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EFFECTIVENESS OF THREE PORTABLE COOLING SYSTEMS IN REDUCING HEAT STRESS

In 1986 the Navy Science Assistance Program (NSAP) requested that Navy clothing and Textile Research Facility (NCTRF) conduct an evaluation of the feasibility of using commercially-available microclimate cooling systems on Navy ships. In April 1987 NCTRF evaluated five commercial cooling systems during a 10-day cruise on the USS Lexington (1). Of those five systems, two an air-cooled and a liquid-cooled system - were found to be feasible and accepted by shipboard personnel. However, because of the limitation on mobility imposed by the tether cord of the air-cooled system, only the portable liquid-cooled system (ILC Dover Cool Vest) was recommended for near-term shipboard use. Several months after the shipboard testing, NCTRF conducted a laboratory evaluation to quantitate and compare the effectiveness of two of the liquid cooling systems (the ILC Dover Cool Vest and the LSSI Cool Head) in reducing heat stress (2). The two systems were found to be equally effective in reducing thermal strain; but due to its simpler operation and much lower cost, the ILC Dover Cool Vest was recommended over the LSSI Cool Head. Therefore, based on the results of the shipboard and laboratory tests, NCTRF recommended the ILC Dover Cool Vest for near-term Navy use.

Recently, NSAP requested that NCTRF evaluate an additional type of cooling system, a "passive" cooling system consisting of a vest which holds frozen gel packs against the torso. These vests are simple to use and contain no moving parts or batteries. If effective in reducing heat stress, they would be particularly suitable for shipboard use where individual cooling systems may be used for 8-12 hours each day. Therefore, in March 1988 NCTRF conducted an evaluation of two passive cooling systems along with the battery-operated liquid cooling system previously tested and recommended. The two passive cooling systems included the SteeleVest manufactured by Steele, Inc. of Kingston, WA, and the Stay Cool Vest manufactured by the American Vest Co. of Sunset Beach, CA; the liquid cooling system was the Model 1905 Cool Vest manufactured by ILC Dover, Inc. of Frederica, DE.

(1) 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, 1987; Technical Report No. 163.

(2) Pimental, N.A., B.A. Avellini, and C.R. Janik. Microclimate cooling systems: a physiological evaluation of two commercial systems. Natick, MA: Navy Clothing and Textile Research Facility, 1988; Technical Report No. 164.

Description of Cooling systems: The ILC Dover Model 1905 Cool Vest contains a battery and pump which circulates cool liquid through the vest. The vest is made of heat-sealed, urethane-coated nylon with an inner bladder through which the liquid flows. A backpack contains the pump, rechargeable battery, and a plastic bag to hold water and ice. In this evaluation, 1 liter of water and 2.3 kg (5.0 lb) of standard ice cubes were used; the total weight of the system was 5.7 kg (12.5 lb). The Cool Vest comes in one size only; side straps are used to tighten the vest against the torso. The systems used in the present evaluation were purchased in January 1988. The cost of each system including two batteries and one battery charger was $359 (Cool Vest with one battery, $249; additional battery, $55; battery charger, $55).

The SteeleVest consists of a torso vest with six pockets for the frozen gel packs (three pockets on front, three on back). The vest has a cotton canvas shell and the pockets are externally insulated with Thinsulate. In this evaluation, the vest was used with 4.6 kg (10.2 lb) of frozen gel packs; the total weight of the system was 5.1 kg (11.3 lb). The vest comes in one size only~ two straps are used to tighten the vest around the torso. As of February 1988, the cost of the SteeleVest including two sets of gel packs was $204 (vest with one set of gel packs, $150~ additional set of gel packs, $54).

The American stay Cool Vest consists of a nylon vest with six pockets for frozen gel packs (two pockets on front, four on back). The vest holds 2.3 kg (5.1 lb) of frozen gel packs~ total weight of the system is 2.5 kg (5.6 lb). The vest has side lacing to adjust the fit and is available in sizes small, medium and large. As of February 1988, the cost of the American vest including two sets of gel packs was $60 (vest with one set of gel packs, $40; additional set of gel packs, $20).

