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MICROCLIMATE COOLING SYSTEMS:
A PHYSIOLOGICAL EVALUATION OF TWO
COMMERCIAL SYSTEMS

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NAVY CLOTHING AND TEXTILE RESEARCH FACILITY

NATICK, MASSACHUSETTS

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Only four of the nine subjects were able to complete the CONTROL test. In most cases, use of either of the two cooling systems enabled subjects to complete the 3-hour heat exposures. Rectal temperature responses were similar when either cooling system was used ($P > 0.05$); final rectal temperature averaged 38.1°C . The ILC system elicited slightly lower heart rates than the LSSI system, by an average of 7 b/min ($P > 0.05$). Total body sweat rates were similar for the two systems, and averaged $566 \text{ g/m}^2/\text{h}$ ($P > 0.05$). (U)

The ILC cooling system, which is lighter, less bulky, easier to operate and much less expensive than the LSSI system, experienced many fewer operational difficulties and system failures than the LSSI system. Based on their similarity in reducing heat stress and the ILC system's better operational characteristics and lower cost, the ILC Model 1905 cooling system is recommended over the LSSI Cool Head system for Navy use. (U)

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MICROCLIMATE COOLING SYSTEMS:
AN EVALUATION OF TWO COMMERCIAL SYSTEMS

INTRODUCTION

↙ The Navy Clothing and Textile Research Facility (NCTRF) conducted a laboratory evaluation to compare two commercially available, portable, liquid microclimate cooling systems for their effectiveness in reducing heat stress and for their operational characteristics. The systems were the Model 1905 Cool Vest manufactured by ILC Dover, Inc. (ILC), and the Cool Head manufactured by Life Support Systems, Inc. (LSSI). The two systems were evaluated on nine test subjects wearing the Navy utility uniform and performing light-to-moderate exercise for 3 hours in an environment of 43° C dry bulb, 29° C dew point (WBGT 36 C). Compared with a control test with no cooling, use of either cooling system enabled subjects to complete the 3-hour heat exposures. Rectal temperature responses were the same when either cooling system was used. Heart rates were slightly lower with the ILC Dover system compared to the LSSI system. The ILC systems experienced fewer failures, and were easier to operate than the LSSI systems. The ILC system is also lighter, less bulky, and much less expensive than the LSSI system. Based on their similarity in reducing heat stress, and the ILC Dover system's profile, reliability and lower cost, the ILC Dover Model 1905 Cool Vest system is recommended over the LSSI Cool Head for Navy use. This report describes the two cooling systems and the results of the heat stress evaluation. (R 1) ↘

BACKGROUND

Microclimate cooling systems which cool the "micro-environment" next to the skin have been studied for a number of years (1-7). Various prototype and commercially available systems have been evaluated, including liquid-cooled, gas-cooled, and ice packet systems. A number of these systems have effectively reduced heat stress, but their effectiveness may be limited in cases of prolonged or extreme heat exposures.

(1) Cosimini, H., et al. Determination of the feasibility of two commercial portable microclimate cooling systems for military use. Natick, MA: US Army Natick Research and Development Center, 1985; Technical Report No. NATICK/TR-85/033L.

(2) Kaufman, W.C., and J.C. Pittman. A simple liquid transport cooling system for aircrewmembers. Aerospace Med. 37: 1239-1243, 1966.

(3) Muza, S.R., N.A. Pimental, and H.M. Cosimini. Effectiveness of an air cooled vest using selected air temperature, humidity and air flow rate combinations. Natick, MA: US Army Research Institute of Environmental Medicine, 1987; Technical Report No. T22-87.

(4) Nunneley, S.A. Water-cooled garments: a review. Space Life Sci. 2: 335-360, 1970.

(5) Pimental, N.A., H.M. Cosimini, M.N. Sawka, and C.B. Wenger. Effectiveness of an air-cooled vest using selected air temperature and humidity combinations. Aviat. Space Environ. Med. 58: 119-124, 1987.

(6) Terrian, D.M., and S.A. Nunneley. A laboratory comparison of portable cooling systems for workers exposed to two levels of heat stress. Brooks Air Force Base, TX: USAF School of Aerospace Medicine, 1983; Technical Report No. USAFSAM-TR-83-14.

