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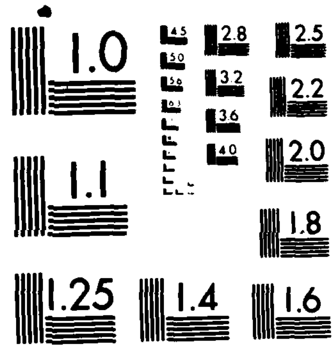

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We evaluated the effectiveness of an air-cooled vest in reducing thermal strain when supplied with five different dry bulb (db) and dew point (dp) temperature combinations. The combinations were selected to determine minimal air conditioning requirements for various military vehicles. Four male soldiers attempted twelve, 300-min heat exposures (49°C db, 20°C dp) at metabolic rates of 175 and 315 W. They wore chemical protective clothing over the combat vehicle crewman uniform; on ten of the test days, they also wore the air-cooled vest. Air supplied to the vest ranged from 20-27°C db, 7-18°C dp. Without

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EFFECTIVENESS OF AN AIR-COOLED VEST USING SELECTED AIR TEMPERATURE AND HUMIDITY COMBINATIONS

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Running Head: Air-cooled vest

ABSTRACT

We evaluated the effectiveness of an air-cooled vest in reducing thermal strain when supplied with five different dry bulb (db) and dew point (dp) temperature combinations. The combinations were selected to determine minimal air conditioning requirements for various military vehicles. Four male soldiers attempted twelve, 300-min heat exposures (49°C db, 20°C dp) at metabolic rates of 175 and 315 W. They wore chemical protective clothing over the combat vehicle crewman uniform; on ten of the test days, they also wore the air-cooled vest. Air supplied to the vest ranged from 20-27°C db, 7-18°C dp. Without the vest, endurance times were 118 min (175 W) and 73 min (315 W). Endurance times with the vest were 300 min (175 W) and 242-300 min (315 W). Rectal temperatures, heart rates and sweating rates were reduced dramatically with the vest. There was a trend for the vest to be more effective when supplied with air at the lower dry bulb temperature. We conclude that effective combinations of cooled and dehumidified air can be provided on military vehicles to reduce the crewmen's thermal strain, with minimized size and weight penalties.

Index terms: auxiliary cooling, heat stress, microclimate cooling, chemical protective clothing.

INTRODUCTION

With the increased threat of chemical warfare, recent research has focused on the ability of the soldier to operate while wearing protective clothing. The insulation and low moisture permeability of the chemical protective clothing severely limit the body's normal heat dissipating mechanisms, most markedly the evaporation of sweat. The magnitude of this heat stress problem is well documented (2-4, 7-10). The US Army Natick Research and Development Center (USANRDC) has developed an air-cooled microclimate vest for soldiers wearing chemical protective clothing. The vest is designed to provide 15 standard cubic feet per minute (scfm) of conditioned air to the chest, neck and back and 3 scfm to the face (see Description of microclimate system, Methods section). Previous tests of the vest have shown it to reduce thermal strain and increase tolerance time of soldiers wearing protective clothing in the heat (5,6,9). During those tests, air supplied to the vest was quite cool and dry. It is desirable to determine minimum air conditioning requirements, which would reduce the space and weight penalties imposed on military vehicles.

The present study evaluated the effectiveness of the USANRDC air-cooled vest when various combinations of vest air dry bulb and dew point temperatures were used. Five combinations of air supplied to the vest were tested: dry bulb temperatures ranged from 20-27°C and dew point temperatures ranged from 7-18°C. Environmental conditions were constant at 49°C db, 20°C dp, typical for the interior of many combat vehicles in hot environments. Subjects exercised at a low (175 W) and a moderate (315 W) metabolic rate, typical of crewmen operating inside vehicles. Control tests during which subjects did not wear the air-cooled vest, but received 3 scfm of ambient air to the facepiece only, were also conducted.

METHODS

Subjects. Four male soldiers participated in the study. They received a physical examination and were informed of the purpose and procedures of the study, any known risks and their right to terminate participation at will without penalty. Each expressed understanding by signing a statement of informed consent. The physical characteristics of the subjects were: age, 21 years (range 19-24); height, 175 cm (range 167-180); weight, 70.6 kg (range 63.0-75.7); body surface area, 1.86 m^2 (range 1.70-1.94); and body fat, 12% (range 6-22) as estimated from skinfold thickness at four sites (1).

Experimental design. Testing was conducted in March in Natick, Massachusetts. All four subjects had previous experience wearing the chemical protective clothing for at least four hours continuously. Subjects were heat acclimated for five consecutive days by walking on a level treadmill at 1.34 $m \cdot s^{-1}$, 3 hours per day, in a 49°C db, 20°C dp environment. During the heat acclimation, they wore shorts, T-shirts, socks and tennis shoes.

Following acclimation, the four subjects attempted twelve, 300-min heat exposures. Environmental conditions in the climatic chamber were kept constant at 49°C db, 20°C dp, 1.1 $m \cdot s^{-1}$ wind speed. During these heat exposures, subjects exercised at time-weighted mean metabolic rates of 175 W and 315 W, as can be expected of crewmen operating inside an armored vehicle (9). These two rates were obtained by having the subjects alternate seated rest (metabolic rate ~105 W) with treadmill walking at 1.01 $m \cdot s^{-1}$ (metabolic rate ~380 W when wearing protective clothing). The 175 W metabolic rate was obtained by having the subjects rest for 45 min and walk for 15 min of each hour. The 315 W rate was obtained by having them walk for 45 min and rest for 15 min of each hour.

During the heat exposures, subjects wore the combat vehicle crewman uniform, fragmentation protective vest and MOPP level 4 protective clothing (overgarment, overboots, mask/hood, gloves). On ten of the twelve test days, they also wore the USANRDC air-cooled vest. The air to the cooling vests was provided by an air conditioning unit located outside the climatic chamber. Five combinations of dry bulb and dew point temperatures were supplied to the vest. Dry bulb temperatures ranged from 20-27°C and dew point temperatures ranged from 7-18°C. During the two control tests, subjects did not wear the air-cooled vest. In these tests, the facepiece was ventilated with 3 scfm of ambient air (using a tank M8 blower). The conditioned air combinations and the test schedule are provided in Table 1.