Test Design: In the present evaluation, the cooling systems' ice cubes and gel packs were frozen and stored in a freezer at -15^{0}C (5^{0}F). During testing, thermocouples were placed in the liquid of the ILC system and against two of the gel packs in the Steele and American vests. When the temperature of a system reached 20^{0}C (68^{o}F), that system's coolant (ice cubes or frozen gel packs) was replaced. In the Steele and American vests, the gel packs were also checked manually for melting to ensure that they were replaced when almost melted. The batteries in the ILC systems were replaced after 2 hours, or earlier if battery failure occurred. The temperature regulating valve of the ILC system was adjusted according to subject preference and these adjustments were noted.

Eight male subjects participated in the evaluation (average age, 20 yr; height, 177 cm; weight, 70.5 kg). They were initially heat acclimated for 2 weeks by daily, 2-hour heat exposures. Each subject then performed four tests one with no cooling system (control test) and one using each of the three cooling systems. The order of presentation of the four tests was randomized. Testing was conducted in a controlled climatic chamber. Environmental conditions were kept constant at 43^{0}C dry bulb temperature (110^{o}F), 29^{0}C dew point temperature (84^{o}F; 45% relative humidity), with minimal wind speed. These conditions resulted in a wet bulb globe temperature (WBGT) of 36^{0}C (96^{o}F). During the heat exposures, subjects wore the Navy utility uniform, consisting of denim trousers, long-sleeved chambray shirt, and T-shirt. When the cooling systems were used, they were worn over both the T-shirt and the chambray shirt. During each test, subjects attempted to complete 3 hours of heat exposure while walking on a level treadmill at 1.6 m/s (3.5 mph). A subject was removed early from the heat exposure if his rectal temperature exceeded 39.5^{0}C (103^{0}F), if his heart rate exceeded 180 b/min for 5 minutes, or if he was unable to continue walking unassisted. To prevent significant dehydration, subjects were encouraged to drink water during the heat exposures.

Measurements: The following physiological parameters were measured on the test subjects: rectal temperature, chest, arm and leg skin temperatures, and heart rate. Total body sweating rate was calculated from pre- and post-test nude body weights, adjusted for water consumption. Periodically during each heat exposure, subjects were asked for a numerical rating corresponding to how cool or warm they felt. The time of each coolant and battery change, and all operational difficulties were recorded. On the last day of testing, the Subjects were individually interviewed and asked for their comments on each of the three cooling systems.

Statistical Analysis: The data were statistically analyzed using repeated measures analyses of variance. since a number of Subjects terminated the heat exposure early during the control test and when the American cooling system was used, data from these tests were statistically analyzed, and compared to the ILC and Steele data, for the first 2 hours only. Separate analyses were performed on the data from the ILC and Steele tests for all 3 hours. Rectal temperature, skin temperature and heart rate data were analyzed using the data points every 30 minutes (two-way repeated measures analyses of variance: time x cooling vest). The thermal sensation data were analyzed at 60-minute intervals. One-way analyses of variance (cooling vest) were used to analyze the sweating rate data and the time of first coolant change. Tukey's test was used to locate the significant differences; significance was accepted at the 0.05 level.

Tolerance Time: During the control test when no cooling system was used, only three of the eight subjects were able to complete the 3-hour heat exposure. Of the five subjects who terminated the test early, two reached a pre-determined rectal temperature limit (39.5^{0}C), one reached a heart rate limit (180 b/min for 5 minutes), and two voluntarily withdrew (nausea, unable to continue walking). Tolerance time for those Subjects ranged from 124-146 minutes. When the American cooling system was used, two of the eight Subjects were unable to complete the 3-hour heat exposure due to nausea and light-headedness; their tolerance times were 138 and 165 minutes. When the ILC and the Steele systems were used, all eight Subjects were able to complete the 3-hour heat exposure.

