

We did not detect differences in muscular endurance related to the different cooling conditions. Muscle endurance should be reduced with an elevated body temperature. However, the first exercise bout was stopped at the same targeted core temperature (38.5^{o}C), and we did not see a significant difference in the rate of body cooling during the recovery period. Therefore, rectal temperatures were similar at the time of the muscle endurance tests. Therefore it is not surprising that the endurance results were not different for the cooling conditions.

Further Work and Recommendations

Even though RTX cooling was not effective in the present study, we feel that further testing of this cooling approach would be valuable. Especially if hand cooling can selectively reduce the temperature of deep venous blood returning to the core, this form of cooling could produce a rapid fall in core temperature. The most valuable immediate application for the RTX may be in treating patients with heat illnesses. The prognosis for recovery from heat exhaustion or heat stroke is dependent on the speed with which core temperature is lowered (Clapp et al, 01). Providing a selective fall in core temperature without lowering skin temperature might prevent shivering, which opposes a fall in body temperature during the standard clinical treatment of immersing a subject in ice water. Thus, hand cooling may be an important advance in treating heat illness. If the Army does not wish to pursue a clinical application for this device, we would encourage the developers to perform studies to rapidly cool hyperthermic subjects and to seek FDA approval for clinical trials.

The exercise and heat stress conditions tested in this study were severe and should not exclude the possibility that the RTX could be effective in other less stressful operational situations. We feel that further testing is justified to understand the basic premises for its application. We need to better understand the factors that regulate hand blood flow to optimize local conditions to insure sustained vasodilation. We also need to quantify the amount of heat that can be removed from the hand to determine the operational scenarios where it would be effective. To characterize the conditions where hand cooling could be effective in preventing or reducing an elevated core temperature, we would recommend the following approach:

1) basic studies to characterize the core temperature, mean skin temperature, and local skin temperature interactions that induce opening of the palm AVAs to increase hand blood flow
2) basic studies to characterize the additional effect of changing metabolic rate (exercise) and psychological stress (cognitive tasks?) on the above temperature and hand blood flow interactions
3) basic studies to characterize the effect of subject characteristics (age, gender, fitness, heat acclimation) on the above temperature and exercise effects on hand blood flow
4) studies to evaluate the effect of local preheating of the hand on the effectiveness of the RTX

5) studies to evaluate the most effective negative pressure to use in the RTX and this study should include measurements of hand blood flow to insure that the wrist cuff does not occlude blood returning from the hand
6) studies to compare cooling the palm only to cooling the whole hand and forearm, to evaluate the effect of the active vasodilatory system in peripheral cooling
7) quantify the watts of heat that can be removed from the hand using the RTX under varying conditions. This information can be used to predict under which conditions the RTX would be effective
8) studies to determine whether specific "indices" can provide feedback to an RTX controller (for temperature and vacuum) to maximize heat extraction. Possible feedback may be provided by specific skin temperatures, watts of heat extraction, skin color or blood flow, some index of core temperature, or subject perception.
9) This device may have important clinical applications in the treatment of patients suffering from heat illnesses. Initial studies could evaluate use of the RTX to lower temperature in healthy hyperthermic subjects.
10) To prevent hand vasoconstriction or to maintain vasodilation, on-off cooling or vacuum application at varying pressures could be compared to continuous application
11) Studies to evaluate intermittent cooling during rest intervals, similar to the studies by House and coworkers, may be an effective and operationally relevant use for the RTX.
12) An integrated study approach, providing data to model thermal responses to a variety of cooling approaches (including the RTX), might provide insight to develop novel cooling methods for specific military needs.

Final Conclusions:

The RTX, Unit B device as we used it in this study did not reduce the rate of heat gain or lower cardiovascular or psychological strain in subjects walking at 50% VO_2max in a hot, dry environment while wearing summer cammy uniforms and body armor. The stress imposed by these conditions may have maintained a strong vasoconstrictor tone in the hand, preventing the expected heat extraction. Further work is needed to quantify the capacity (how much heat can be removed) and limitations (from the environment and the subject) of hand cooling. Conceptually this device could provide significant cooling in subjects with high heat storage and a low metabolic rate: e.g., cooling during intermittent work/rest cycles or for treatment of hyperthermia. A better understanding of the capacity of heat extraction of the RTX system would allow a more precise prediction of the environmental/work conditions where it might be most effective.

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References:

ACSM's Guideline for exercise testing and prescription. American College Sport Medicine, 7th edition, 2006.

Allsop AJ and KA Poole. The effect of hand immersion on body temperature when wearing impermeable clothing. J Roy Nav Med Serv 77:41-47, 1991.

Army report: Air Warrior microclimate cooling garment, Data item number: A032, Thermal Performance Test Report, Test dates 11 July-13 August, 2001. Prepared by US Amry Natick Soldier Center, AMSSB-RIP-C(N), Natick, MA., report date 5 February, 2002.

