March 1998

DCIEM No. 98-R-36

Efficacy of Liquid, Air, and Phase Change Material Torso Cooling During Light Exercise While Wearing NBC Clothing

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Executive Summary

This study compared the thermoregulatory responses with liquid, air and phase change material (PCM) torso cooling during light exercise at 40°C while wearing NBC protective clothing. The liquid- (LC) and air-cooling (AC) systems were powered from external portable chiller units. The PCM cooling vests, which were supplied by MicroClimate Systems Incorporated, were worn under the nuclear, biological and chemical (NBC) overgarment and were tested with a vertical (CVV) and horizontal (CVH) design. Seven males (29 yrs, 75.6 kg, 1.78 m) performed a no cooling (NC) and 4 cooling trials while walking at 3.5 $km \cdot h^{-1}$ on a treadmill in the environmental chamber. During the NC condition, tolerance times were 100 min and final core temperature was 39.1°C. For the PCM trials (CVV and CVH), tolerance times were extended by 30 min but core temperature still rose to reach values close to 39.0°C indicating that the cooling vests could only delay the exhaustion from the heat exposure. However, with both the LC and AC trials, all subjects completed 180 min of exercise and they could have continued longer given that their core temperatures were still below 38.0°C. The results have shown that the PCM cooling vests are of benefit for work tasks that continue between 1 to 2 hours but these vests are not as effective in reducing the heat strain of wearing NBC protective clothing in hot environments as liquid- or air-cooling systems.

Index Terms: temperature regulation, heat tolerance, heat flows, skin vapour pressure, NBC clothing, cooling vests

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Introduction

The heat strain associated with wearing the military's current-issue nuclear, biological and chemical (NBC) protective clothing is well documented for many countries at different ambient temperatures, vapour pressures and metabolic rates (Carter and Cammermyer 1985; Goldman 1963; Henane et al. 1979; McLellan 1993; McLellan et al. 1993; Montain et al. 1994; Tilley et al. 1981). One strategy to reduce this heat strain has focused on the development of new garment materials and designs. Several nations have reported the success, during trials in hot environments, of new undergarment (McLellan et al. 1994; Levine et al. 1993) or stand-alone clothing designs (Amos and Hansen 1997; Etienne et al. 1994; McLellan et al. 1997) which feature a reduced total clothing insulation and/or increased water vapour permeability of the protective ensemble.

Another effective strategy to reduce the heat strain is to provide cooling close to the skin surface of the wearer of the NBC protective garment. If operational conditions permit, the cooling garment can be tethered to a chiller unit which provides either a liquid- or air-cooled medium to increase conductive or evaporative heat loss, respectively. Both liquid- and air-cooled tethered systems have been trialed successfully during light or heavy intermittent exercise in hot environments (Bomalaski et al. 1995, Constable et al. 1994; Shapiro et al. 1982). These studies have shown the efficacy of cooling systems in general compared with no cooling in an operatinal scenario (Shapiro et al. 1982), the effects of cooling provided only during rest periods to simulate operational capability (Constable et al. 1994), or the combined effects of ambient and conditioned air-cooling provided during exercise and rest periods, respectively (Bomalaski et al. 1995). In addition, a liquid-cooled ice-based system was adapted for use in the 1991 Gulf War which allowed Canadian Forces Sea King helicopter pilots to extend mission durations compared with other Coalition Forces (Bossi et al. 1993). Frim and Glass (1991) also documented the success of this liquid-cooled system for personnel working in the boiler room outside of the citadel protection area of our ships. However, the problem of resupply of ice for this system for operations in excess of 30-60 min durations and/or the added metabolic cost of carrying larger chiller unit technologies make liquid-cooling systems impractical for the foot soldier exercising in a hot environment and wearing protective clothing. Thus, cooling vests such as these that employ phase-change materials (PCM) technology have been evaluated solely as a microclimate cooling option (Bain 1991; Hagan et al. 1994; Ramirez et al. 1994). The efficiacy of PCM cooling vest technology has generally been reserved for lighter exercise where the rate of heat production does not overwhelm the heat capacity of the phase-change material (Bain 1991; Hagan et al. 1994; Ramirez et al. 1994).

DCIEM was approached recently by MicroClimate Systems Incorporated (Sanford, Michigan) to evaluate a cooling vest design that employs a material that changes from a liquid to a solid state at 18.3°C. Compared with the use of water, this PCM technology, because of its higher phase-change temperature (i.e., 18.3° vs 0°C), has the advantage of requiring less power for a refrigeration unit to solidify the material in hot environments, and the advantage of decreasing subject discomfort due to contact with a cold surface. The efficacy of this alternative cooling vest design has not been evaluated, however, under controlled laboratory conditions that involve the wearing of NBC protective clothing during exercise in hot environments similar to conditions in the Middle East where recent military operations have required the use of protective clothing. The purpose of the present study, therefore, was to document and compare the extent of the reduction in heat strain conferred with the use of either this stand alone cooling vest or a tethered liquid- or air-cooled system while wearing NBC protective clothing during light exercise in a hot environment.

Methods

Subjects

Following approval from the Institute's Human Subject Ethics Committee, seven unacclimatized males volunteered to participate in the study. Mean values (± S.D.) for age, weight, height, body surface area and $\dot{V}O_{2peak}$ were 29.7 ± 8.1 y, 85.0 ± 14.0 kg, 1.81 ± 0.04 m, 2.05 ± 0.17 m^2 and 50.7 ± 8.0 $mL \cdot kg^{-1} \cdot min^{-1}$, respectively. They were informed of all details of the experimental procedures and the associated risks and discomforts. After a medical examination to ensure that there were no medical contraindications to their participation in the experiment, each subject gave informed consent prior to the first day of data collection.

Determination of Peak Aerobic Power ($\dot{V}O_{2peak}$)

$\dot{V}O_{2peak}$ was determined on a motor-driven treadmill using open-circuit spirometry before the series of experiments in the climatic chamber. Following two minutes of running at a self-selected pace, the treadmill grade was increased $1\% \cdot min^{-1}$ until subjects were running at a 10% grade. Treadmill speed was then increased 0.22 $m \cdot s^{-1}$ (0.8 $km \cdot h^{-1}$) each minute until the subject could no longer continue. $\dot{V}O_{2peak}$ was defined as the highest $\dot{V}O_2$ observed during the incremental test. Heart rate (HR) was monitored throughout the incremental test from a telemetry unit (Polar Electro PE3000, Stamford, CT). The heart rate value recorded at the end of the exercise test was defined as the individual's peak value (HR_{peak}).

Experimental Design

All subjects performed five experimental sessions with each trial separated by a minimum of 4 days and a maximum of 14 days. The majority of trials were performed on a weekly basis for a given subject. The following items were worn during each trial; underwear or jogging shorts, socks, lightweight cotton combat jacket and pants, semipermeable NBC overgarment, jogging shoes, impermeable overboots and gloves, and C4 respirator. The trials involved continuous treadmill walking at 0.97 $m \cdot s^{-1}$ (3.5 $km \cdot h^{-1}$) in an environmental chamber set at 40°C, 30% relative humidity and a wind speed less than 0.1 $m \cdot s^{-1}$. Subjects performed trials with no cooling (NC), liquid- (LC) and air-cooling (AC), and a cooling vest with the PCM arranged in either a vertical (CVV) or horizontal (CVH) arrangement. A cotton/polyester T-shirt was worn next to the skin for all trials except for LC. The total thermal resistance of the NBC ensemble worn during the NC condition determined on a heated copper manikin was 0.29 $m^{2} \cdot {}^{\circ}C \cdot W^{-1}$ (1.88 clo) and the Woodcock vapour permeability coefficient (i_m) determined with a completely wetted manikin was 0.33 (Gonzalez et al. 1993). All experiments were conducted in the late fall and winter months and performed at the same time of day for a given subject. Subjects were also asked to avoid alcohol for a 24 h period and caffeine for 12 h preceding each trial. Each session continued for a maximum of 3 h or until rectal temperature (T_{re}) reached 39.3°C, heart rate remained at or above 95% of HR_{peak} for 3 min, nausea or dizziness precluded further exercise, the subject asked to be removed from the chamber, or the investigator removed the subject from the chamber. Subjects also performed a familiarisation trial which involved wearing the NBC protective ensemble with no cooling, included all aspects of the experimental sessions and used the same criteria for termination of the trial. This session was performed 3-7 days prior to the first experimental condition. The CVH and CVV trials were evaluations added to a larger study that compared LC and AC systems during light and heavy metabolic rates. As a result, the presentation of the 5 trials reported herein was not randomly assigned for a given subject. Instead, the randomisation occurred within the NC, LC and AC configurations, and between the CVH and CVV trials which represented the last two trials for all subjects.

Decsription of Cooling Systems

The liquid cooling garment (Delta Temax Inc., 320 Boundary Road, Pembroke, Ontario, Canada) was a long-sleeved front-zippered undershirt made of flame retardant Nomex fabric onto which plasticised PVC tubing (1/8 inch o.d.) is sewn onto the inner surface in parallel serpentine "loops" with overstitching. Note that a single cooling loop consists of a length of tubing running up and down the garment several times. Eight parallel tubing loops are distributed over the torso and down the sleeves; they connect to fluid distribution and collection manifolds at the waist of the garment. Cold water from a laboratory chiller was pumped to the garment through an insulated umbilical at a flow rate of approximately 0.4 $L \cdot min^{-1}$. The garment inlet temperature was fairly constant at about 6°C while fluid outlet temperature depended on garment heat transfer and ranged from 13 to 17°C.