Rectal Temperature: Figure 1 illustrates the changes in rectal temperature for the control test (no cooling) and when each of the three cooling systems was used. The graph depicts the averaged data for all eight test Subjects. For the control and American tests, the data are plotted up to 120 minutes, before any Subjects dropped out; the data from the ILC and Steele tests are plotted up to 180 minutes. Comparing the rectal temperature data for the ILC and the Steele tests over the 3-hour heat exposure, there were no significant differences between the two systems ($p<0.05$). Comparing the data for all of the tests over the first 2 hours, several statistical differences were found. At 60 minutes of heat exposure, the increases in rectal temperature with the ILC and Steele systems were less than for the control test ($p<0.05$); the increase in rectal temperature with the American system compared to the control test approached statistical significance ($p=0.06$). At 90 and 120 minutes, all three cooling systems resulted in less of an increase in rectal temperature than for the control test ($p<0.05$). Also, the increase in rectal temperature with the Steele system was less than when the American system was used (at 90 and 120 minutes) ($p<0.05$). The increases in rectal temperature after 2 hours of heat exposure averaged 1.8 (±SD=±0.6), 1.4 (±0.4), 1.3 (±0.5) and 1.1 (±0.3) °c for the control, American, ILC and Steele tests, respectively. At 2 hours, absolute rectal temperatures were 38.7 (±0.4), 38.4 (±0.3), 38.3 (±0.3) and 38.0 (±0.2) °c for the control, American, ILC and Steele tests, respectively. After 3 hours of heat exposure, the increases in rectal temperature averaged 1.4 (±0.5) and 1.2 (±0.4) °c for the ILC and Steele tests, respectively.

Skin Temperature: Mean weighted skin temperature was calculated from chest (50%), arm (14%) and leg (36%) skin temperatures. Figure 2 illustrates mean weighted skin temperature responses for the control test and when each of the three cooling systems was used. At all times, skin temperatures with the American cooling system were not significantly different than for the control test. Throughout the test, skin temperatures with the ILC and Steele systems were lower compared to the control and American ($p<0.05$), with one exception: at 120 minutes, there was no significant difference between Steele and American. Due to lower chest temperatures, mean skin temperatures with the ILC system were lower than the Steele system ($p<0.05$) at all times except at 90 minutes. Mean weighted skin temperatures after 2 hours of heat exposure averaged 37.0 (±0.5), 36.6 (±0.6), 35.4 (±0.9) and 32.3 (±1.4) °C for the control, American, Steele and ILC tests, respectively.

Heart Rate: Figure 3 illustrates heart rate responses for the control test and when each of the three cooling systems was used. Comparing the ILC and Steele cooling systems, there were no significant differences in the heart rates at any time period. From 60 minutes on, however, heart rates with these two systems were lower than for the control test ($p<0.05$). Also, heart rate with the Steele system was lower than with the American system at 120 minutes ($p<0.05$). After 2 hours of heat exposure, heart rates averaged 150 (±21), 142 (±21), 131(±15) and 129 (±22) b/min for the control, American, ILC and Steele tests, respectively. After 3 hours of heat exposure, heart rates averaged 142 (±14) and 138 (±23) b/min for the ILC and Steele tests, respectively.

Sweating Rate: Total body sweating rates for the various test conditions are illustrated in Figure 4. Sweating rates with the ILC and Steele systems were not significantly different from each other; they averaged 526 (±107) $g/m^2/h$ for the ILC and 477 (±81) $g/m^2/h$ for the Steele test. Sweating rate for the control test (666 ±134 $g/m^2/h$) was not significantly different than for the American system test (603 ±121 $g/m^2/h$). Sweating rates with the ILC and Steele systems were significantly lower than for the control test. In addition, sweating rate with the Steele system was lower than with the American system.