TABLE 1 HERE

Description of microclimate system. The USANRDC vest is designed to provide chest, neck and back cooling via a hose and manifold system mounted on an open weave fabric (see Figure 1). The hoses are lightweight, crush-resistant and maintain a constant inside diameter upon bending. Eighteen scfm of conditioned air is split by an air connector into 15 scfm to the vest and 3 scfm to the ventilated facepiece. The air is distributed through the chest and back manifolds and holes in the hoses at a ratio of approximately 40% to the chest, 20% to the neck and 40% to the back. The ventilated facepiece can be used without the vest. The vest side of the air connector is self-sealing when disconnected to prevent the entry of chemical agents. The vest is worn over the undershirt and under the body armor and weighs 0.45 kg.

FIGURE 1 HERE

Cooling capacity of vest. Maximal theoretical evaporative and convective cooling capacities of the vest when supplied with the five different air combinations are shown in Table 1. The maximal dry convective cooling capacity was calculated as the product of flow rate, density and specific heat of air, and gradient between inlet air temperature and an assumed skin temperature of 35°C. The evaporative cooling capacity was calculated as the product of flow rate, latent heat of evaporation of water at 35°C, and gradient between moisture content of inlet air and air saturated at an assumed skin temperature of 35°C.

Physiological measurements. Rectal temperatures were measured with thermistor probes, inserted approximately 10 cm beyond the anal sphincter. The electrocardiogram was obtained from chest electrodes (CM5 placement) and displayed on an oscilloscope and cardiotachometer unit. Total body sweating rates were calculated from pre- and post-test nude body weights, adjusted for water intake. Subjects were encouraged to drink water during the heat exposures. Since the M17 mask has no drinking tube, a plastic tubing "straw" was threaded under the hood and mask.

The test was terminated for any subject: whose rectal temperature reached 39.5°C, whose heart rate exceeded 180 $b \cdot min^{-1}$ for five minutes continuously, who voluntarily withdrew, or who was removed at the discretion of the medical monitor or principal investigator.

Statistical treatment. The data from the control tests (no cooling) are presented only descriptively and graphically. Separate statistical analyses were performed on the 175 and the 315 W metabolic rate data.

A one-way repeated measures analysis of variance was used to compare endurance times among the five experimental (cooling combinations) tests at 315 W. (No statistics were performed on the 175 W endurance time data, since all times were 300 min.) Rectal temperatures at each metabolic rate (175 and 315 W) and heart rate (175 W) data were analyzed using three-way (cooling combination by rest/walk by time) repeated measures analyses of variance. Heart rate (315 W) data during walking were analyzed using a two-way (cooling combination by time) repeated measures analysis of variance. The 315 W analyses include only the first 120 min of data, because one of the subjects dropped out at that time. The 175 W analyses include all 300 min of data. For both the 175 and 315 W data, sweating rates were analyzed using one-way (cooling combination) repeated measures analyses of variance. Significance was accepted at the 0.05 level.

RESULTS

Figure 2 presents endurance times for the five experimental (cooling combinations) tests and the control tests. When the air-cooled vest was used, all subjects were able to complete the 300-min exposures at the 175 W metabolic rate. For the control test, endurance time was 113 (± 27) min.

FIGURE 2 HERE

Figure 3 illustrates rectal temperature responses at the 175 W metabolic rate, for the experimental and control tests. There were no significant differences in rectal temperature responses among the five cooling combinations during either the rest periods or the exercise bouts ($p>0.05$). After the first hour of exposure, rectal temperatures did not increase significantly over time when cooling was provided. Rectal temperatures were higher at the end of each exercise bout than at the end of each subsequent rest period ($p>0.05$). For the five cooling combinations, average rectal temperatures at the end of the final rest period (285 min) ranged from 37.2 to 37.4°C. At the end of the final exercise bout (300 min), rectal temperatures ranged from 37.4 to 37.6°C for the five combinations.

FIGURE 3 HERE

Figure 4 presents mean heart rates during the 175 W tests, during the first and final rest periods (rest 1 and rest 5), and at the end of the first and final exercise bouts (walk 1 and walk 5). The data is shown only for the experimental tests, since subjects terminated the heat exposures early during the control test. There were no significant differences in the heart rates among the five cooling combinations during either the rest periods or exercise bouts ($p>0.05$). Heart rates during the final rest period (rest 5) ranged from 76 to 92 $b \cdot min^{-1}$ for the five cooling combinations. At the end of the final exercise bout (walk 5), heart rates ranged from 123 to 134 $b \cdot min^{-1}$ for the five combinations. Heart rates increased over time ($p<0.05$).

FIGURE 4 HERE

The sweating rates for the five cooling combinations as well as for the control tests are presented in Figure 5. At 175 W, the sweating rate for combination A was significantly lower than for combinations C, D and E ($p<0.05$). The sweating rate for combination B was lower than D ($p<0.05$). The average sweating rates for the five cooling combinations at 175 W were: A, 198; B, 223; E, 267; C, 273; and D, 290 $g \cdot m^{-2} \cdot h^{-1}$. For the control test at 175 W, sweating rate averaged 737 $g \cdot m^{-2} \cdot h^{-1}$.

FIGURE 5 HERE

At the 315 W metabolic rate, endurance times were not significantly different among the five cooling combinations ($p>0.05$) (see Figure 2). Mean endurance times ($\pm$SD) were: 242 ($\pm$74), 275 ($\pm$30), 281 ($\pm$38), 293 ($\pm$14) and 300 ($\pm$0) min for cooling combinations E, C, D, A and B, respectively. For the control test at 315 W, endurance time was 73 ($\pm$ 19) min.

Rectal temperature responses at 315 W are illustrated in Figure 6. Rectal temperatures were lower for combination A than C and E ($p<0.05$). With all five cooling combinations, rectal temperature decreased during the rest periods, but increased over time ($p<0.05$). Peak rectal temperatures after the fourth exercise bout (~235 min) averaged 38.0 for combination A (n=4), 38.2 for B (n=4), 38.3 for D (n=3), 38.5 for E (n=3) and 38.6°C for C (n=4).