The air cooling garment was a vest made of two layers of air-impermeable urethane-coated nylon separated by a mesh spacer fabric. The inner layer of fabric is perforated with a grid of 1/8 inch diameter holes to create an air distribution manifold. A second layer of mesh spacer fabric over the perforated layer ensures an unobstructed low resistance air flow path even under the weight of heavy overgarments. Cool air for the vest was supplied by blowing air through a heat exchanger immersed in a cold water reservoir maintained at 4°C. Flow rate was 550 $L \cdot min^{-1}$ and vest inlet temperature was typically 12°C; outlet temperature could not be measured because the air vest is an open system.

The torso cooling vests from MicroClimate Systems Incorporated were constructed from a polyester shell-material with pockets that allowed the PCM to be inserted in either a vertical or horizontal configuration. The vest consisted of a zippered front with velcro straps at the shoulders and the sides to ensure closeness of fit for each subject. For the vertical configuration, 4 PCM packs, each weighing 0.42 kg, were inserted into the vest, 2 in the back and 1 on each side of the zipper at the front of the vest. The total weight of this vest configuration was 2.25 kg. The horizontal vest design consisted of 3 larger 0.36 kg PCM packs inserted into the back of the vest and 3 smaller 0.18 kg PCM packs inserted into each side of the zippered front area to give a total weight for this vest configuration of 2.8 kg.

Dressing and Weighing Procedures

Subject preparation, insertion of the rectal thermistor and placement of heat flux transducers have been detailed previously (11, 12). In addition, relative humidity capacitance sensors (Vaisala Sensor Systems, Woburn, MA) and thermistors were taped onto the skin and the outer layer of the combat clothing at the upper back, abdomen and upper thigh. These humidity sensors have an accuracy of ± 3% and the linearity of response was verified for each sensor with saturated salt solutions of lithium chloride, sodium chloride and potassium sulphate to provide relative humidity measurements of 12%, 75% and 97%, respectively. Both nude and dressed weights were recorded prior to entry into the chamber. Upon entering the chamber, the subject receiving tethered cooling was connected to the liquid or air cooling system, and the subject's humidity sensors and thermistors, heat flux transducers and rectal thermistor monitoring cables were connected to a computerised data acquistion system (Hewlett-Packard 3497A control unit, 236-9000 computer and 2934A printer) and the exercise began. Mean values over 1-min periods for T_{re}, skin temperature, heat flow and vapour pressure were recorded and printed by the data acquisition system. Weighted mean skin temperatues ($\overline{T}_{sk}$) and heat flows ($\overline{HF}$) were subsequently calculated for the 4 torso sites (upper and lower back, chest and abdomen) that were directly affected by all cooling garments and the 7 sites that did not directly receive cooling (front and rear thigh, calf, shin, foot, hand and forehead). The forearm, which was covered by the liquid cooling vest, was not included in these analyses since the air-cooling and stand-alone vests did not cover the forearm. The forearm did respond in a similar fashion to the other cooling sites for the LC trials and the other uncooled sites for the AC, CVV and CVH exposures. Unweighted averages were calculated from the abdomen and upper back humidity sensors to represent the torso skin and garment vapour pressures. HR was recorded every 5 min from the display on the telemetry receiver. No water was provided during the exposures. After the completion of each trial, dressed weight was recorded within 1 min after exit from the chamber and nude weight was recorded following a 5-min undress procedure.

Differences in nude and dressed weights before and after each trial were corrected for fluid intake and respiratory and metabolic weight loss (see below). The rate of sweat production was calculated as the difference between the corrected pre-trial and post-trial nude weights divided by tolerance time, which was defined as the difference in time between removal from and entry into the environmental chamber. Evaporative sweat loss was calculated from the differences in pre- and post-trial corrected dressed weights. The evaporative efficiency represented the evaporative sweat loss expressed as a percentage relative to the total sweat produced. Sweat evaporation and evaporative efficiency calculations were not corrected for sweat drippage from the exhaust valve of the respirator, an unaccountable weight errror that was common to all trials.

Gas Exchange Analyses

During each trial, open-circuit spirometry was used to determine expired minute ventilation and oxygen consumption ($\dot{V}O_2$) using a 2-min average obtained every 15 min. For all trials, an adaptor was attached to the respirator which allowed expired air to be collected. Respiratory water loss was calculated using the $\dot{V}O_2$ measured during the trial and the equation presented by Mitchell et al. (15). Metabolic weight loss was calculated from $\dot{V}O_2$ and the respiratory exchange ratio using the equation described by Snellen (17). The metabolic rate ($\dot{M}$) was determined from the measured $\dot{V}O_2$ and respiratory exchange ratio using the equation outlined by Nishi (16).

Ratings of Perceived Exertion and Thermal Comfort

Immediately following the gas exchange measurement, subjects were asked to provide a rating of perceived exertion (RPE) between 6 and 20 for the whole body (Borg 1962) and a rating of thermal comfort (TC) between 1 (so cold I am helpless) and 13 (so hot I am sick and nauseous) for the torso and whole body.

Blood Sampling

Prior to beginning the dressing procedure, but after the insertion of the rectal thermistor, and after the subject had been standing for 10 min, a 5 mL venous blood sample was taken and later analysed for hematocrit (by microcentrifugation) and plasma osmolality as calculated from sodium, glucose and urea nitrogen determinations (Stat Profile Ultra, Nova Biomedical).

Statistical Analyses

Data are presented as mean values and the standard error of the mean (S.E.). A one-factor (trial) repeated measures ANOVA was used to evaluate any differences among the trials for hematocrit, osmolality, sweat production, sweat evaporation, evaporative efficiency, average metabolic rate and tolerance time. A two-factor (trial and time) repeated measures ANOVA was performed for evaluating the changes in RPE, TC, $\dot{V}O_2$, HR, T_{re}, $\overline{T}_{sk}$, and skin and garment vapour pressures during the exposures. When a significant F-ratio was obtained, a Newman-Keuls post-hoc analysis was used to isolate differences among treatment means. For all statistical analyses, the 0.05 level of significance was used.

Results

Indices of Hydration Status

Nude body weights, hematocrit and osmolality are reported in Table 1. There was no difference among the cooling configurations for any of these dependent measures, thus indicating that hydration status was similar prior to initiating the heat-exposures.

Table 1 Nude body weight, hematocrit and plasma osmolality prior to beginning the light exercise at 40°C and 30% relative humidity while wearing the nuclear, biological and chemical protective ensemble with no cooling (NC), a tethered liquid- (LC) or air-cooling (AC) system, and a stand-alone cooling vest with a horizontal (CVH) or vertical (CVV) configuration for the cooling material. Values are means (S.E.) for n = 7.

	NC	**LC**	**AC**	**CVH**	**CVV**
Nude Body Weight (kg)	84.8 (5.2)	84.2 (5.1)	84.5 (5.1)	85.2 (5.5)	85.2 (5.6)
Hematocrit (%)	47.8 (1.2)	47.2 (1.3)	48.0 (0.9)	48.3 (1.3)	47.8 (1.2)
Osmolality ($mOsm \cdot kgH_2O^{-1}$)	285.6 (0.4)	284.6 (0.7)	286.1 (0.5)	284.6 (0.5)	284.6 (0.4)

Mean values among the trials were not significantly different for these dependent measures.

Liquid-Cooling and PCM Cooling Vests

Cooling power could not be determined for the air-cooled vest because it is an open system. For the liquid-cooled vest, total heat removal by the garment was calculated from the mass flow rate, temperature change, and heat capacity of the cooling fluid (water). Heat removal increased during the first hour and then plateaued at approximately 250 W for the remainder of the exercise trial. For the PCM vest, heat removal capability was estimated from the heat capacity of the PCM (215 $kJ \cdot kg^{-1}$ (Grzyll 1991)) and the weights of material used in the two vest configurations. Complete conversion of solid PCM to liquid in the CVV and CVH designs would require approximately 360 and 460 kJ, respectively. These quantities of energy absorbtion could provide 100 W of cooling power for about 60 and 75 min, respectively. Note that all above values of heat removal refer to the total cooling capacity of the garment; a portion of this capability will be wasted on heat exchange with the ambient environment and will not be available for body cooling.

Indices of Heat Strain

Metabolic Rate

During the heat stress tests, $\dot{V}O_2$ increased significantly faster during the NC, CVV and CVH cooling vest trials compared with the LC and AC configurations. Because of the added carried weight of the PCM in these cooling vest trials, the metabolic rate averaged throughout the heat stress exposure was significantly greater for the CVV and CVH trials compared with LC. Average values approximated 1.0 $L \cdot min^{-1}$ or 335 W (165 $W \cdot m^{-2}$) for the NC, LC and AC cooling trials and 1.1 $L \cdot min^{-1}$ or 370 W (182 $W \cdot m^{-2}$) for the CVV and CVH cooling vest trials.

Rates of Sweat Production and Evaporation, and Evaporative Efficiency

The rates of sweat production and evaporation and the evaporative efficiency of sweat from the NBC ensemble are presented in Table 2 for the different trials. Sweat rates were significantly reduced for the tethered cooling systems compared with the other

Table 2 The rate of sweat production, rate of sweat evaporation and efficiency of sweat evaporation (which is the ratio of sweat evaporated to sweat produced expressed as a percentage) during light exercise at 40°C and 30% relative humidity while wearing the nuclear, biological and chemical protective ensemble with no cooling (NC), a tethered liquid- (LC) or air-cooling (AC) system, and a stand-alone cooling vest with a horizontal (CVH) or vertical (CVV) configuration for the cooling material. Values are means (S.E.) for n = 7.