(7) Young, A.J., M.N. Sawka, Y. Epstein, B. DeCristofano, and K.B. Pandolf. Cooling different body surfaces during upper and lower body exercise. J. Appl. Physiol. 63: 1218-1223, 1987.

The Navy has been concerned with the problem of heat stress, particularly onboard its old, steam-powered ships. On behalf of the Commander in Chief, Atlantic Fleet, the Navy Science Assistance Program (NSAP) requested that NCTRF conduct a shipboard evaluation of commercially available microclimate cooling systems. During April 1987, that evaluation was conducted on the USS LEXINGTON (8). The report of that test details the logistics, feasibility and acceptance of microclimate cooling systems by shipboard personnel. Unfortunately, unseasonably cool weather limited the evaluation of heat stress reduction. Consequently, NSAP requested that NCTRF conduct a laboratory evaluation to directly compare two of the portable, liquid cooling systems for their effectiveness in reducing heat stress. The two systems were the Model 1905 Cool Vest manufactured by ILC, and the Cool Head manufactured by LSSI.

In 1983, a laboratory evaluation of these two systems was conducted at Brooks Air Force Base (6). In that evaluation, subjects wore heavy clothing and worked at a moderate-to-heavy rate in two environments having wet bulb globe temperatures of 36° C and 25° C. In the first environment, the level of heat stress proved so severe that neither cooling system was effective. In the second environment, only three subjects were used, and the cooling medium was replenished in only one of the two cooling systems. Therefore, the data from that test are difficult to interpret.

In 1987, the US Army Natick Research, Development and Engineering Center (USANRDEC) conducted a laboratory evaluation of the LSSI system, the ILC system, and a freon gas cooling system (9). Five subjects wore heavy clothing and exercised at a light-to-moderate work rate in a 38° C dry bulb, 12° C dew point environment (WBGT 26° C). In that evaluation, the LSSI and the ILC cooling systems provided the same calculated heat removal rates and resulted in similar increases in rectal temperature during the first hour of heat exposure. Data after the first 60 minutes, however, could not be analyzed due to subject attrition when the LSSI system was used. Average tolerance times when the LSSI and ILC systems were used were 80 and 175 minutes, respectively. In another evaluation conducted by USANRDEC, the LSSI cooling system was compared with an earlier version of the ILC system (1). However, that ILC system (Model 78) had a totally different configuration from that tested in the present evaluation (Model 1905).

(8) Janik, C.R., B.A. Avellini, and N.A. Pimental. Microclimate cooling systems: a shipboard evaluation of commercial models. Natick, MA: Navy Clothing and Textile Research Facility, 1988; Technical Report No. 163.

(9) DeCristofano, B.S., J.S. Cohen, B.S. Cadarette, and A.L. Allen. An evaluation of commercial microclimate cooling systems. Natick, MA: US Army Natick Research, Development and Engineering Center, 1987; Technical Report No. Natick/TR-88/009L.

DESCRIPTION OF COOLING SYSTEMS

The two cooling systems used in the present evaluation are commercially available, portable, circulating liquid systems. The Model 1905 Cool Vest is manufactured by ILC Dover, Inc., of Frederica, DL (see Figures 1 and 2). It includes a torso vest made of heat-sealed, polyurethane-coated nylon with an inner bladder that allows liquid to flow through. Its backpack contains an 8-volt, rechargeable battery and pump/motor assembly. The backpack also contains a resealable plastic bag, which is filled with water (the circulating liquid) and ice (the cooling medium). The manufacturer recommends 4-8 pounds (1.8-3.6 kg) of ice. In the present evaluation, 6 pounds (2.7 kg) of ice cubes and 1 litre of water were used, making the total weight of the system 13.5 pounds (6.1 kg). As of January 1988, the cost of the ILC system was \$359, which included the vest, two batteries, and one battery charger.

The LSSI Cool Head system used in this evaluation is manufactured by Life Support Systems, Inc., of Mountainview, CA (see Figures 3 and 4). The Cool Head system consists of a torso vest and a head cap constructed of heat-sealed, polyurethane-coated nylon with channels through which the liquid flows. The backpack contains a 6-volt, rechargeable battery, pump/motor assembly, and two frozen liquid canisters. The combined weight of the two canisters is 2.4 kg (the liquid inside the canisters weighs 2.1 kg). The circulating liquid used in the LSSI system is a mixture of propylene glycol in water (23% propylene glycol by weight). The liquid circulates from the pump, to the cap, to the torso vest, to the canisters and then back to the pump. The total weight of the LSSI cooling system is 17 pounds (7.7 kg). The cost of the system as of January 1988 was \$2376. This included one vest/backpack assembly, four canisters, two batteries, one battery charger, one refill kit and 1 liter of recirculating fluid.