FIGURE 6 HERE

Figure 7 presents mean heart rates at 315 W, at the end of each of the first four exercise bouts (walks 1-4). Heart rates increased over time ($p<0.05$). There were no significant differences in heart rates among the five cooling combinations ($p>0.05$). At the end of the fourth exercise bout (walk 4), heart rates ranged from 144 to 156 $b \cdot min^{-1}$ for the five combinations.

FIGURE 7 HERE

At 315 W, the sweating rate for combination A was lower than D ($p<0.05$). The mean sweating rates for the five cooling combinations at 315 W were: A, 380; B, 412; C, 426; E, 504; and D, 530 $g \cdot m^{-2} \cdot h^{-1}$ (see Figure 5). The sweating rate for the control test was 1086 $g \cdot m^{-2} \cdot h^{-1}$.

DISCUSSION

In the control tests using ventilated facepiece only, endurance time was limited to only 118 min at the 175 W metabolic rate and 73 min at the 315 W rate, for soldiers working in the heat in protective clothing. The USANRDC air-cooled vest significantly extended endurance time. With the vest, all subjects were able to complete the 300-min heat exposures at the lower metabolic rate. At the higher metabolic rate, in 14 of 20 instances subjects were able to complete the heat exposures; average endurance time was 280 min. The difference in endurance times and rectal temperature responses when the air-cooled vest is used is seen in Figures 3 and 6. During the control test, even at the 175 W metabolic rate when subjects sat at rest for 45 min of each hour, rectal temperatures increased dramatically (Figure 3). During the initial 45-min rest period, there was little or no rise in rectal temperature during the control test. The thermal stress imposed by the first exercise bout (15 min of walking at 1.01 $m \cdot s^{-1}$) caused a sharp increase in rectal temperature. Although the subjects then rested for 45 min, rectal temperature continued to rise, becoming less steep only toward the end of the rest period. This demonstrates the intolerance of soldiers wearing protective clothing in hot environments to even short-term, light intensity work.

Among the five experimental tests, cooling combination A resulted in statistically lower rectal temperatures (315 W only) and sweating rates, and combination B resulted in lower sweating rates at 175 W. In addition, subjects usually had the lowest rectal temperatures, heart rates and sweating rates when the vest was used with cooling combination A. It is not surprising that this combination resulted in the lowest physiological strain. It was the coolest and driest air of the five combinations tested and therefore had both the highest evaporative and convective cooling capacities. Combination B often resulted in the second lowest physiological responses. Combination B had a lower evaporative cooling capacity than A, but the same convective cooling. The convective cooling capacity both of A and B was about 120 W, as compared to about 65 W for combinations C, D and E. The endurance time data agree with the trends in the physiological data. The number of subjects removed early from the heat exposures and their endurance times were: one in combination A (272 min), none in B, two in C (240 and 259 min), one in D (223 min) and two in E (145 and 224 min).

There was a trend for subjects to have the highest rectal temperatures and heart rates when cooling combination C was used. This is not explained by the cooling capacity of combination C, as it had the same convective cooling capacity as D and E, but the highest evaporative capacity of the three. Combination C had a lower convective cooling capacity than A and B. Therefore it may be that the convective cooling capacity of the air supplied to the vest significantly alters its effectiveness.

It is not obvious why the cooling combinations that appeared to be most effective (physiologically) should be distinguished by high convective cooling capacity, rather than evaporative cooling capacity. The ratio of maximal evaporative to convective cooling capacity (Table 1) ranges from 4.4 to 8.5. Actual evaporative and convective cooling rates were both probably lower than the maximal values, but since we could not measure dry bulb and dew point temperatures of the air leaving the vest, we cannot compute these actual rates. However, the ratios of actual evaporative to convective cooling rate, computed assuming the Lewis relation of 2.2°C/torr, and a totally wet skin under the vest, range from 4.9 to 9.4, similar to the ratios of maximal evaporative to convective cooling capacity. Since sweating rate over the whole body at 315 W ranged from 707 to 986 $g \cdot h^{-1}$, corresponding to potential evaporative cooling rates of 476-664 W, the assumption of a totally wet skin under the vest with all cooling combinations may be wrong, unless nearly all sweating occurred on skin under the vest. Furthermore, it is likely that non-uniform air circulation around the vest would have kept some skin areas drier than others, even if total trunk sweating exceeded the evaporative capacity of a particular cooling combination.

The contribution of dry convection to total cooling may thus be greater than implied by comparing the last three columns of Table 1. This, in turn, would help explain why combinations A and B, with the greatest potential convective cooling, were associated with the least thermal strain, even though maximal total cooling in B is only slightly higher than in C, which was associated with the greatest thermal strain.

The metabolic rate of 175 W used in the present study approximates that of a driver or gunner of an armored vehicle (9). A metabolic rate of 240 W was used in a previous test of the USANRDC air-cooled vest, under the same environmental conditions (5). In that study, the air supplied to the cooling vest was 16°C dry bulb, 2°C dew point. The subjects were able to complete the 720-min (12-hour) heat exposure; final rectal temperature averaged 37.7°C. In the present study, final rectal temperature after 300 min (5 hours) was 37.5°C for the five cooling combinations. Figure 3 illustrates the nearly flat rectal temperature response in the present study at 175 W. It is reasonable to expect that, under these conditions, the air-cooled vest would enable subjects to continue for considerably longer than our 5-hour test period.

The 315 W metabolic rate used in the present study approximates that of an armored vehicle's loader or commander (9). This was similar to the 340 W metabolic rate tested previously, under slightly more stressful environmental conditions (5). In that study, 16°C dry bulb, 2°C dew point air was provided to the vest. Rectal temperature after 180 min was 38.5°C. In the present study, rectal temperature averaged 38.3°C after 300 min with the five cooling combinations. The air-cooled vest reduced but did not prevent body heat storage. Subjects were able to complete the five-hour heat exposures 70% of the time. Eighty-five percent of the time, subjects were able to complete at least four hours. Therefore, with the air-cooled vest endurance time is extended, but limited to about 5 hours at the higher metabolic rate.