	NC	LC	AC	CVH	CVV
Sweat Production Rate ($kg \cdot h^{-1} \cdot m^{-2}$)	0.53[a] (0.08)	0.19[b] (0.02)	0.19[b] (0.01)	0.39[c] (0.05)	0.43[ac] (0.06)
Sweat Evaporation Rate ($kg \cdot h^{-1} \cdot m^{-2}$)	0.15[a] (0.01)	0.08 (0.01)	0.14[ab] (0.01)	0.12[b] (0.01)	0.14[ab] (0.01)
Evaporative Efficiency (%)	31.1[a] (2.7)	46.7 (3.4)	75.8 (2.2)	33.1[a] (2.5)	34.5[a] (2.9)

Mean values superscripted with the same letter denote a nonsignificant difference.

trials. In addition, sweat rates were lower for the stand-alone cooling vest trials compared with NC, although the reduction noted for the CVV configuration did not reach significance.

Rates of sweat evaporation calculated from changes in dressed weight were similar during the NC, AC and CVV trials (Table 2). Significant reductions in evaporation rates were found for CVH compared with NC and for LC compared with all other trials.

The efficiency of the evaporation of sweat from the NBC ensemble was significantly increased for the AC trial. This increase in sweat evaporation to 76% compared with the NC trial reflected the reduction in sweat rate (Table 2). For the LC trial, both sweat rate and rate of sweat evaporation decreased compared with the NC exposures. However, the reduction in sweat rate exceeded the decrease in sweat evaporation, thus leading to a significant increase in evaporative efficiency. No change in evaporative efficiency was noted for the PCM cooling vest trials compared with NC.

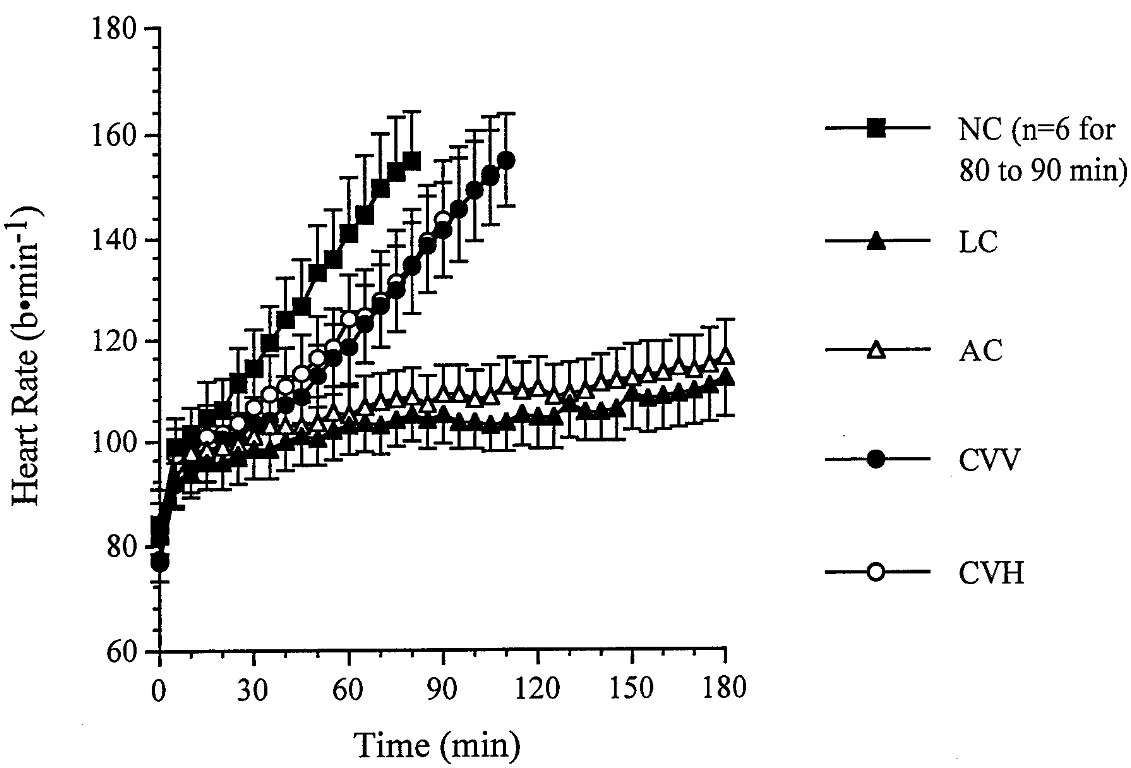
Heart Rate

Figure 1 presents the changes in heart rate (HR) throughout the exercise for the different cooling conditions. During the NC condition, HR was significantly increased compared with the other trials after 15-20 minutes of exercise, and the difference between the no cooling and cooling trials widened with the time of heat exposure. The HR response during the CVH configuration became significantly greater than the tethered cooling systems after 30 min. For the CVV design, a significantly higher HR was also noted compared with both LC and AC after 40-45 min. There was no difference in the HR response between the two PCM cooling vest designs. A small but significantly lower HR averaged throughout the trial was noted for LC compared with AC.

Rectal Temperature

There was no difference in the initial T_{re} among the conditions which averaged 36.9 ± 0.1, 36.9 ± 0.1, 36.9 ± 0.1, 36.8 ± 0.1 and 36.8 ± 0.1°C for the NC, LC, AC, CVV and CVH trials, respectively. The use of a delta T_{re} attempts to normalise small differences in T_{re} at the beginning of each trial for a given subject. The changes in delta T_{re} are presented in Figure 2. The increase in delta T_{re} was similar for all conditions for the first 30 min. After 40-50 min, the delta T_{re} was significantly greater for the NC trial compared with the other cooling sessions. After 60-70 min, the changes in delta T_{re} were significantly greater for both of the PCM cooling vest trials compared with both the LC and AC cooling conditions; the latter which did not differ from each other for the 3 hour exposure. A small but significantly lower delta T_{re} was observed from 30 to 55 min for the CVV condition compared with the CVH trial, but this difference (~ 0.1°C) is physiologically unimportant.

Figure 1: Changes in heart rate during light exercise at 40°C and 30% relative humidity while wearing the nuclear, biological and chemical protective ensemble with no cooling (NC), a liquid- (LC) or air-cooling (AC) system, and a phase-change material cooling vest with a vertical (CVV) or horizontal (CVH) configuration for the cooling material. Values are means (S.E.) for n=7 unless otherwise noted.

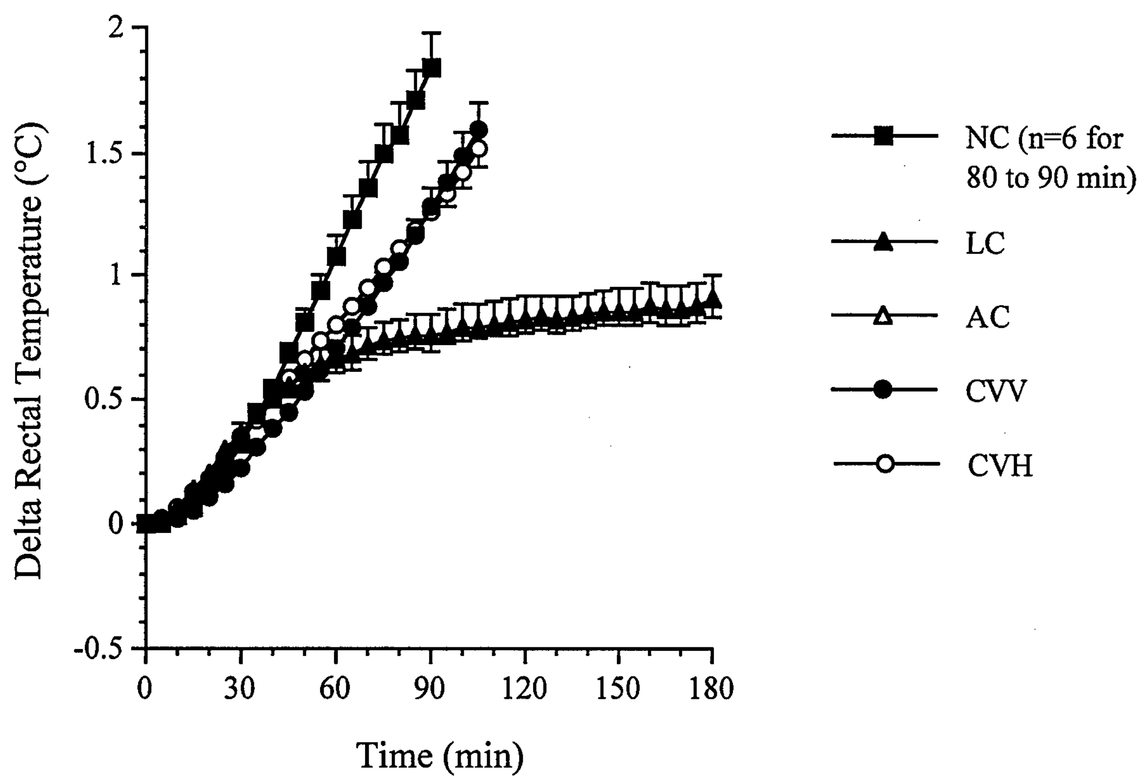


Mean Skin Temperature of Cooled Sites

Figure 3 presents the T_{sk} for the 4 torso sites (upper and lower back, chest and abdomen) that were directly influenced by the cooling systems, and Figure 4A presents $\bar{T}_{sk}$ for the torso. It is apparent that $\bar{T}_{sk}$ for the torso when no cooling was provided was significantly increased compared with the cooling trials shortly after exercise began. Also, initially the torso was cooler when liquid-cooling was provided compared with AC. The differences between LC and AC disappeared during the second hour of walking and then reappeared during the final 70 min of the exposure. For the PCM cooling vests, $\bar{T}_{sk}$ for the

4 torso sites was lower until 85 min of exposure for CVH compared with CVV. These differences reflected a higher skin tempertature for the upper back and chest with the CVV design as shown in Figure 3 whereas abdomen and lower back temperatures were more alike. The $\overline{T}_{sk}$ of the torso for the CVV design was also greater than the $\overline{T}_{sk}$ of the LC and AC systems after 15 min. The $\overline{T}_{sk}$ of the torso for CVH exceeded the $\overline{T}_{sk}$ of LC and AC after 35-40 min of heat exposure. Note that $\overline{T}_{sk}$ of thermoneutrality is 33-34°C, so any system that can keep temperatures at or below this level during exercise in the heat is working well.