Thermal Ratings: Comparing the ILC and Steele cooling systems, there were no significant differences in numerical ratings of thermal sensation (hourly). Both the ILC and Steele systems were rated numerically lower, i.e., cooler, than the control test. The Steele system was also rated cooler than the American system ($p<0.05$). When the American system was used, thermal ratings were not significantly different from the control test. After 2 hours of heat exposure, thermal ratings averaged "hot to very hot" during the control test, "warm" with the American system and "slightly warm to warm" with the Steele and ILC systems.

Coolant changes: In all tests of the Steele cooling system, only one coolant change was required per subject during the 3-hour heat exposure. The average time of the coolant change for the eight subjects was 117 (±13) minutes. In five of the eight tests of the ILC cooling system, one coolant change was required per subject; three subjects required a second coolant change. The average time for the first coolant change was 98 (±9) minutes. Of the six subjects who completed 3 hours using the American system, two required one coolant change and four required two coolant changes. The average time for the first change was 85 (±9) minutes. The coolant in the Steele system (117 minutes) lasted statistically longer than the coolant in either the ILC system (98 minutes) or the American system (85 minutes).

Operational Difficulties: In the present evaluation, two ILC cooling systems were used; each was used for four, 3-hour periods for a total of 12 operating hours. During this time, the plastic zipper on the backpack of one of the systems broke. On both systems, the pull tabs used to open the seal of the plastic bag broke. In one of eight instances a battery failed and had to be replaced before the 2 hour time. It was noted that the drain tube (used during coolant changes) was difficult to close without spilling water. The two ILC systems used in this evaluation were purchased in 1988 and had not been previously used. In 1987 ILC Dover changed the manufacturer of its Cool Vest and some changes to the system were made. One of those changes included reducing the size of the plastic bag which holds the water and ice. In the present evaluation, 2.3 kg of standard ice cubes filled the bag; in previous evaluations using the older ILC systems, either 2.7 (1) or 2.5 kg (2) of ice were used. With the smaller plastic bag, the ice will have to be replaced slightly more often. The other problems noted above did not occur in previous evaluations of the older ILC systems (1,2).

No operational difficulties occurred with any of the Steele cooling systems during our evaluation. One of the American vests had to have some stitching removed in order to fit one of the gel packs. Due to the vest design and location of the gel packs, the American vest could not be adjusted to allow good contact between the torso and the gel packs.

Subjects' Comments: six of the eight subjects rated the Steele vest as their overall preference of the three cooling systems (one subject rated the ILC as his first choice, and one subject rated the ILC and Steele as equal). With one exception, the ILC cooling system was rated second best and the American system was rated third. The reasons subjects gave for rating the Steele system as their first choice included: better fit and more consistent cooling than the other two systems, and more comfortable weight distribution and lower profile than the ILC system. Several subjects stated that the straps on the Steele vest were too long, and that for better fit they would prefer a slightly smaller vest (the Steele vest comes in one size only). In most cases the ILC cooling system was rated second. Although several subjects commented that the ILC system felt cooler than the Steele immediately following the coolant change, they thought the Steele's cooling was more consistent. Three subjects stated that the ILC system felt heavier than the Steele and that the ILC tended to slide down on the back. They also commented that the ILC was bulkier and would be more difficult to operate than the passive cooling systems. Most of the comments on the American system were negative - subjects stated that they felt very little cooling with this system and could not adjust the vest to hold the gel packs against the body.