METHODS

Test Design and Measurements

Nine male test subjects (average age, 24 years; height, 177 cm; weight, 72 kg) participated in the evaluation. For 6 days prior to testing, subjects were heat acclimated to hot-dry and hot-humid environments by daily, 2-hour heat exposures. Following the heat acclimation, each subject performed five tests: two tests using the ILC cooling system, two tests using the LSSI system, and one control test when no cooling system was worn. Since the performance of the cooling systems could be subject to mechanical difficulties, both systems were tested twice. The order of presentation of the five tests was randomized. The tests were conducted in a controlled climatic chamber: environmental conditions were 43°C (110°F) dry bulb, 29°C dew point (45% relative humidity), with minimal wind speed. These conditions resulted in a wet bulb globe temperature (WBGT) of 36°C (96°F). During each 3-hour heat exposure, subjects walked on a level treadmill at 1.6 m/s (3.5 mph), with 5 minutes of seated rest every half hour (light-to-moderate work rate). They wore the Navy utility uniform, which consists of a T-shirt, long-sleeved chambray shirt, and denim trousers ($i_{cl} = 1.1$, $i_{sk} = 0.6$). When the cooling system was used, it was worn over the T-shirt and under the chambray shirt.

The ice cubes and the canisters that were used in the present evaluation were stored in a freezer at -18°C (0°F). During the heat exposures, thermistor probes were placed in the ice/water of the ILC backpack and against the recirculating fluid in the LSSI heat exchanger unit. (Because of the pressurization of the system and fear of causing a leak, a thermistor was not placed within the LSSI circulating fluid.) When temperature reached 16°C (61°F), the ice or frozen canisters were changed. Although adequate cooling may still be obtained at temperatures above 16°C, this temperature was chosen in the present study to maximize the cooling potential of the two systems. During actual field use of these systems, replenishment of the cooling medium may not be necessary until coolant temperature reaches ~24°C (7 & B. DeCristofano, USANRDEC, personal communication).

In the present study, batteries were replaced after 2 hours of each heat exposure. The following physiological parameters were measured on the test subjects: rectal temperature, chest, arm and leg skin temperatures, and heart rate. Nude and clothed body weights were measured, and evaporation and sweat rates calculated. During any test, a subject was removed from the heat exposure if his rectal temperature exceeded 39.5°C (103°F), if his heart rate exceeded 180 b/min for 5 minutes, or if he was unable to continue walking unassisted.

Statistical Analysis

The data from the control tests (no cooling system) are presented graphically; but, since five of the nine subjects dropped out early during those tests, these data were not included in the statistical analyses. Statistical analyses were performed on the physiological data from the second trial of each of the two cooling systems. The second trial was chosen rather than the first because fewer complete mechanical failures of the cooling systems occurred during the second trial. (When complete mechanical failure occurred, the subject was withdrawn from the heat exposure.) The data were analyzed using repeated measures analyses of variance. Tukey's test was used to locate the significant differences. Significance was accepted at the 0.05 level.

RESULTS

During the control test, only four of the nine subjects were able to complete the 3-hour heat exposure; tolerance time for the remaining five subjects ranged from 88-134 minutes (average 114 minutes). Tolerance time was increased when either of the two cooling systems was used. Of the 18 tests using the ILC system (nine subjects x two trials), only once was a subject removed early from the heat exposure (after 148 minutes). At that time, although there were no problems with the cooling system, his rectal temperature was 39.2°C, and he felt quite faint. Of the 18 tests with the LSSI cooling system, there were four cases when subjects were removed early from the heat exposure. In two cases, the cooling system became totally inoperable (trial #1). The third subject was removed because of nausea (trial #1); the fourth subject reached our heart rate limit (trial #2). In all other cases, subjects completed the 3-hour heat exposures when the cooling systems were used.