Bruck K and H Olschewski. Body temperature related factors diminishing the drive to exercise. Can J Physiol Pharmacol 65:1274-1280, 1987.

Cheung SS and GG Sleivert. Multiple triggers for hyperthermic fatigue and exhaustion. Exerc Sport Sci Rev 32:100-106, 2004.

Cheuvront SN, MA Kolka, BS Cadarette, SJ Montain, and MN Sawka. Efficacy of intermittent, regional microclimate cooling. J. Appl. Physiol. 94:1841-1848, 2003.

Clapp AJ, PA Bishop, I Muir, JL Walker. Rapid cooling techniques in joggers experiencing heat strain. J. Sci. Med. in Sport 4:160-167, 2001.

Curran, S. L., Andrykowski, M. A., & Studts, J. L. (1995). Short form of the Profile of Mood States (POMS-SF): Psychometric information. Psychological Assessment, 7, 80-83.

Delis, D. C., Kaplan, E., & Kramer, J. H. (2001). Delis-Kaplan Executive Functioning System. New York: The Psychological Corporation.

Dill DB and DL Costill. Calculation of percentage changes in volumes of blood, plasma and red cells in dehydration. J. Appl. Physiol. 37:247-248, 1974.

Fox SH and AB DuBois. The effect of evaporative cooling of respiratory protective devices on skin temperature, thermal sensation, and comfort. Am. Ind. Hyg. Assoc. J. 54:705-710, 1993.

Galloway SDR and RJ Maughan. Effects of ambient temperature on the capacity to perform prolonged exercise in man. Med. Sci Sports Exerc 29:1240-1249, 1997.

Gardiner JW, JA Kark, K Karnel, JS Sanborn, E Gastaldo, P Burr, CB Wenger. Risk factors predicting exertional heat illness in male Marine Corps recruits. Med. Sci. Sport Exerc. 28:939-944, 1996.

Gonzalez-Alonso J, R Mora-Rodriguez, PR Below, and EF Coyle. Dehydration markedly impairs cardiovascular function in hyperthermic endurance athletes during exercise. J Appl Physiol 82:1229-1236, 1997.

Gonzalez-Alonso, J, C Teller, SL Andersen, FB Jensen, T Hyldig and B Nielsen. Influence of body temperature on the development of fatigue during prolonged exercise in the heat. J Appl Physiol 86:1032-1039, 1999.

Grahn D, JG Brock-Utne, DE Watenpaugh, HC Heller. Recovery from mild hypothermia can be accelerated by mechanically distending blood vessels in the hand. J. Appl. Physiol. 85:1643-1648, 1998.

Grahn D, VH Cao and HC Heller. Heat extraction through the palm of one hand improves aerobic exercise endurance in a hot environment. In press, J. Appl. Physiol.

Hadaad E, M Rav-Acha, Y Heled, Y Epstein, DS Moran. Heat stroke: a review of cooling methods. Sports Med. 34:501-511, 2004.

Hagobian TA, KA Jacobs, BJ Kiratli, AL Friedlander. Foot cooling reduces exercise-induced hyperthermia in men with spinal cord injury. Med. Sci. Sport Exerc. 36:411-417, 2004.

Hales JRS, RW Hubbard, and SL Gaffin. Limitation of heat tolerance. In: Handbook of Physiology. Environmental Physiology. Bethesda, MD: Am Physiological Soc, 1996, Sect 4, Vol II, Chapt 15, p 285-355.

Hancock PA. & I Vasmatzidis. Effects of heat stress on cognitive performance: The current state of knowledge. International Journal of Hyperthermia 19: 355-372, 2003.

Hardy JD, EF DuBois. The technic of measuring radiation and convection. J. Nutr. 15:461-475, 1938.

Heyward VH. *Advanced Fitness Assessment and Exercise Prescription.* Fifth Edition. Human Kinetics, Champaign, IL, 2006.

Houdas Y and EF Ring. Temperature distribution. In: *Human body temperature*. Plenum Press, New York, 1982, pg 81-103.

House J. Modelling the effectiveness of techniques for reducing heat strain in Royal Navy nuclear, biological and chemical cleansing stations' teams. J Roy Med Serv 89:19-26, 2003.

House J. Extremity cooling as a method for reducing heat strain. J. Defense Sci 3:108-114, 1998.

House JR, C Holmes, AJ Allsopp. Prevention of heat strain by immersing the hands and forearms in water. J. Royal Naval Medical Service 83:26-30, 1997.

House JR, H Lunt, A Magness, and J Lyons. Testing the effectiveness of techniques for reducing heat strain in Royal Navy nuclear, biological and chemical cleansing stations' teams. J Roy Nav Med Ser 89:27-34, 2003.

Hsu AR, TA Hagobian, KA Jacobs, H Attallah, AL Friedlander. Effects of heat removal through the hand on metabolism and performance during cycling exercise in the heat. Can. J. Appl. Physiol. 30:87-104, 2005.