Figure 2: Changes in delta rectal temperature during light exercise at 40°C and 30% relative humidity while wearing the nuclear, biological and chemical protective ensemble with no cooling (NC), a liquid- (LC) or air-cooling (AC) system, and a phase-change material cooling vest with a vertical (CVV) or horizontal (CVH) configuration for the cooling material. Values are means (S.E.) for n=7 unless otherwise noted.



Mean Skin Temperature of the Uncooled Sites

Figure 4B shows the $\overline{T}_{sk}$ response for the 4 uncooled temperature sites (leg, foot, hand and head) for the different conditions. Throughout the exercise, AC significantly lowered $\overline{T}_{sk}$ of the uncooled sites compared with both the NC and LC trials. In addition, after 30-40 min of heat exposure, $\overline{T}_{sk}$ of the uncooled areas for AC was significantly reduced compared with the PCM cooling vests. These latter vest designs also showed a small but significant reduction in the $\overline{T}_{sk}$ of the uncooled sites compared with NC after 45 min of exercise. Finally, the $\overline{T}_{sk}$ of these uncooled regions of the body was significantly lower for LC compared with both CVV and CVH after 75 min of heat exposure.

Mean Heat Flow of Cooled Sites

Figure 5A presents $\overline{HF}$ of the torso for the different configurations. The extent of the significant increase in $\overline{HF}$ that approximated 170 $W \cdot m^{-2}$ from the torso was similar for LC and AC compared with the no cooling trial which showed a heat gain during the first 25 min of heat exposure. For the PCM CVH design, $\overline{HF}$ from the torso was similar to LC and AC for the first 90 min of exposure. Thereafter, $\overline{HF}$ for the CVH was significantly reduced and similar to the much lower values of 100 $W \cdot m^{-2}$ observed for the CVV condition.

Mean Heat Flow of Uncooled Sites

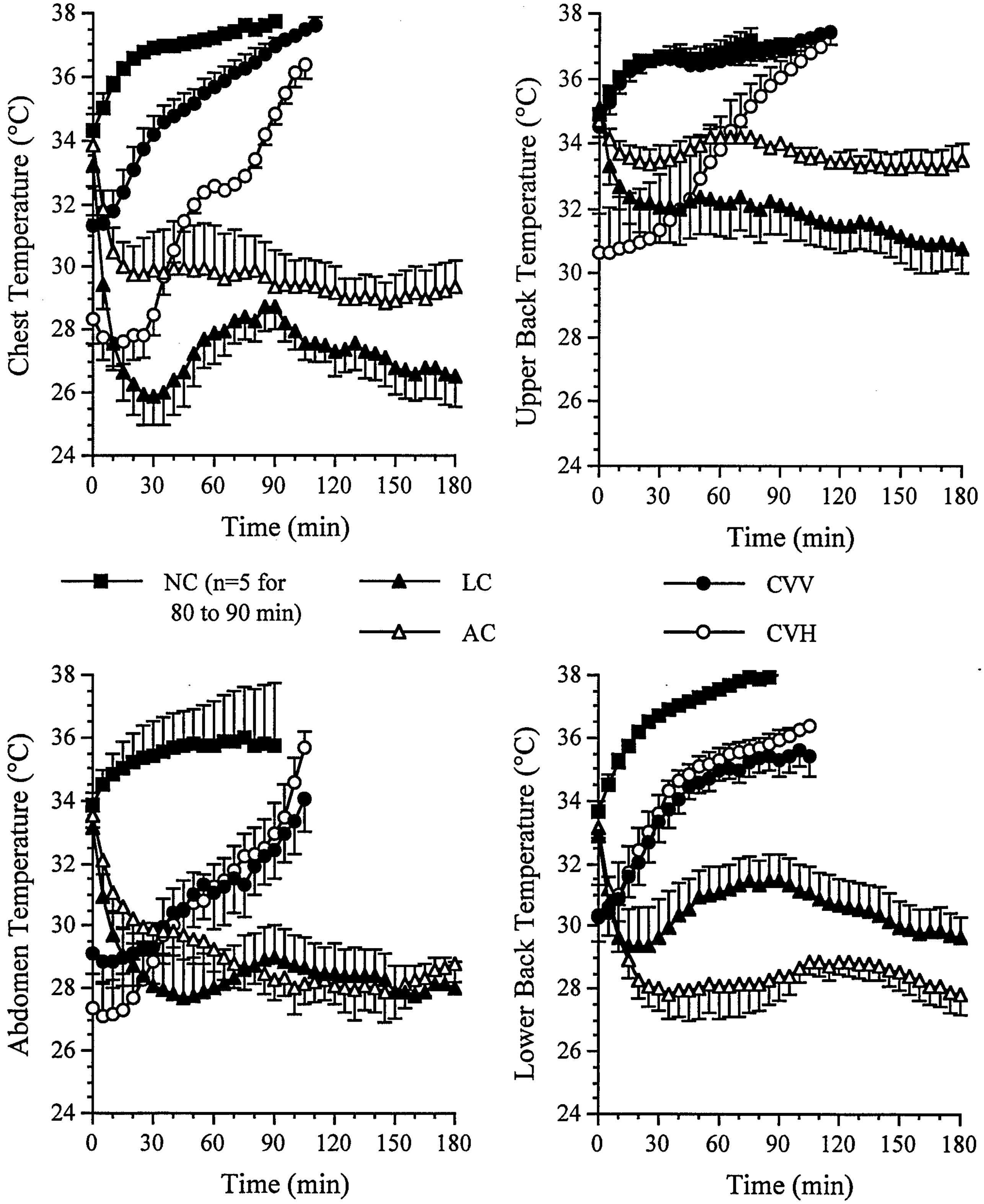
Mean $\overline{HF}$ of the uncooled leg, head, hand and foot is presented in Figure 5B. Throughout the 3 hour exposure, $\overline{HF}$ of 20-25 $W \cdot m^{-2}$ was significantly greater for AC compared with LC which revealed a heat gain that approximated 5 $W \cdot m^{-2}$. Also, $\overline{HF}$ for AC was greater than the other trials for the initial 40 min of data collection. $\overline{HF}$ for NC was increased compared with LC and the PCM vest designs after 30-40 min of heat stress, and eventually the $\overline{HF}$ of 30 $W \cdot m^{-2}$ for the NC condition was significantly greater than all of the other cooling trials. There was no difference in the $\overline{HF}$ of these regions of the body for CVV and CVH, and after 70 min of exercise the $\overline{HF}$ from both of these vests was similar to the air-cooling trial.