During the 3-hour heat exposures, subjects walked at 1.6 m/s (3.5 mph) for 25 minutes and sat for 5 minutes every half hour. The metabolic rate during rest is approximately 105 watts, and while walking at this speed is approximately 395 watts (10). The additional weight of the cooling systems (7 kg) increases the metabolic rate during the walk by approximately 30 watts (10). Time-weighted metabolic rates, therefore, were 350 watts when the cooling system was not used, and 370 watts when the systems were used. This represents a light-to-moderate work rate.

As seen in Figure 5, there was no significant difference in rectal temperature responses when either the ILC or the LSSI cooling system was used ($P>0.05$). Final rectal temperature at 180 minutes averaged 38.0 and 38.2°C with the ILC and the LSSI systems, respectively.

Mean weighted skin temperatures were to be calculated from the chest, arm and leg skin temperatures, which were measured with thermocouples. Chest temperature measurements, however, were often unusually low. This may have been because the non-insulated thermocouple lay against one of the cooling channels of the vest (not truly measuring chest skin temperature). The skin temperature data, therefore, are not detailed in this report.

Heart rate responses are presented in Figure 6. Heart rate was slightly lower when the ILC system was used than when the LSSI system was used ($P<0.05$). Final heart rate averaged 133 b/min with the ILC system and 140 b/min with the LSSI system.

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

As depicted in Figure 7, there was no significant difference in total body sweat rate when either of the cooling systems was used ($P > 0.05$). Sweat rate averaged 525 and 606 g/m²/h for the ILC and the LSSI systems, respectively. Evaporation rates were calculated from differences between initial and final nude and clothed body weights. These calculated rates (~400 watts), however, far exceeded the calculated maximum evaporative capacity of the environment (<200 watts). This was probably because our method of calculating evaporation rates from body weight losses assumes that all of the sweat was evaporated except for that left in the clothing. This method does not account for the sweat which dripped onto the floor. In this evaluation, the amount of dripped sweat was probably significant, accounting for the large discrepancy between our "measured" evaporation rates and the calculated maximum capacity of the environment. Therefore, the evaporation rate data from the present study were not analyzed.

DISCUSSION

Effectiveness in Reducing Heat Stress

Rectal temperature responses were the same when either the ILC or the LSSI cooling system was used. Both systems enabled subjects to thermoregulate after an initial rise in core temperature of approximately 1.0°C (see Figure 5). For the first 30 minutes of heat exposure, rectal temperature rose at similar rates for all tests regardless of whether a cooling system was used (Figure 5). This "obligatory" heat storage results from a change in the thermoregulatory set point as a function of exercise level (11,12). During the control test, body temperature continued to rise; this is expected because the environment falls outside the "prescriptive zone" in which thermal equilibrium will be achieved as a function of work only and not external heat load (13). In effect, use of the microclimate cooling systems served to extend the boundaries of the prescriptive zone for exercise at this intensity. This initial rise in rectal temperature during the first 30 minutes of exercise, even when microclimate cooling is used, can be seen in other evaluations of microclimate cooling (5,6).

(11) Nielsen, B., and M. Nielsen. Body temperature during work at different environmental temperatures. Acta Physiol. Scand. 56: 120-129, 1962.

(12) Saltin, B., and L. Hermansen. Esophageal, rectal, and muscle temperature during exercise. J. Appl. Physiol. 21: 1757-1762, 1966.

(13) Lind, A.R. A physiological criterion for setting thermal environmental limits for everyday work. J. Appl. Physiol. 18: 51-56, 1963.

When the ILC cooling system was used, heart rate was slightly lower than when the LSSI system was used. This could be due to the difference in weight between the two systems: the ILC is 1.6 kg (3.5 pounds) lighter than the LSSI. When the ILC system was used, temperatures from the thermocouple on the chest were significantly lower than when the LSSI system was used. This could be attributed to colder circulating liquid in the ILC system, due to a more efficient heat exchanger design. Firstly, in the ILC system, there is direct contact between the circulating fluid and the cooling medium (ice cubes); in the LSSI system, heat transfer must occur across the plastic bag containing the circulating fluid and the metal canister. Secondly, as the ice in the ILC system melts, it is mixed with the circulating fluid, resulting in lower fluid temperature. In the LSSI system, this does not occur because the cooling medium is isolated from the circulating fluid. Thirdly, the surface area of the ice cubes used in the ILC system is greater than the surface area of the canisters in the LSSI system, thereby creating a greater area for heat transfer.