At the 175 W metabolic rate, sweating rates averaged 737 $g \cdot m^{-2} \cdot h^{-1}$ in the control test (ventilated facepiece only), and 250 $g \cdot m^{-2} \cdot h^{-1}$ when the air-cooled vest was used. At 315 W, sweating rates averaged 1086 $g \cdot m^{-2} \cdot h^{-1}$ in the control test, and 450 $g \cdot m^{-2} \cdot h^{-1}$ with the vest. Sweating rates, and thus drinking water requirements, were therefore reduced with the air-cooled vest by 2-1/2 to 3 times. This is an obvious advantage for military operations conducted in hot environments, where supplies of drinking water may be limited. The reduced water requirement is also advantageous since drinking through the protective mask may be compromised due to procedural restrictions and fear of contamination.

In summary, the five cooling combinations tested in the present study were similarly effective in reducing thermal strain, and extending endurance time, of soldiers working in protective clothing. At the lower metabolic rate, the vest enabled subjects to thermoregulate at a constant body temperature. In the extreme environment tested (49°C db), the ability of the vest to extend endurance time is limited at the higher metabolic rate. There was a trend for the air-cooled vest to be more effective when supplied with air at a lower dry bulb temperature (higher convective cooling capacity). The air-cooled vest also significantly reduced sweating rates, and therefore water requirements.

ACKNOWLEDGEMENTS

Recognition is due the test subjects for their cooperation and commitment.

The views, opinions and/or findings in this report are those of the authors, and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other official documentation.

Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRDC Regulation 70-25 on Use of Volunteers in Research.

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FIGURE LEGENDS

Figure 1. Air-cooled vest developed by the US Army Natick Research and Development Center, Natick, MA.

Figure 2. Endurance times ($\bar{X}$, SD), 175 W and 315 W.

Figure 3. Rectal temperatures plotted across time for the five cooling combinations and the control test, 175 W.

Figure 4. Heart rates ($\bar{X}$, SD) during the first and final rest periods and exercise bouts for the five cooling combinations, 175 W.

Figure 5. Sweating rates ($\bar{X}$, SD) for the five cooling combinations and the control tests, 175 W and 315 W.

Figure 6. Rectal temperatures plotted across time for the five cooling combinations and the control test, 315 W.

Figure 7. Heart rates ($\bar{X}$, SD) during the first four exercise bouts for the five cooling combinations, 315 W.