Vapour Pressure

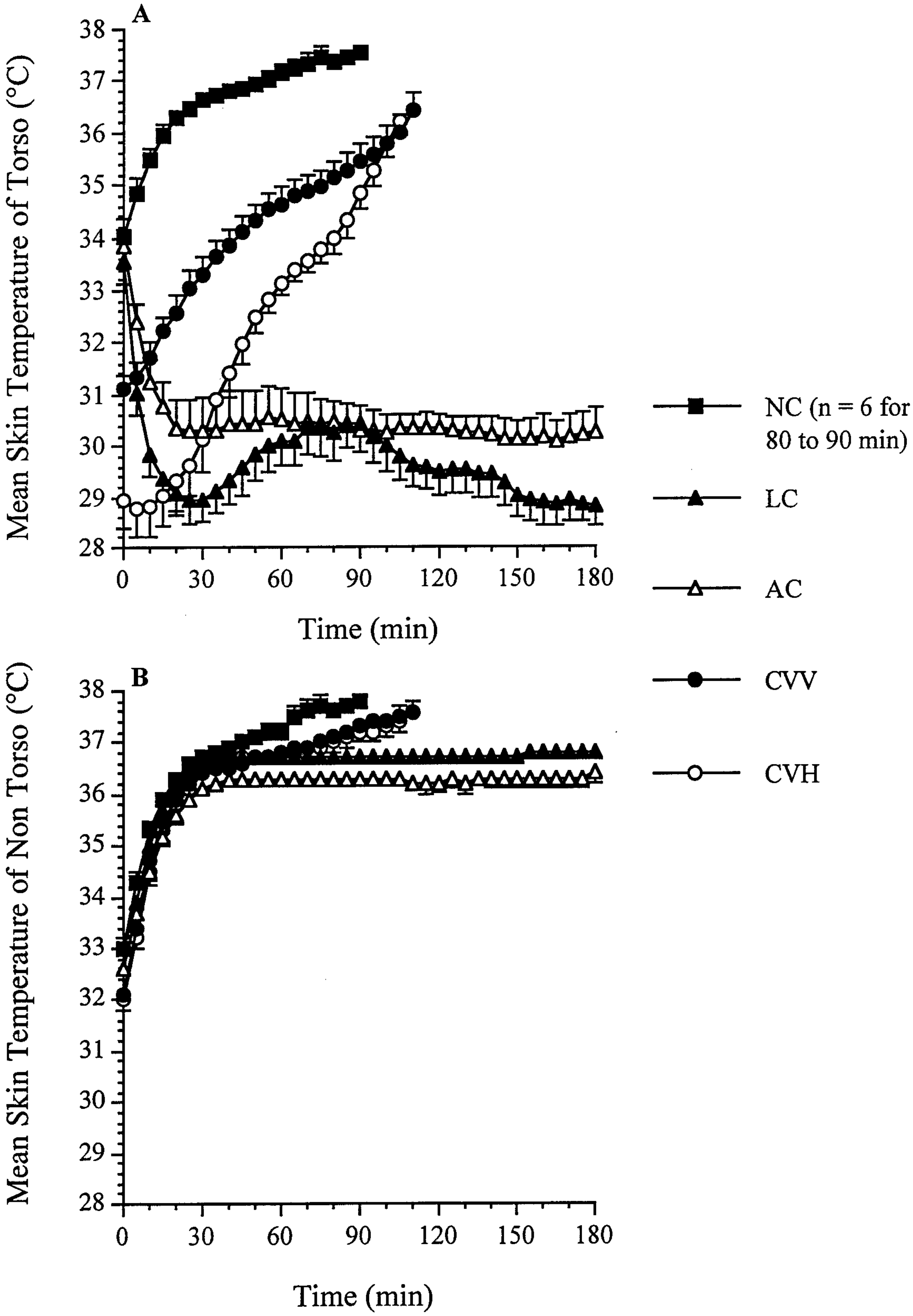
An unweighted average of the upper back and abdomen vapour pressures on the skin surface is presented in Figure 6A. Throughout the exposure, the skin was the driest with the air-cooling and the most wet when no cooling was provided. There was no difference in the vapour pressure at the skin surface under the stand-alone cooling vests but both of these configurations had an increased skin vapour pressure after 10 min of exposure compared with the tethered cooling systems.

A similar pattern of response for the skin vapour pressure was noted for the uncooled thigh as shown in Figure 6B. The main differences between Figures 6A and B were the greater overall vapour pressures recorded on the thigh compared with the torso

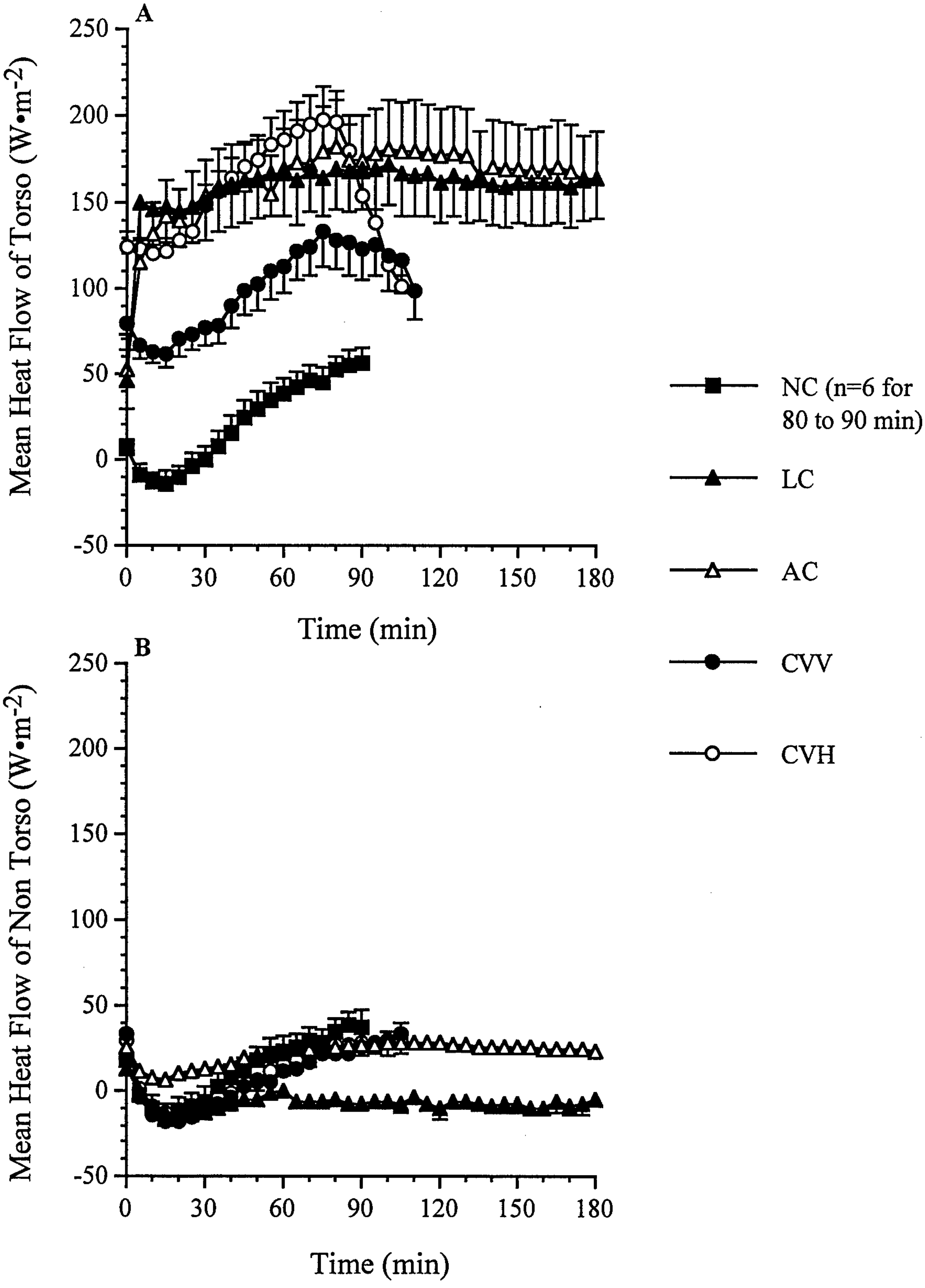
Figure 3: Changes in skin temperature of the chest, upper back, abdomen and lower back during light exercise at 40°C and 30% relative humidity while wearing the nuclear, biological and chemical protective ensemble with no cooling (NC), a liquid- (LC) or air-cooling (AC) system, and a phase-change material cooling vest with a vertical (CVV) or horizontal (CVH) configuration for the cooling material. Values are means (S.E.) for n=7 unless otherwise noted.



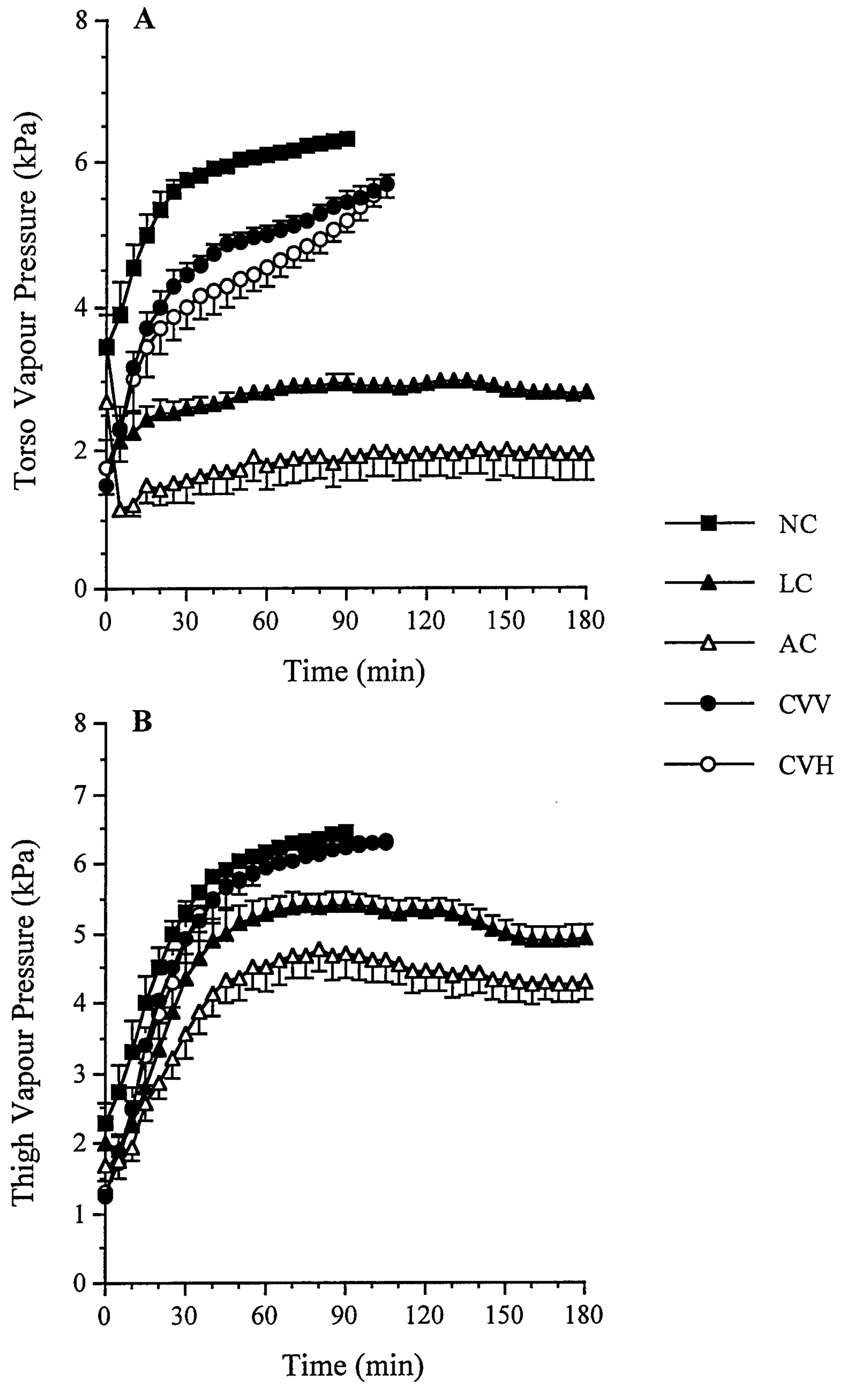
Figures 4A and B: Changes in mean skin temperature of the torso and non-torso regions of the body during light exercise at 40°C and 30% relative humidity while wearing the nuclear, biological and chemical protective ensemble with no cooling (NC), a liquid- (LC) or air-cooling (AC) system, and a phase-change material cooling vest with a vertical (CVV) or horizontal (CVH) configuration for the cooling material. Values are means (S.E.) for n=7 unless otherwise noted.