In one instance, a subject using the ILC cooling system was removed early from the heat exposure because he felt faint. The cooling system had been working properly during the test, and although the subject's skin temperature was low, his rectal temperature rose at a steep rate. Upon removal from the heat chamber, the subject's chest felt cold to the touch. In this case, it appeared that the coldness of the cooling vest caused local vasoconstriction, reducing the body's ability to dissipate heat. (The same subject did not show this vasoconstrictive response during the first trial of the ILC cooling system.) This could be prevented by wearing the ILC vest over the shirt, lowering the cooling setting, or turning the cooling vest off for a while. (In the case of this subject, local vasoconstriction was not considered. Therefore, as the increase in his rectal temperature was observed, his cooling system was set at maximum.)

Operational Characteristics

Three different ILC units and three different LSSI units were used in the present evaluation. All of the systems were purchased in 1986. The ILC systems were used in one previous evaluation; the LSSI systems were used in two previous evaluations. In the present evaluation, each individual cooling unit was used six times, for 3 hours per test. During the tests, there were no significant operational problems with the ILC systems. On several occasions, the on/off toggle switch was accidentally shut off when the subjects sat down for the rest break; however, the loss of cooling was soon noticeable (within 1 or 2 minutes) and therefore corrected.

Of the 18 trials using the LSSI cooling system, on five occasions the system became inoperable and could not be restarted; these failures occurred with each of the three different LSSI units tested. During several other tests, the LSSI units had intermittent difficulties, which were corrected by shaking the backpack (probably releasing air blocks) and/or loosening the backpack straps (which had presumably pinched off the flow). When this occurred and the LSSI system lost cooling, it was not as quickly noticed by the subjects as when the ILC system was used; this was also reported in the study by USANRDEC (9). On at least three occasions, only part of the LSSI vest provided cooling, presumably due to air blocks or crimping.

Our operational data are consistent with the findings of Brooks Air Force Base, who described the reliability of the ILC system as "excellent" and the LSSI system as "extremely poor" (6). In the evaluation conducted by USANRDEC, it was concluded that, due to logistical burdens, neither cooling system is desirable for large scale military use; however, the ILC system has potential for specialized, short-term missions (9).

In most cases, the LSSI systems required two canister changes during the 3-hour heat exposures: at an average of 70 and 134 minutes. The ILC systems required one ice change, at an average of 98 minutes. Both cooling systems tested have controls to adjust the amount or rate of coolant which flows through the vest. In the present evaluation, the amount of cooling was adjusted according to each subject's preference. When the LSSI system was used, seven of the nine subjects used the maximum cooling setting by 12 minutes into the heat exposure. One of the remaining subjects used maximum cooling after 32 minutes, and one subject chose mid-cooling for the entire 3 hours. With the ILC system, seven of the nine subjects used maximum cooling after 10 to 146 minutes (average 60 minutes); two subjects chose mid-cooling throughout the exposure.

Subject Preference

All nine of the test subjects in this evaluation preferred the ILC cooling system over the LSSI system. They commented that the ILC system felt cooler than the LSSI system, was lighter and less bulky, and was less susceptible to problems. Several subjects recommended that the ILC shoulder straps be padded, and that the side straps be improved so that the backpack would not tend to slide down. One subject liked the cooling cap included in the LSSI system; the other subjects, however, complained of feeling only minimal head cooling, and/or headaches from wearing the cap.

Other Factors

Even when performed by experienced personnel, the filling, fluid replenishment, and purging procedures required on the LSSI cooling systems took much more effort than the filling procedure required on the ILC system. It was faster, however, to change the canisters of the LSSI system than to drain the water and add ice cubes to the ILC system (although the LSSI system required a cooling medium change more often than the ILC). The ILC system uses either ice or plastic freezer packs as the cooling medium. If freezer packs were used, the procedure to replenish the cooling medium would be much faster, because the need to drain the excess water would be eliminated. The LSSI system uses a glycol/water mixture as the circulating liquid (made by the manufacturer, \$18 per liter); the ILC system uses water. A filler kit (\$35) is needed to fill the LSSI system with the circulating liquid. The LSSI canisters are \$11 each; the ILC uses ice or freezer packs (\$2 each). The LSSI batteries are \$130 each and the ILC batteries are \$55 each. The LSSI battery charger is \$43; the ILC charger is \$55. The total cost of purchasing the ILC Model 1905 cooling system (\$359) is only 15% of the cost of the LSSI Cool Head system (\$2376); seven ILC systems could be purchased for the price of one LSSI system. (These prices are correct as of January 1988.)