Two of the three portable cooling systems tested in this evaluation - the ILC Dover Cool Vest and the Steele SteeleVest - were similarly effective in reducing thermal strain when used by subjects exercising in a 43^{0}C (110 F), 45% rh environment. The third cooling system - the American Vest Stay Cool Vest - reduced body core temperature compared to no cooling, but was not nearly as effective as the other two systems. When the American system was used, skin temperature, heart rate and sweating rate were not reduced compared to control values, and were generally higher than when either the ILC or Steele systems were used. Because skin temperature was not reduced with the American system, the gradient for heat transfer from the core to the skin was less than when the other two cooling systems were used. This reduced core-to-skin temperature gradient resulted in higher skin blood flow and therefore higher heart rates when the American system was used. Combined with the higher sweating rate, this additional physiological strain probably contributed to the reduced tolerance time when the American system was used.

The comparative table below describes several factors which influenced the effectiveness and coolant life of the cooling vests:

	Vest Surface Area For Cooling (cm^2)	Chest Temperature (Degrees C)	Coolant (kg)	Coolant Insulation
ILC	1710	28.6	2.3	Yes
Steele	2761	34.8	4.6	Yes
America	1381	37.2	2.3	No

The third and fourth factors the amount of coolant and the insulation between the coolant and the outside environment - are design features of the systems which affect how often the coolant must be replaced. In addition to these design features, the individual's work rate and clothing and the environmental heat load will also influence coolant life.

The surface area available for cooling in the ILC vest (1710 cm^2) is only 62% of that in the Steele vest (2761 cm^2); however, in this evaluation, chest temperatures with the ILC system were 6^{0}C lower than the Steele. This may be because the ILC's design allows for good contact of the vest to the body, and there is very little insulation between the body and the circulating liquid. The net result was that the ILC and the Steele were similarly effective in reducing heat stress.

The poor results of the American cooling system in reducing heat strain may be due to two reasons. First, the surface area available for cooling in the American vest is only 81% of that in the ILC and 50% of that in the Steele. Second, the American vest cannot be tightened to make good contact between the body and the gel packs; evidence for this was seen in the high chest temperatures measured even when the gel packs were completely frozen.

The cooling vests used in the present evaluation were made of nylon (ILC, American) or cotton/Thinsulate (stele). None of these materials is fire-retardant; in accordance with the Navy's Passive Fire Protection Program, the vests could not be used onboard ship without first being covered with a fire-retardant fabric. In the previous shipboard evaluation, per direction from the Special Assistant to the Secretary of the Navy, the vests were covered with a Kynol/Nomex fabric.

In summary, the ILC Dover Cool Vest and the SteeleVest were much more effective than the American Stay Cool Vest in reducing heat strain. Both the ILC system and the Steele system enabled Subjects to perform moderate exercise for 3 hours in a $43^{0}C$ ($110^{o}F$), 45% humidity environment. with either system, however, there are logistical concerns which must be addressed for shipboard use. When adjusted for duration between coolant changes, the Steele system used 70% more coolant by weight and approximately 20% more coolant by volume than the ILC. In that respect the ILC may be considered a more efficient cooling system than the Steele. Because of its mechanical nature, however, the ILC may require more maintenance than the passive cooling system. The ILC batteries require storage space and must be recharged for a minimum of 8 hours after every 2-3 hours of use. Ship's personnel must evaluate the logistical burdens of the additional freezer capability required by the Steele system at the maintenance and battery support required by the ILC system. If the added freezer capability is not a limiting factor, the Steele system, because of its simplicity, ease of use and low profile is recommended for potential shipboard use.