Figures 5A and B: Changes in mean heat flow of the torso and non-torso regions of the body during light exercise at 40°C and 30% relative humidity while wearing the nuclear, biological and chemical protective ensemble with no cooling (NC), a liquid- (LC) or (AC) air-cooling system, and a phase-change material cooling vest with a vertical (CVV) or horizontal (CVH) configuration for the cooling material. Values are means (S.E.) for n=7 unless otherwise noted.



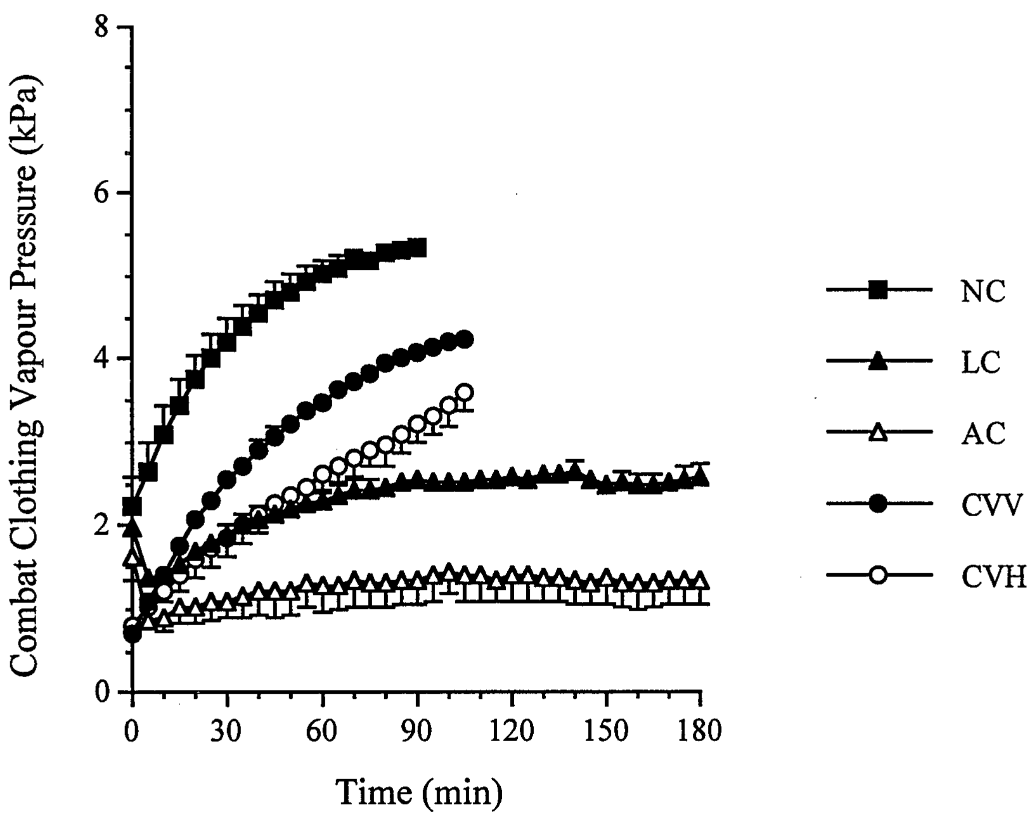
Figures 6A and B: Changes in torso and thigh vapour pressure on the skin during light exercise at 40°C and 30% relative humidity while wearing the nuclear, biological and chemical protective ensemble with no cooling (NC), a liquid- (LC) or air-cooling (AC) system, and a phase-change material cooling vest with a vertical (CVV) or horizontal (CVH) configuration for the cooling material. Values are means (S.E.) for n=6.



and the fact that there were no differences between the NC condition and the stand-alone cooling vests after 25 min of exposure.

Figure 7 presents an unweighted average of the vapour pressures from the upper back and abdomen locations on the outside of the combat clothing. In general, the response was very similar to Figure 6A, with lower overall vapour pressures being observed on the clothing layer. Further, lower values were noted for the horizontal PCM cooling vest compared with the vertical PCM vest design after 15 min of exposure, reflecting both the greater mass of the horizontal vest design and the lower (nonsignificant) vapour pressures at the skin surface.

Figure 7: Changes in torso vapour pressure over the combat clothing layer during light exercise at 40°C and 30% relative humidity while wearing the nuclear, biological and chemical protective ensemble with no cooling (NC), a liquid- (LC) or air-cooling (AC) system, and a phase-change material cooling vest with a vertical (CVV) or horizontal (CVH) configuration for the cooling material. Values are means (S.E.) for n=6.



Rating of Thermal Comfort and Perceived Exertion

Ratings of TC for the torso and whole body are shown in Figures 8A and 8B, respectively. Torso and whole body TC were significantly increased throughout the NC trials compared with the other trials. Ratings of both torso and whole body TC were significantly lower for the LC trial compared with AC and the PCM cooling vests. In addition, torso TC ratings were reduced for AC compared with CVV and CVH throughout the exposure, and whole body ratings were lower for AC compared with the stand-alone vests at 45 min and after 75 min of heat stress.

Figure 9 depicts the changes in RPE for the different conditions. During the heat stress, RPE was increased during NC compared with the LC and AC cooling tests after 30 min and increased compared with the PCM cooling vest trials after 45 min . There were no differences between LC and AC or between CVV and CVH for RPE. The RPE was increased for the CVV and CVH trials compared with LC and AC after 30 min of exposure.

Indices of Heat Tolerance

Table 3 presents the end-point criteria for termination of the trials. It should be noted that all subjects were able to complete the 3 hours of exercise when either the liquid- or air- cooling system was provided and could have continued walking, given that Tre was still below 38.0°C. None of the subjects completed the 3 hours with the PCM cooling vest or with no cooling. For the NC, CVV and CVH trials, volition was stated as the reason for ending the exposure for 67% or 14 or the 21 tests. For 12 of these 14 trials, T_{re} exceeded 38.8°C, thus indicating that a substantial increase in body heat storage had occurrred. Final T_{re} was not different among the trials with no cooling or the stand-alone cooling vest and approached or exceeded 38.9°C for these exposures. Tolerance times were significantly extended when cooling was provided, the increase being greatest with the tethered cooling systems (Table 3). The stand-alone cooling vest with either the horizontal or vertical configuration of the PCM extended tolerance times approximately 30 min or 30% compared with the NC condition.

The time required for a 1.0° or 1.5°C increase in T_{re} was significantly increased when cooling was provided for the exercise trials (Table 3). This increase was greater for the tethered systems compared with the stand-alone vest. There was no difference between LC and AC or between CVV and CVH for these dependent measures.

Figures 8A and B: Changes in ratings of thermal comfort of the torso and whole body during light exercise at 40°C and 30% relative humidity while wearing the nuclear, biological and chemical protective ensemble with no cooling (NC), a liquid- (LC) or air-cooling (AC) system, and a phase-change material cooling vest with a vertical (CVV) or horizontal (CVH) configuration for the cooling material. Values are means (S.E.) for n=7 unless otherwise noted.