CONCLUSIONS AND RECOMMENDATION

1. Under the conditions tested, the ILC Dover Cool Vest and the LSSI Cool Head were similarly effective in reducing physiological strain and increasing tolerance time to work in the heat.
2. Very few operational difficulties occurred with the ILC system; the LSSI system, however, experienced a significant number of failures and operational difficulties.
3. All nine of the test subjects in this evaluation rated the ILC system as cooler, lighter, less bulky, and better overall than the LSSI system.
4. There is a dramatic cost difference between the two systems: \$359 for the ILC Dover Model 1905, compared to \$2376 for the LSSI Cool Head.
5. The ILC Dover cooling system is recommended over the LSSI system for potential Navy shipboard use.

ADDENDUM

The ILC Dover cooling systems used in this evaluation (Model 1905 Cool Vest) were purchased in 1986. In 1987, ILC Dover changed the manufacturer of its Cool Vest and some changes to the system were made. On the newer cooling systems,

- 1) the polarity of the battery is reversed;
- 2) the plastic bag which contains the water and ice is smaller;
- 3) the zipper on the backpack is plastic rather than brass and is less sturdy;
- 4) the pull tabs on the seal of the plastic bag are less sturdy;
- 5) the drain tube is difficult to close without spilling water.

Because the polarity of the battery was reversed, the mechanical components of the old and the new systems cannot be interchanged (battery, pump, charger). With the smaller plastic bag, less ice can be used and therefore the coolant will have to be replaced slightly more often. Items 3-5 may make the newer systems more prone to operational difficulties than the older systems.

Appendix A. Illustrations



Figure 1. ILC Dover Model 1905 Cool Vest (front view).



Figure 2. ILC Dover Model 1905 Cool Vest (rear view).



Figure 3. LSSI Cool Head System (front view).



Figure 4. LSSI Cool Head System (rear view).