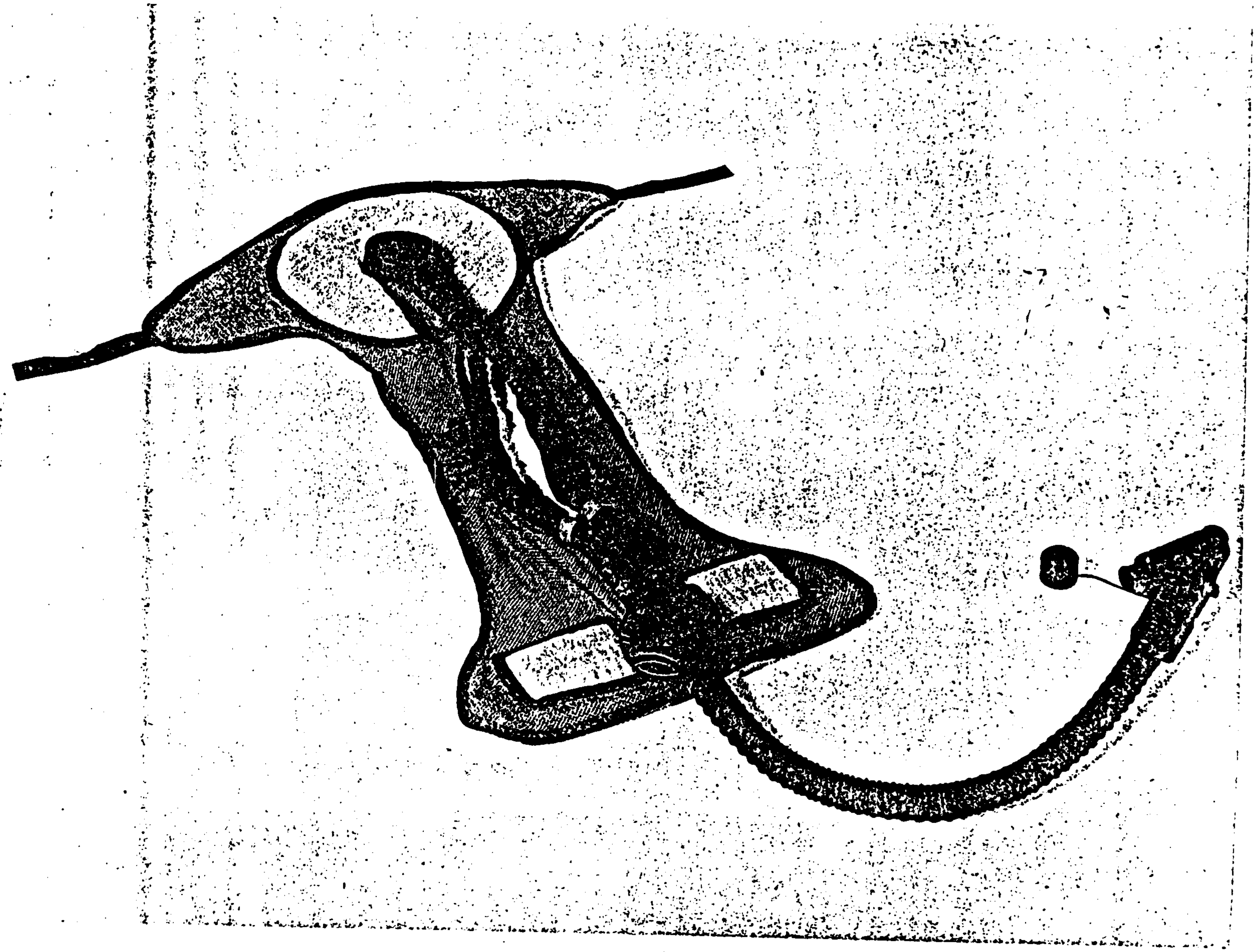
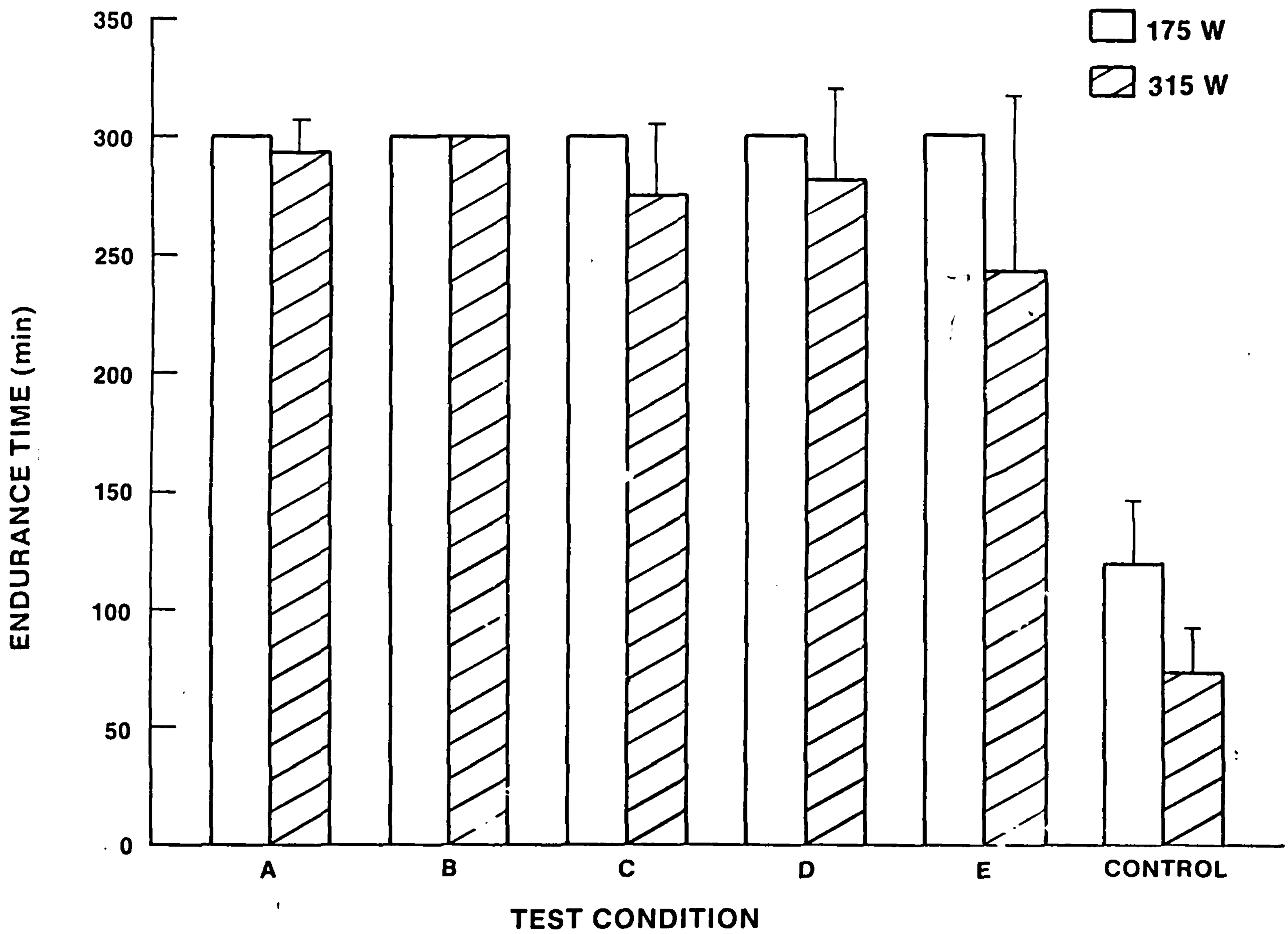