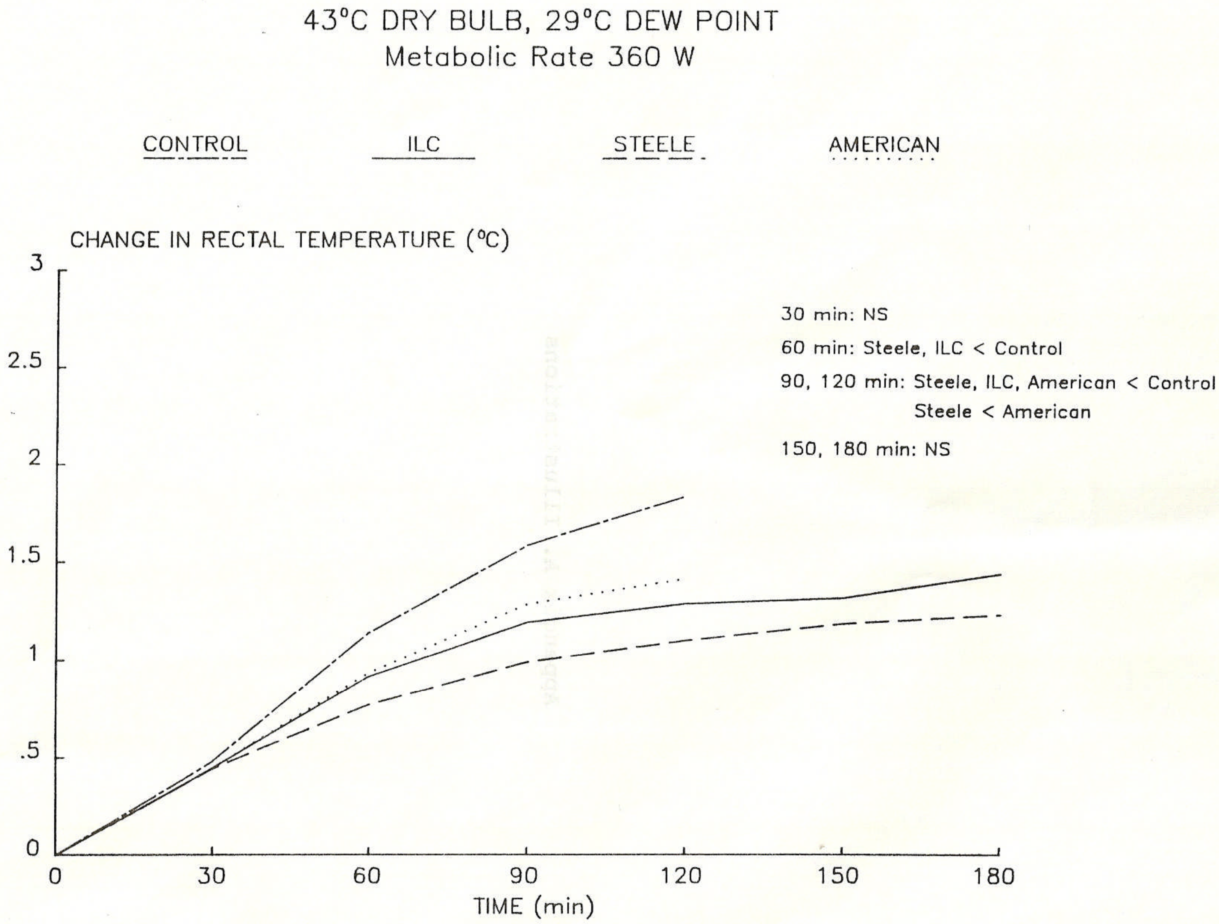

FIG. 1. Change in rectal temperature from initial value for the control and cooling tests.