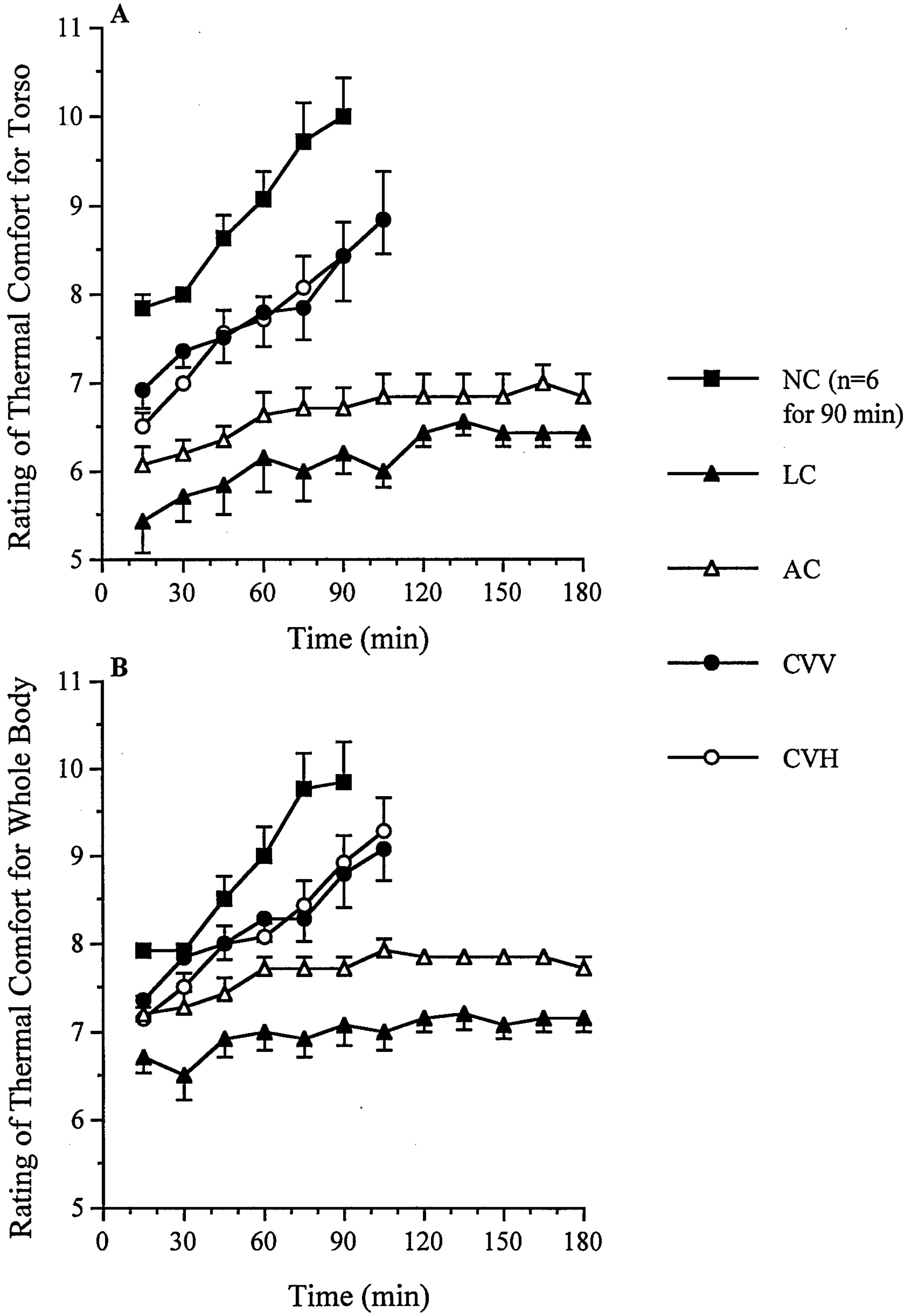
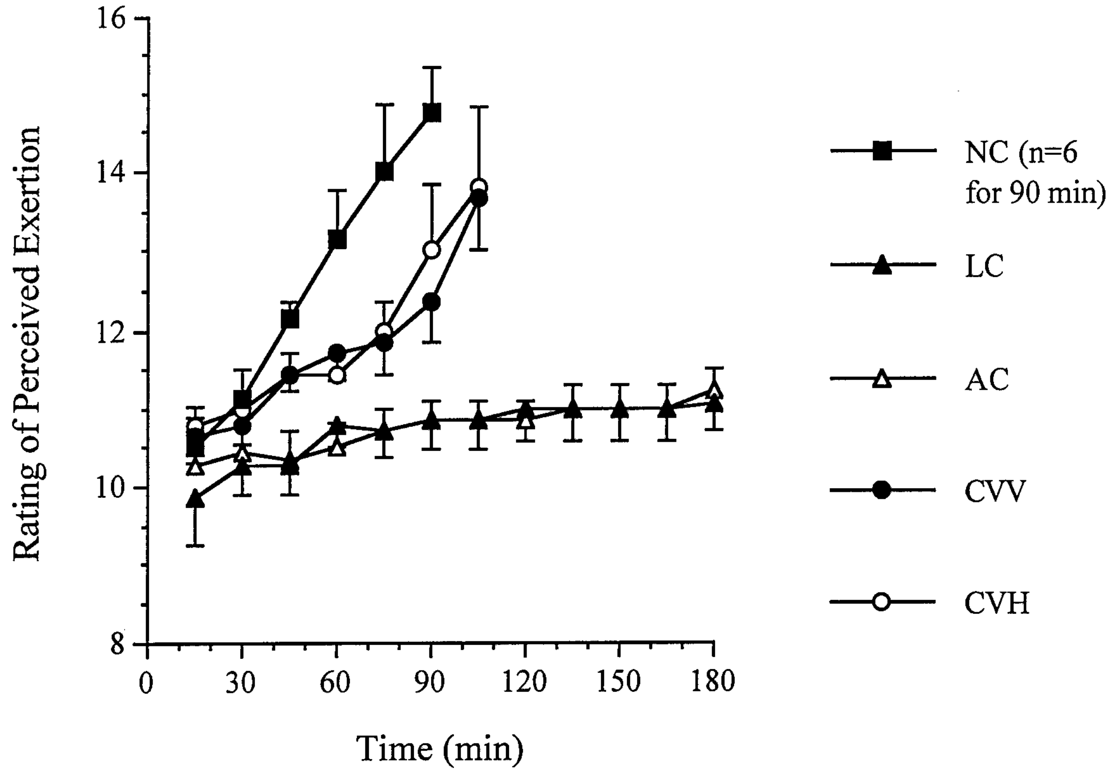


Figure 9: Changes in the ratings of perceived exertion during light exercise at 40°C and 30% relative humidity while wearing the nuclear, biological and chemical protective ensemble with no cooling (NC), a liquid- (LC) or air-cooling (AC) system, and a phase-change material cooling vest with a vertical or horizontal (CVH) configuration for the cooling material. Values are means (S.E.) for n=7 unless otherwise noted.



Discussion

The findings from the present study have clearly shown the effectiveness of both the liquid- and air-cooling systems for reducing the heat strain associated with wearing the NBC protective ensemble during exercise in a hot environment. Application of a liquid- or air-cooling system during light exercise was successful in changing the environmental conditions from uncompensable to compensable. The data have also shown that both of these cooling systems are equally effective and there would be no compelling physiological evidence to favour the selection of one cooling method over the other. This conclusion would agree with the findings reported previously by Shapiro et al. (1982).

The findings from the present study have revealed also that both designs of the

Table 3 Reasons for termination of the trials, tolerance time, final rectal temperature (T_{re}), and the time required for a 1.0°C and 1.5°C increase in T_{re} during light exercise at 40°C and 30% relative humidity while wearing the nuclear, biological and chemical protective ensemble with no cooling (NC), a tethered liquid- (LC) or air-cooling (AC) system, and a stand-alone cooling vest with a horizontal (CVH) or vertical (CVV) configuration for the cooling material. Values are means (S.E.) for n = 7.

Subject	NC	LC	AC	CVH	CVV
1	T_{re}	time	time	volition	volition
2	T_{re}	time	time	volition	volition
3	volition	time	time	volition	volition
4	volition	time	time	volition	T_{re}
5	volition	time	time	volition	volition
6	T_{re}	time	time	volition	volition
7	HR	time	time	HR	HR
Tolerance Time (min)	100.1 (4.3)	180.0^{a} (0.0)	180.0^{a} (0.0)	131.9^{b} (7.5)	129.3^{b} (7.3)
Final T_{re} (°C)	39.10^{b} (0.08)	37.77^{a} (0.07)	37.75^{a} (0.08)	38.90^{b} (0.08)	38.97^{b} (0.10)
Time for a 1.0°C Increase in T_{re} (min)	58.3 (2.4)	167.5^{a} (7.8)	147.5^{a} (16.0)	73.4^{b} (1.6)	77.6^{b} (2.9)
Time for a 1.5°C Increase in T_{re} (min) (n=7)	76.7 (3.9)	>180^{a} (0.0)	>180^{a} (0.0)	105.7^{b} (4.1)	102.0^{b} (4.0)

T_{re} represents 39.3°C, heart rate (HR) represents ≥ 95% of maximal heart rate, volition represents subject's request or experimenter's decision to end the trial and time represents 180 min. Mean values superscripted with the same letter denote a nonsignificant difference.