FIG. 1



ENDURANCE TIME (min)
350
300
250
200
150
100
50
0
A
B
C
D
E
CONTROL
TEST CONDITION
175 W
315 W

FIG. 6

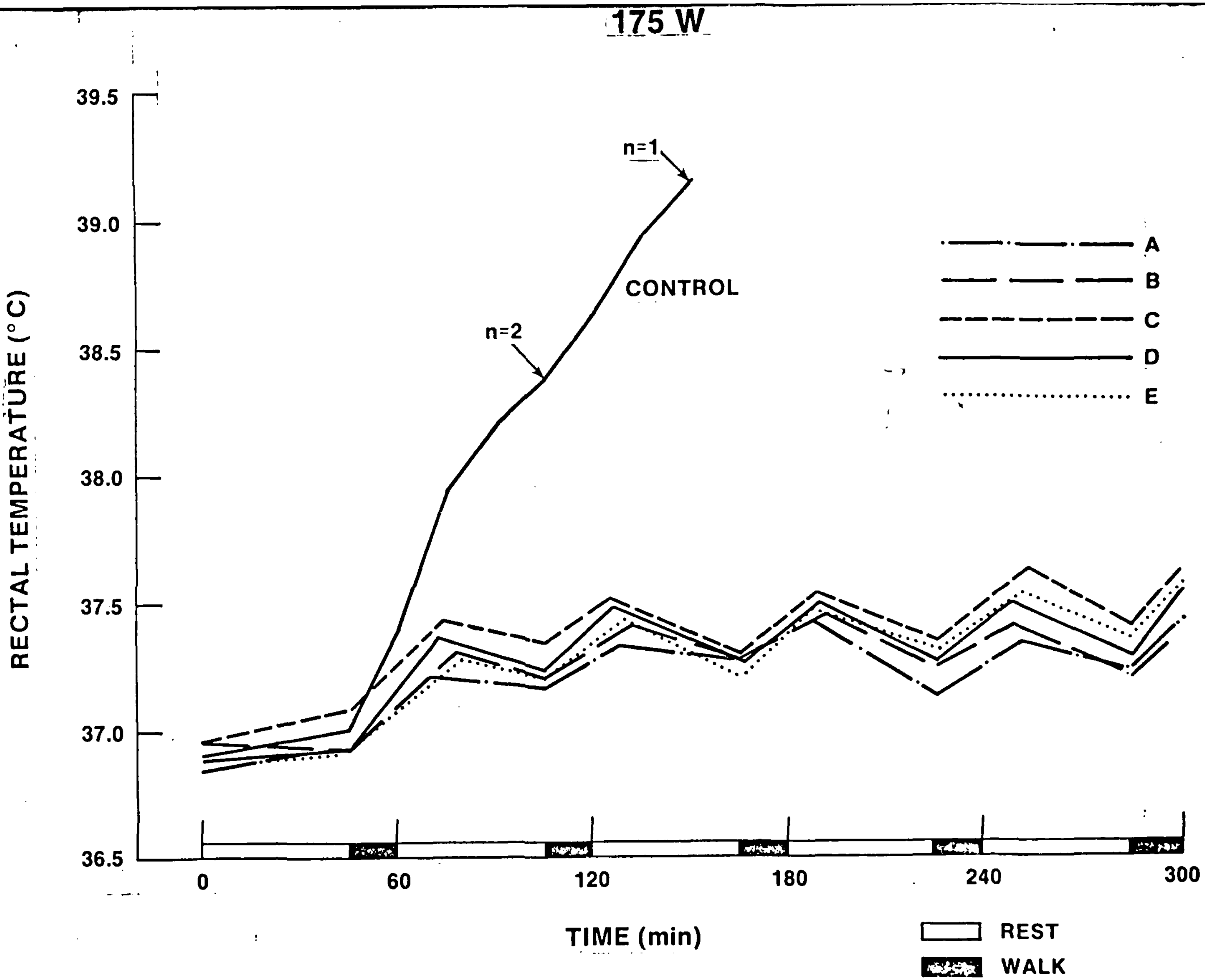

175 W
RECTAL TEMPERATURE (°C)
39.5
39.0
38.5
38.0
37.5
37.0
36.5
n=1
n=2
CONTROL
A
B
C
D
E
0
60
120
180
240
300
TIME (min)
REST
WALK

FIG. 3

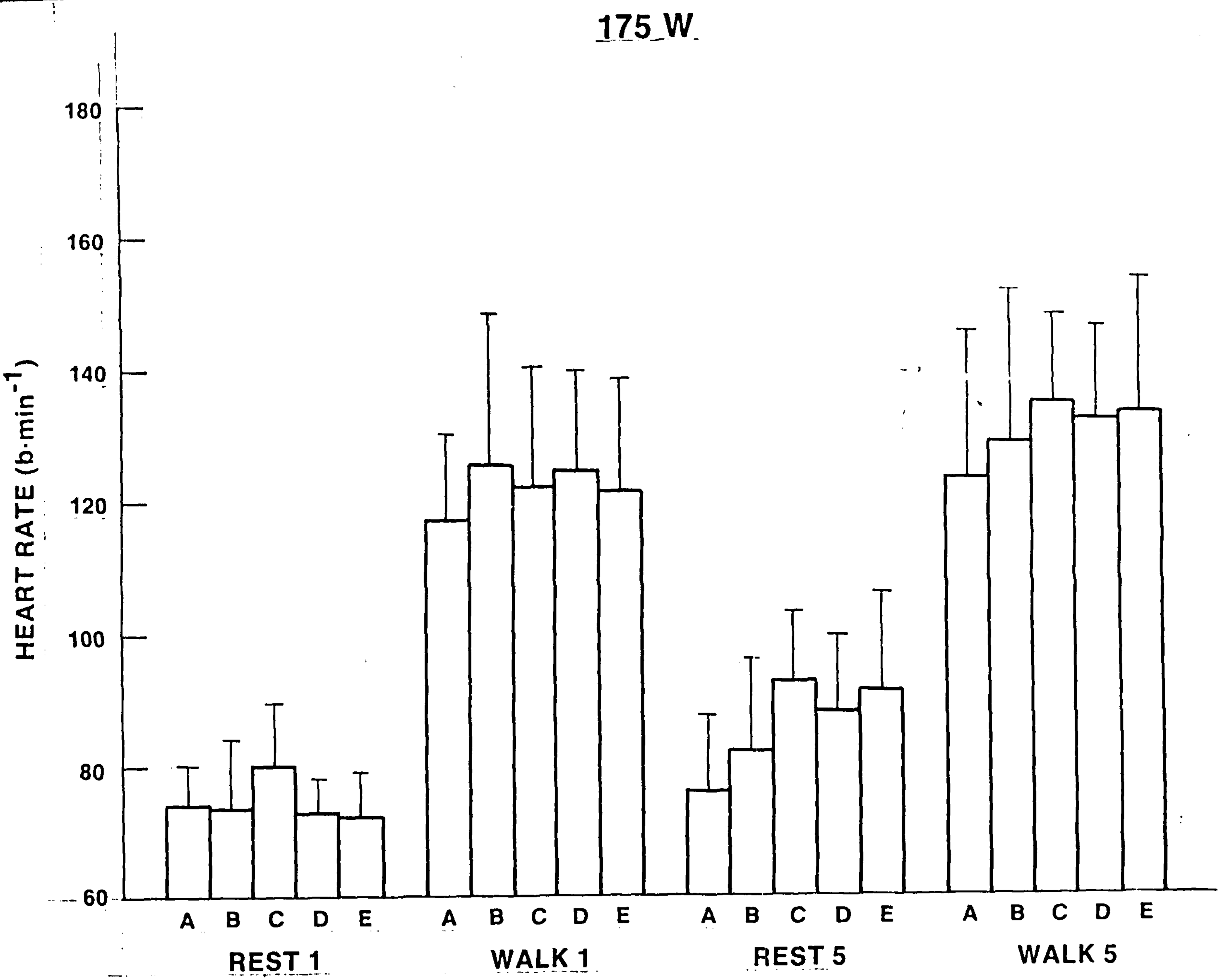

175 W
HEART RATE (b·min^{-1})
180
160
140
120
100
80
60
A B C D E
REST 1
A B C D E
WALK 1
A B C D E
REST 5
A B C D E
WALK 5

FIG. 4.