43°C DRY BULB, 29°C DEW POINT
 Metabolic Rate 360 W

CONTROL ILC SYSTEM LSSI SYSTEM

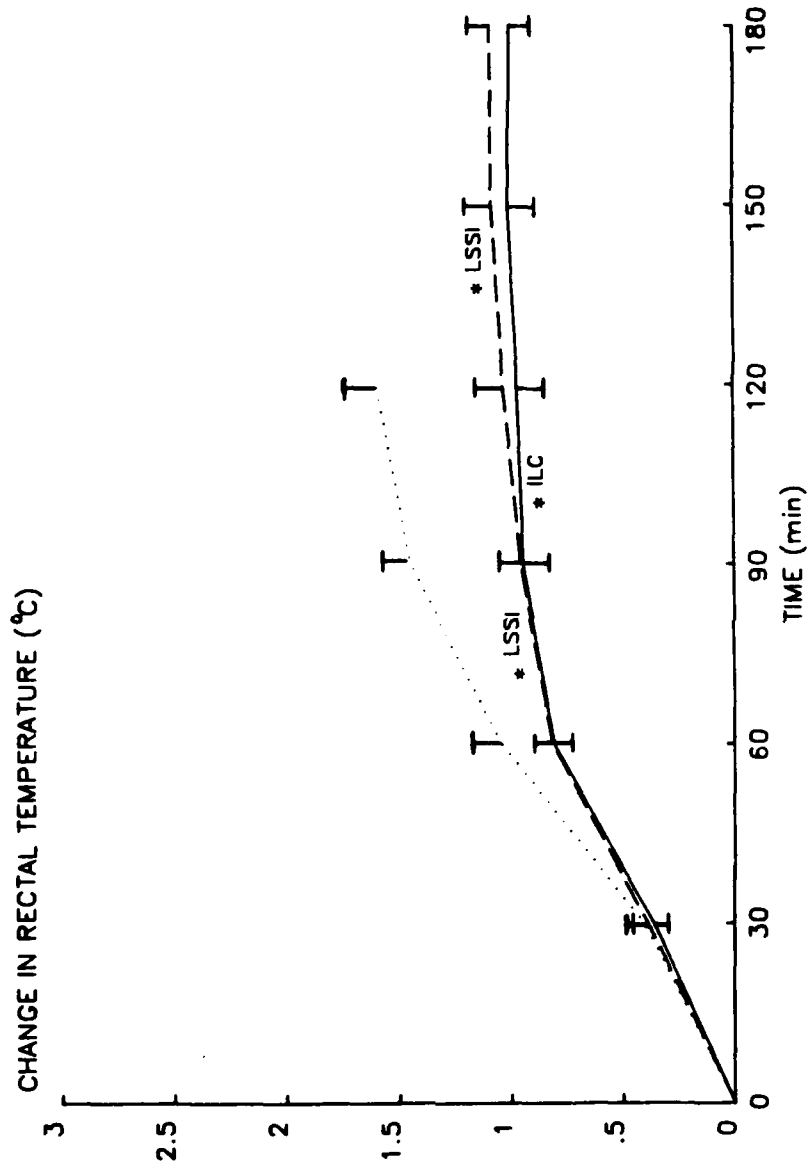


FIG. 5. Change in rectal temperature from initial value for the control and cooling tests. T indicates SE; * indicates average time of cooling system ice change.

43°C DRY BULB, 29°C DEW POINT
Metabolic Rate 360 W

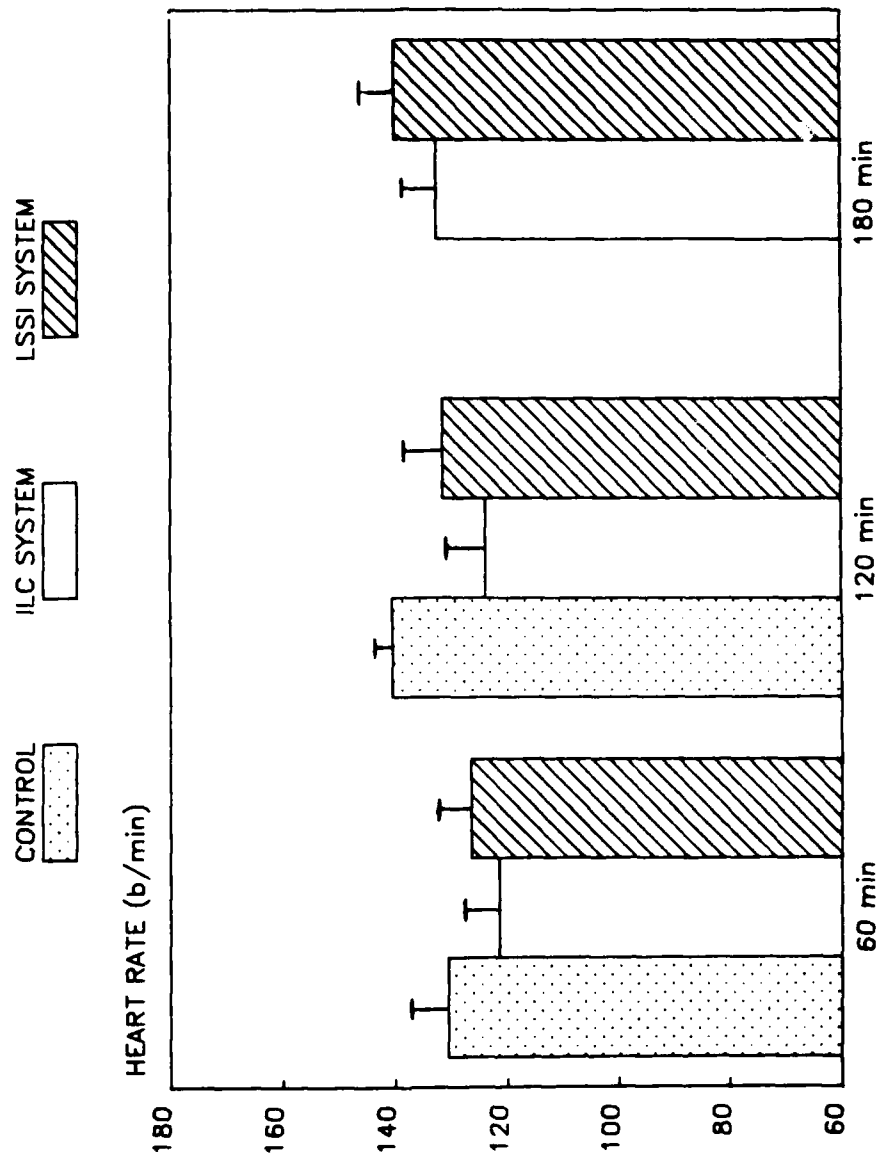


FIG. 6. Heart rate at 60, 120 and 180 min for the control and cooling tests.
T indicates SE.