Johnson JM, PE Pergola, FK Liao, DL Kellogg, and CG Crandall. Skin of the dorsal aspect of human hands and fingers possesses an active vasodilator system. J Appl Physiol 78:948-954, 1995.

Kolka MA, L Levine, LA Stephenson. Use of ingestible telemetry sensor to measure core temperature under chemical protective clothing. J. Thermal Biol. 22:343-349, 1997.

Ku YE, LD Montgomery, HC Lee, B Luna, BW Webbon. Physiologic and functional responses of MS patients to body cooling. Am. J. Phys. Med. Rehab. 79:427-435, 2000.

Lee SMC, WJ Williams, SMF Schneider. Core temperature measurement during supine exercise: esophageal, rectal, and intestinal temperatures. Aviat. Space Environ. Med. 71:939-945, 2000.

Livingstone SD, RW Nolan, SW Cattroll. Heat loss caused by immersing the hands in water. Aviat. Space Environ. Med. 60:1166-1171, 1989.

McNair, P. M., Lorr, M. & Droppleman, L. F. *POMS manual* (2nd ed.). San Diego: San Diego Educational and Industrial Testing Service, 1981.

Mitchell JE, BK McFarlin, JP Dugas. The effect of pre-exercise cooling on high intensity running performance in the heat. Int. J. Sports Med. 24:118-124, 2003.

Mitchell JW, ER Nadel, JAJ Stolwijk. Respiratory weight losses during exercise. J. Appl. Physiol. 32:474-476, 1972.

Montain SL, MN Sawka, BS Cadarette, MD Quigley, and JM McKay. Physiological tolerance to uncompensable heat stress: effects of exercise intensity, protective clothing, and climate. J Appl Physiol 77:216-222, 1994.

Muir IH, PA Bishop, P Ray. Effects of a novel ice-cooling technique on work in protective clothing at 28 ^{o}C, 23 ^{o}C, and 18 ^{o}C WBGTs. Am. Ind. Hygiene Assoc. J. 60:96-104, 1999.

Newburgh LH. (ed.) *Physiology of heat regulation and the science of clothing.* WB Saunders, Philadelphia, 1949.

Nielsen B, JRS Hales, S Strange, NJ Christensen, J Warberg, and B Saltin. Human circulatory and thermoregulatory adaptations with heat acclimation and exercise in a hot, dry environment. J Physiol (London) 460:467-485, 1993.

Nishihara N, S Tanabe, H Hayama, M Komatsu. A cooling-vest for working comfortably in a moderately hot environment. J. Physical. Anthropology 21:75-82, 2002.

Nunneley SA. Water cooled garments: a review. Space Life Sci. 2:335-360, 1970.

Pandolf K, B Givoni, and R Goldman. Predicting energy expenditure with loads while standing or walking slowly. J Appl Physiol 43:577-581, 1977.

Quesada PM, LJ Mengelkoch, RC Hales, SR Simon. Biomechanical and metabolic effects of carrying backpack loading on simulated marching. Egonomics 43:293-309, 2000.

Sampson JB. Measurement of subjective reactions to extreme environments: the environmental symptoms questionnaire. Military Psychology 6:215-233, 1994.

Sawka MN and CB Wenger. Physiological response to acute exercise-heat stress. In *Human Performance Physiology and Environmental Medicine at Terrestrial Extremes*. Ed. by KB Pandolf, MN Sawka, and RR Gonzalez. Benchmark Press, Indianapolis, IN; 1988.

Sawka MN, AJ Young, WA Latzka, PD Neufer, MD Quicley, and KB Pandolf. Human tolerance to heat strain during exercise: influence of hydration. J Appl Physiol 73:38-375, 1992.

Selkirk GA, TM McLellan, J Wong. Active versus passive cooling during work in warm environments while wearing firefighting protective clothing. J Occup and Environ Hygiene 1:521-531, 2004.

Shapiro Y, KB Pandolf, MN Sawka, MM Toner, FR Winsmann, RF Goldman. Auxilliary cooling: comparison of air-cooled vs. water-cooled vests in hot-dry and hot-wet environments. Aviat. Space Environ. Med.53:785-789, 1982.

Tipton MJ, A Allsopp, PJ Balmi, JR House. Hand immersion as a method of cooling and rewarming: a short review. J. Roy. Nav. Med. Serv. 79:125-131, 1993.

Vallerand AL, RD Michas, J Frim, KN Ackles. Heat balance of subjects wearing protective clothing with a liquid- or air-cooled vest. Aviat. Space Environ. Med. 62:383-391, 1991.

Vogel JA, Patton JF, Mello RP, Daniels WL. An analysis of aerobic capacity in a large United States population. J. Appl. Physiol. 60(2):494-500, 1986.

Wechsler D. *WAIS-III Manual.* New York: The Psychological Corporation, 1997.