PCM cooling vest successfully reduced the heat strain associated with wearing the NBC clothing. However, although tolerance time was extended approximately 30%, the subjects still succumbed to conditions of uncompensable heat stress. Some differences in skin temperature and heat flow were noted between the two PCM cooling vest designs during the initial 90 min of heat exposure, but changes in core temperature, heart rate, tolerance time, and ratings of perceived exertion and thermal comfort ultimately were not affected by the vertical or horizontal configuration of the PCM within the cooling vest. Thus, it would appear that the additional 100 kJ or 25% increase in heat capacity associated with the CVH design was unsuccesful in extending heat tolerance compared with the CVV condition in this uncompensable heat stress environment. The increase in heat capacity for the CVH cooling vest should provide an additional cooling power of 100 W for approximatley 15 min. However, it must be remembered that heat would also be gained from the warmer clothing overlaying the vest at a rate dependent on the temperature gradient between this clothing and the vest and the thermal resistance of the covering air and clothing layers. Further, heat flow and skin temperature data are reflective only of the small surface area in contact with the heat flow transducer. Thus, although heat flow data suggested greater cooling with the CVH configuration, these findings do not necessarily reflect the heat flow for the entire vest. The similarities in the heart rate and delta T_{re} responses between the CVV and CVH configurations are not consistent with an apparent increase in heat flow for the latter vest design. Similarly, the fact that heat flow from the CVH cooling vest was similar to both of the tethered cooling systems for the intial 90 min of exposure also is not consistent with the greater increases in heart rate and delta T_{re} for the CVH condition.

The estimates of the heat transfer from the entire body (see Figures 5A and B) during the exercise with the liquid- or air-cooling systems averaged 150 W. However, differences in the rate of evaportive heat loss estimated from changes in dressed weight (see Table 2) between the AC and NC conditions would not suggest that 150 W of additional cooling was provided by the air-cooling system. In fact, changes in dressed weight would imply that there was no difference in the rate of evaporative heat loss with AC during the exercise. However, estimates about the extent of the evaporative cooling at the skin surface determined from changes in dressed weight are difficult because of the uncertainty as to the location of the evaporation within the clothing layers of the protective ensemble. It is suggested that evaporative heat loss could be overestimated by as much as 50% when changes in dressed weight are used to calculate this dependent measure (Cain and McLellan 1998; McLellan et al. 1996).

The improvements in heat tolerance associated with the liquid- or air-cooling systems far exceed the changes that are recorded following the use of the PCM cooling vest or other physiological or clothing manipulations. For example, the separate and combined effects of heat acclimation, aerobic training and hydration status on tolerance during uncompensable heat stress have been examined extensively. Increases in heat tolerance of 20-30 minutes during light exercise at 40°C and 30% relative humidity are common following heat acclimation (Aoyagi et al. 1995, McLellan and Aoyagi, 1996), aerobic training (Cheung and McLellan, 1998b), rehydration during the heat exposure (Cheung and McLellan, 1998a) or the use of the PCM cooling vest in the present study. However, these manipulations were not successful in creating a compensable heat stress environment, as appeared to be the case with both the liquid- and air-cooling configurations in the present study. All subjects were able to complete the 180 min of exercise with the liquid- and air-cooling systems and could have continued longer to extend tolerance times by at least 100% compared with the no cooling condition and at least 50% compared with the PCM cooling vest trials. Changes in clothing design to either undergarment (McLellan et al. 1994 and 1997) or stand-alone concepts (Amos and Hansen 1997, Etienne et al. 1994, McLellan 1996 and McLellan et al. 1997) are more effective in improving heat tolerance than physiological manipulations and in some limited cases, the improvements would be comparable with the liquid- or air-cooling responses recorded in this investigation (Amos and Hansen 1997, McLellan et al. 1994).

The use of a PCM cooling vest for industrial workers may be an easier option than ensuring personnel undergo repeated heat exposures to acquire heat acclimation, participate in regular aerobic exercise to improve cardiovascular fitness, or replenish fluid loss while wearing protective clothing. The use of the cooling vest may also have an application in military and industrial settings where exposure times during light exercise are expected to be between 1 and 2 hours. As shown in Figure 2, the change in T_{re} during the initial 45 min of heat exposure was similar regardless of whether or not cooling was provided. During the second hour of exposure, however, lower T_{re} responses became more apparent when the cooling systems were used. Compared with no cooling after 90 min of exposure, the change in delta T_{re} was reduced by approximately 0.5°C when the PCM cooling vests were worn. In addition to the reduction in physiological strain, these lower core temperatures would be expected to have a positive impact on cognitive performance (Hancock 1982).

In the present study, the objective was to evaluate the cooling capabilities of the various garments, not the heat sinks or refrigeration sources; furthermore, there are no portable chillers that can satisfy the air vest supply requirements; hence, the decision was made to operate the liquid-cooled vest from a tethered supply. However, the PCM cooling garment cannot be separated from its integral heat sink. Thus, it makes sense to compare the PCM cooling system results with other studies of self-contained systems. It should be noted that the liquid-cooled garment used in this study is actually a component of an untethered personal cooling system that uses a 2-L plastic bottle filled with ice as the heat sink. The ice bottle, water pump and battery are carried in an insulated nylon pouch that can be strapped to the body in a variety of positions. Together with the cooling vest, this system represents an additional carried mass of 3.5 kg. The heat of fusion for 2 kg of ice is 670 kJ; if released over 60-75 min one could obtain total maximum cooling levels approximating 185 and 150 W, respectively. These values represent an increase of 85% and 50% compared with the estimates for the CVV and CVH PCM vest designs, respectivley. However, it must be remembered that the ice block will absorb some heat from the environment through the pouch, and this heat gain will be greater than for the PCM vests due to the larger temperature gradient between the ambient environment and the ice bottle, assuming that the insulation covering the ice block and the vest are similar.

From a weight-only perspective, one can expect metabolic rates to be elevated if one carries a greater load. The PCM vests, which weighed 2.3-2.8 kg, showed a 10% increase in metabolic rate compared with the NC condition. Carrying the 3.5 kg ice pack and vest, therefore, should raise metabolic rate by a similar or slightly greater amount. This expected increase in heat production is much less than the increase in cooling capacity of the ice-based or PCM systems (assuming no change in vest performance).

However, if volume and weight are considerations, then the PCM system may be a more practical alternative for short duration heat exposure. The garments can be designed to suit a variety of clothing requirements while being less obtrusive than a liquid-cooling pack. They also operate totally passively and totally quietly, which may be important considerations in some circumstances. From a military NBC perspective, a drawback to the PCM approach is that the cooling vest must be worn close to the skin to be effective; hence, under the NBC coverall. This makes it difficult to replenish the PCM packs without compromising the NBC protection of the current suit. However, future NBC clothing designs may overcome this limitation and allow for the exchange of PCM material.

In summary, the present study has shown that personal cooling systems can significantly attenuate the physiological stress responses to exercise in the heat while wearing NBC clothing. The extent of the impact is highly dependent on cooling garment/system design. Systems such as the air- or liquid cooled garments used in this study can provide relief from thermal stress for extended periods of time if tethered to a suitable chiller. Shorter duration high rates of cooling can/could be achieved by carrying a high-energy-density cooling pack, such as an ice block or the PCM cooling vest, but at a cost of extra weight and bulk.

Acknowledgements

The authors would like to thank Ms. S. Tenaglia and Mr. R. Limmer and Mr. J. Pope for their technical assistance. The time and effort of the subjects in this investigation are greatly appreciated.

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(Security classification of title, body of abstract and indexing annotation must be entered when the overall document is classified)

1. ORIGINATOR (the name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g., Establishment sponsoring a contractor's report, or tasking agency, are entered in section 12.)
Defence and Civil Institute of Environmental Medicine, 1133 Sheppard Ave W., North York, ON M3M 3B9

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Unclassified

3. DOCUMENT TITLE (the complete document title as indicated on the title page. Its classification should be indicated be the appropriate abbreviation (S,C,R or U) in parentheses after the title.)
Efficacy of liquid, air and phase change material torso cooling during light exercise while wearing NBC clothing.

4. DESCRIPTIVE NOTES (the category of the document, e.g., technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)
Technical Report

5. AUTHOR(S) (Last name, first name, middle initial. If military, show rank, e.g. Burns, Maj. Frank E.)
McLellan, Tom M. and Frim, John

6. DOCUMENT DATE (month and year of publication of document)	7.a. NO. OF PAGES (total containing information. Include Annexes, Appendices, etc.)	7.b. NO. OF REFS. (total cited in document)
April 1998	31	33

8.a. PROJECT OR GRANT NO. (if appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant)	8.b. CONTRACT NO. (if appropriate, the applicable number under which the document was written)
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9.a. ORIGINATOR'S DOCUMENT NUMBER (the official document number by which the document is identified by the originating activity. This number must be unique to this document.)	9.b. OTHER DOCUMENT NO.(S) (any other numbers which may be assigned this document either by the originator or by the sponsor.)

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This study compared the thermoregulatory responses with liquid, air and phase change material (PCM) torso cooling during light exercise at 40°C while wearing NBC protective clothing. The liquid- (LC) and air-cooling (AC) systems were powered from external portable chiller units. The PCM cooling vests, which were supplied by Microclimate Systems Incorporated, were worn under the NBC overgarment and were tested with a vertical (CVV) and horizontal (CVH) design. Seven males (29 yrs, 75.6 kg, 1.78 m) performed a no cooling (NC) and 4 cooling trials while walking at 3.5 $km \cdot h^{-1}$ on a treadmill in the environmental chamber. During the NC condition, tolerance times were 100 min and final core temperature was 39.1°C. For the PCM trials (CVV and CVH), tolerance times were extended by 30 min but core temperature still rose to reach values close to 39.0°C indicating that the cooling vests could only delay the exhaustion from the heat exposure. However, with both the LC and AC trials, all subjects completed 180 min of exercise and they could of continued longer given that their core temperatures were still below 38.0°C. The results have shown that the PCM cooling vests are of benefit for work tasks that continue between 1 to 2 hours but these vests are not as effective in reducing the heat strain of wearing NBC clothing in hot environments as liquid- or air-cooling systems.

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