43°C DRY BULB, 29°C DEW POINT
Metabolic Rate 360 W

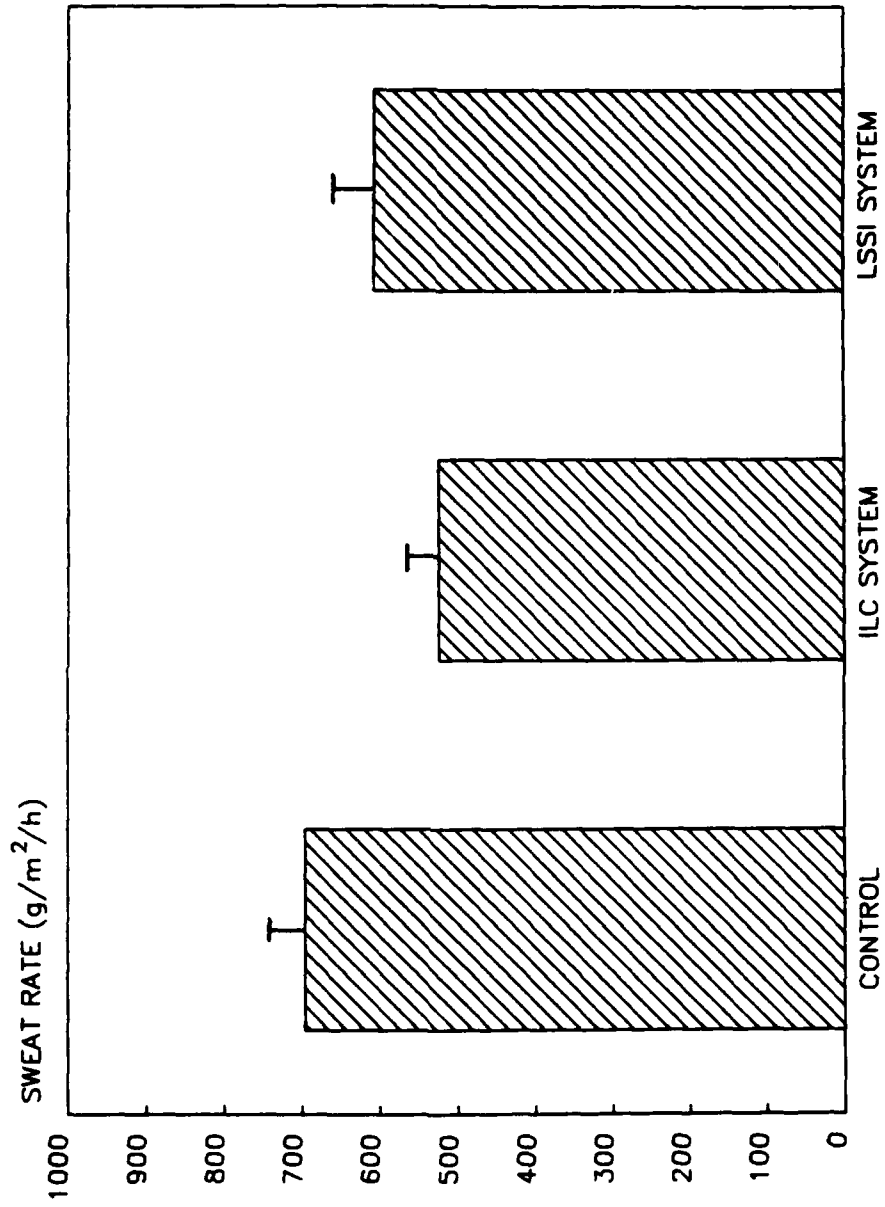


FIG. 7. Total body sweat rate for the control and cooling tests. T indicates SE.