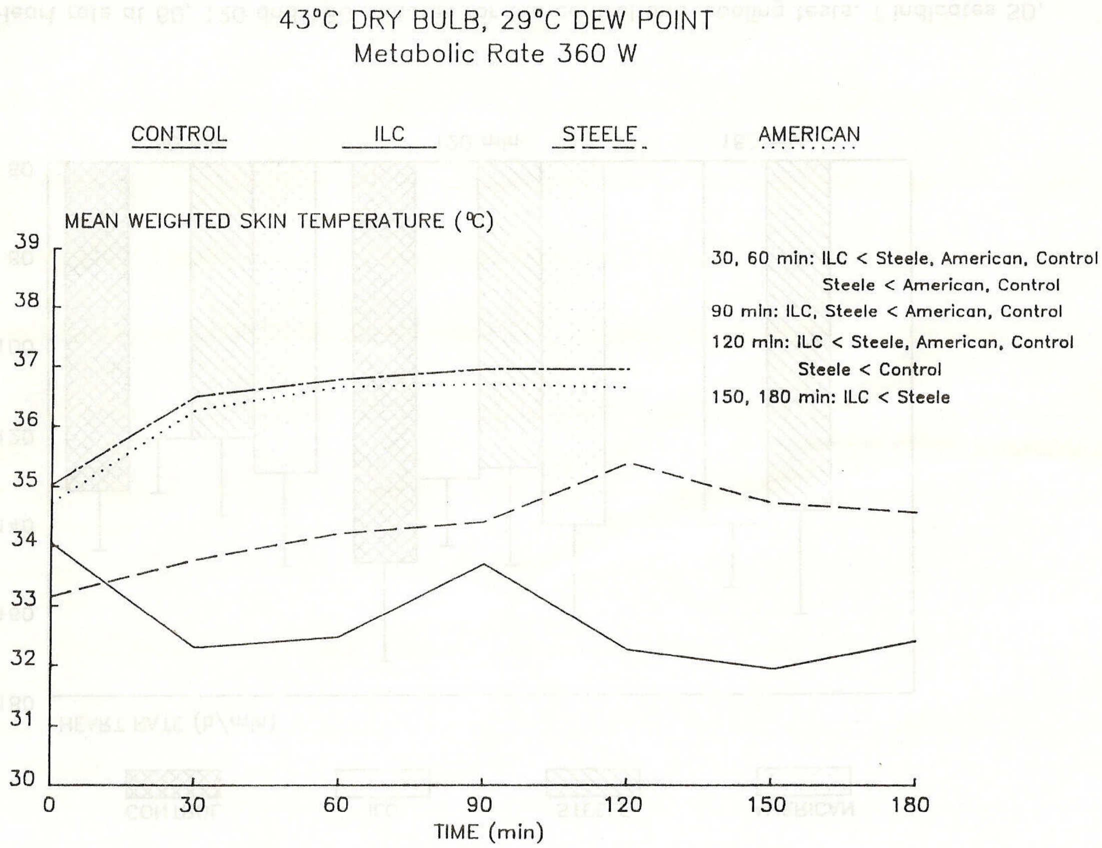

FIG. 2. Mean weighted skin temperature for the control and cooling tests.