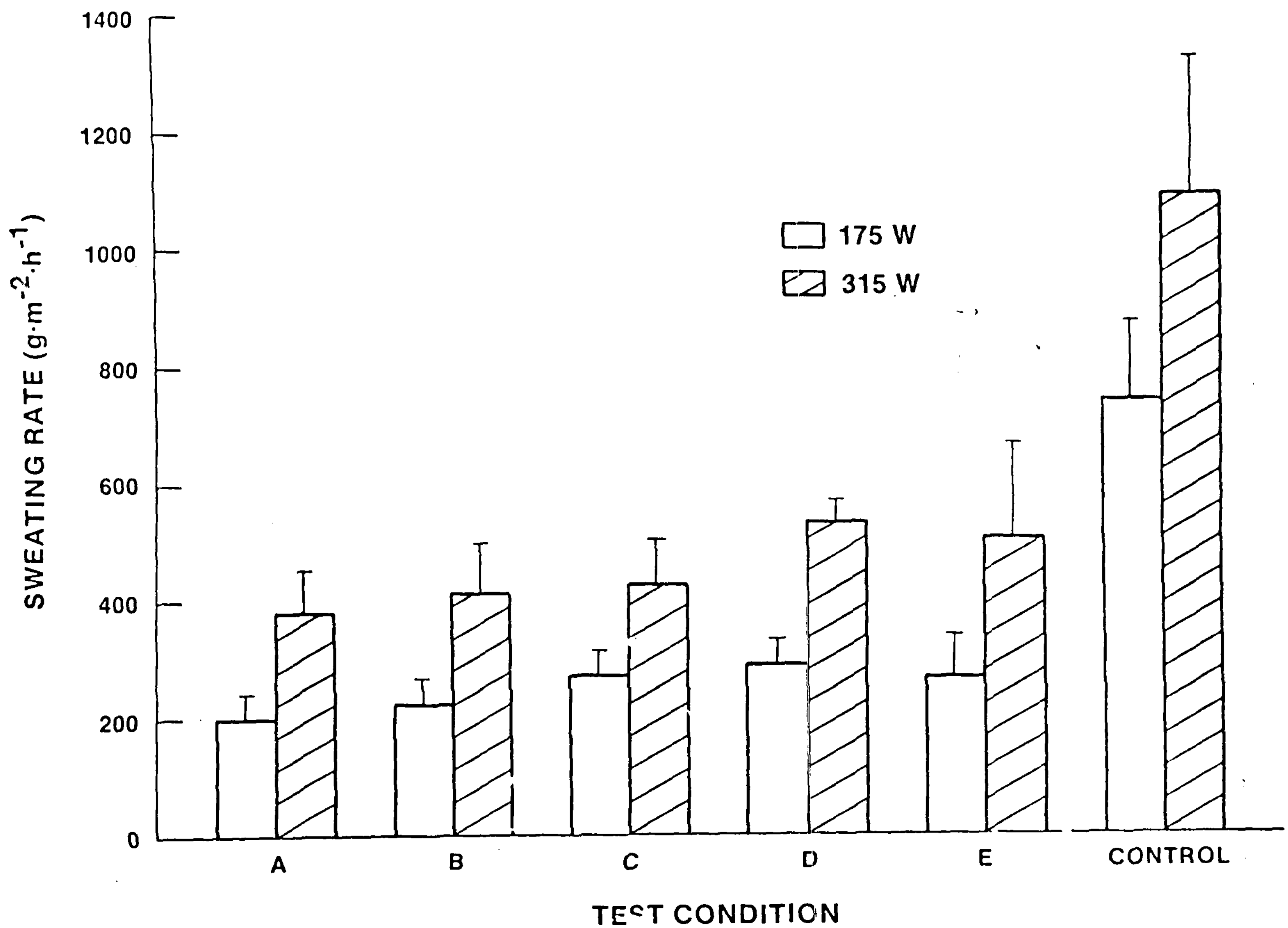

SWEATING RATE (g·m-2·h-1)
1400
1200
1000
800
600
400
200
0
175 W
315 W
A
B
C
D
E
CONTROL
TEST CONDITION

FIG. 5

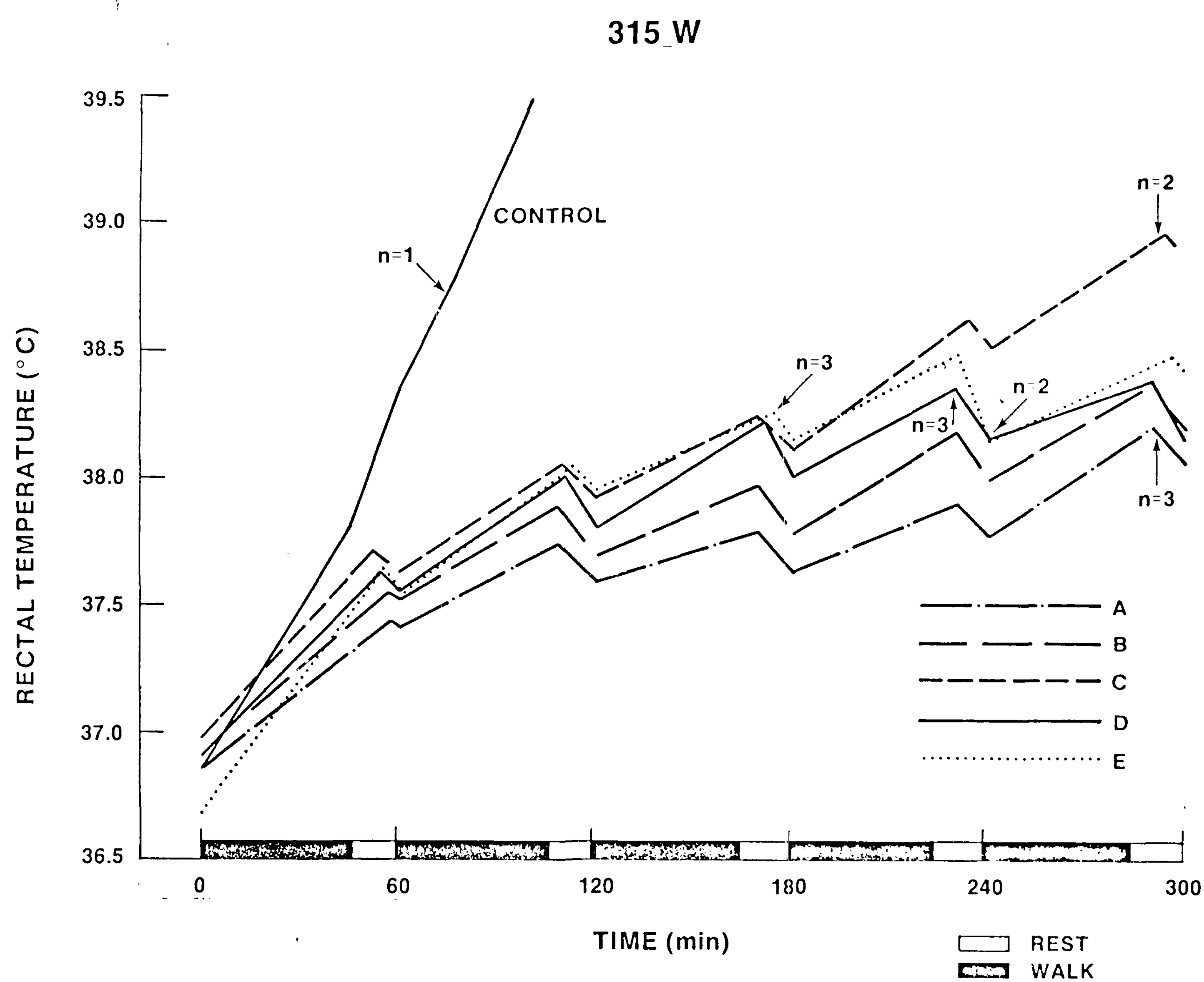

315 W
RECTAL TEMPERATURE (°C)
39.5
39.0
38.5
38.0
37.5
37.0
36.5
CONTROL
n=1
n=3