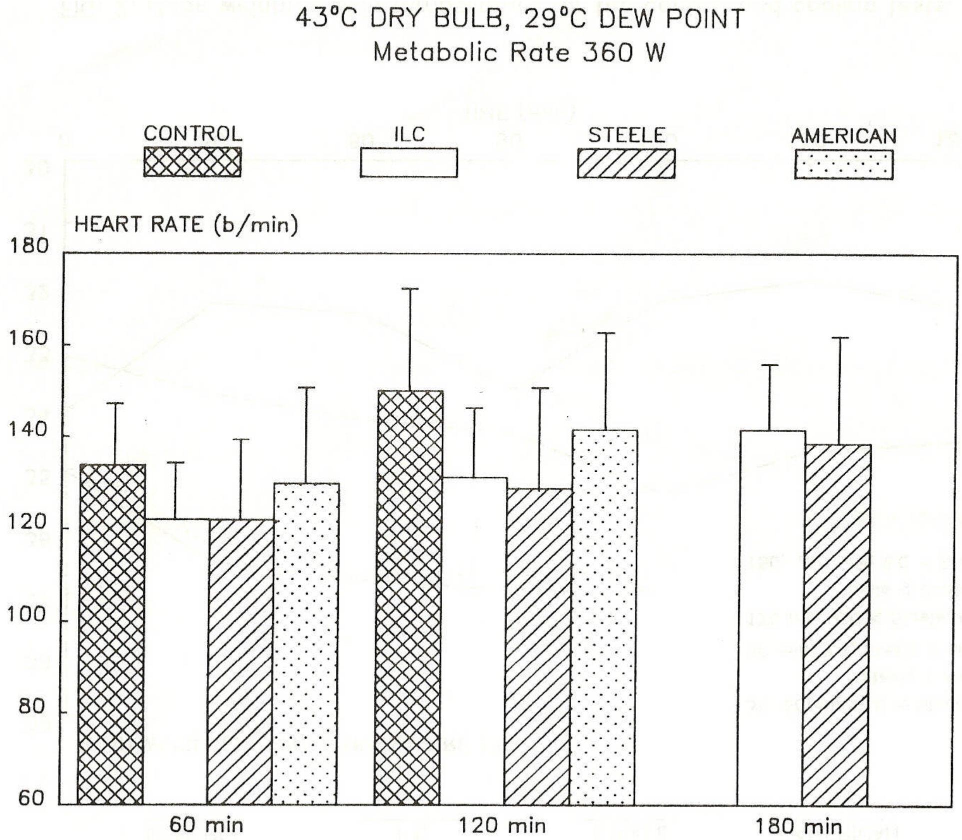

FIG. 3. Heart rate at 60, 120 and 180 minutes for the control and cooling tests. T indicates SD.

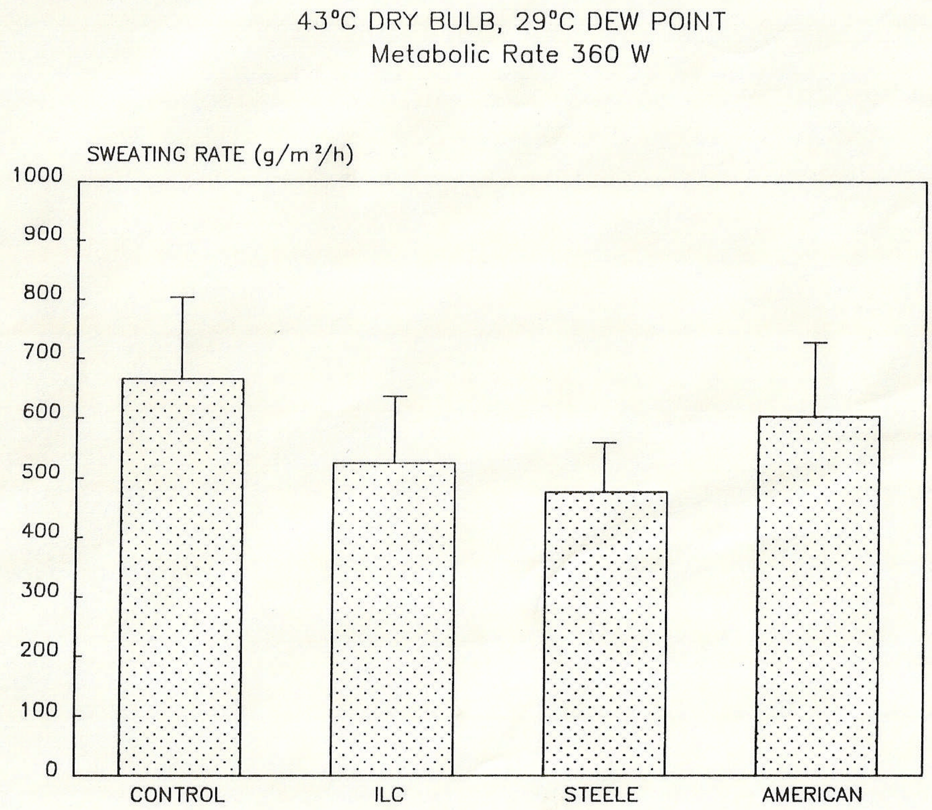

FIG. 4. Total body sweating rate for the control and cooling tests. T indicates SD.