n=3
n=2
n=2
n=3
A
B
C
D
E
0
60
120
180
240
300
TIME (min)
REST
WALK

FIG. 6

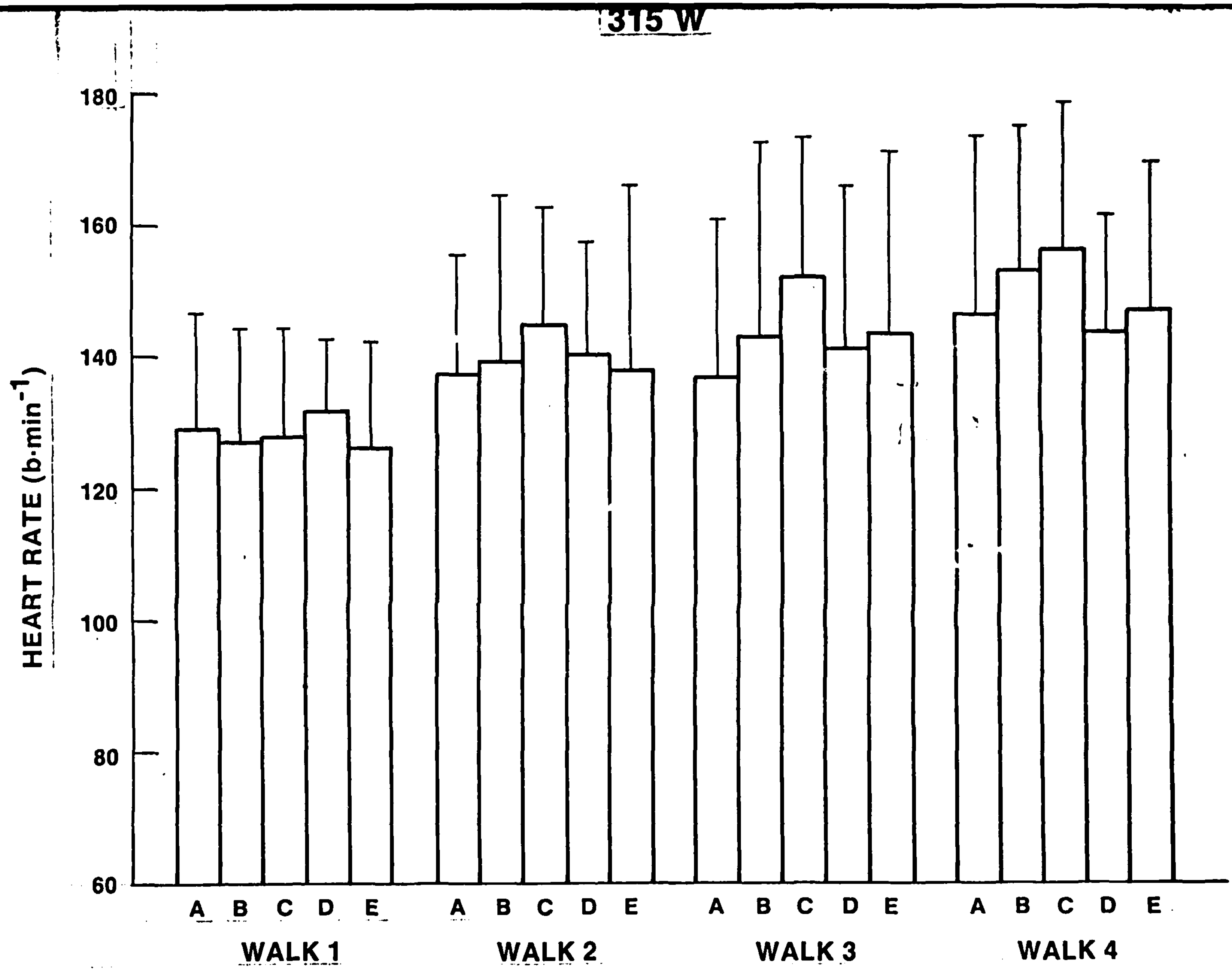

315 W
HEART RATE (b·min⁻¹)
60
80
100
120
140
160
180
A B C D E
WALK 1
WALK 2
WALK 3
WALK 4

FIG. 7

END

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